Model
JET ENGINES

THIRD EDITION

BY THOMAS KAMPS

THE MODELLER'S WORLD
SERIES

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Translated from the original German by Keith Thomas

Technical support by Tom Wilkinson

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Front Cover: The Wren MW44 is currently the smallest production model aircraft gas turbine - a marvel of miniaturisation.

Back Cover: Two PST 600R gas turbines power David Law's F-14 Tomcat.

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About the Author

Thomas Kamps, Dipl.-Kaufmann (approx. GB equivalent: B.Sc. business studies), born 1970. The author's liking for technology stretches back as far as he can remember. No sweets or chocolate in his Christmas stocking: it was full of electrical and mechanical components. Following his practical inclinations, he converted the family cellar workshop first into a precision engineering manufacturing workshop, and subsequently into an engine testing station. He is lucky – his neighbours are very sympathetic towards his hobby.

His practical capabilities are matched by his theoretical understanding – as witness the efficient, smooth-running engines he has made, a number of published articles, and not least this book.

Currently he is living in Zurich/Switzerland and works in a major Swiss bank. In addition to modelling he enjoys in his leisure time, reading, skiing and running.

Foreword

The idea of the gas turbine can be traced back to a patent filed by the Frenchman Guillaume in the year 1921, and is therefore quite old. However, it was many years before it proved possible to put the principle into practice in the form of the jet engine. In the late nineteen-thirties Hans-Joachim Pabst von Ohain and Sir Frank Whittle succeeded virtually simultaneously in applying the principle to construct a working engine.

It has taken us modellers a great deal more time to bring the idea to fruition. Too complex and too much trouble – that was always the verdict. Now and then rumours of successful model-scale gas turbines filtered to the outside world, but in many cases the engines were only capable of running when their constructor was dreaming.

As a result we in the model world were truly astonished to learn that amateurs had actually managed to produce working jet engines using relatively straightforward methods. The key to success lay not so much in high-level precision manufacture, but in simplicity and careful matching of individual components. As Kurt Schreckling has shown with his engines, if the design is right, then it is possible to use a wooden compressor wheel and still achieve a thrust:weight ratio comparable to that of a full-size aircraft jet engine.

However how do we go about designing a working jet engine? What special characteristics have to be considered? How do these engines work, anyway? This book attempts to answer these questions and many others, with the overall aim of helping you to understand this new type of engine. As such it is really aimed at the beginner to jets, but don't give up if you are already familiar with that special kerosene fragrance; you will still find a few useful ideas here even if you already have some experience of jet engines.

At this point I would like to offer my grateful thanks to my like-minded friends and colleagues for their help and encouragement. My special thanks must go to Kurt Schreckling, Bennie van de Goor and Han Jenniskens for their helpful and useful comments. I would also like to thank Karl-Heinz Collin and Arno Foerster, who were very helpful in imparting their specialist knowledge and information.

Foreword to the second edition

In recent years model jets have become more and more common at our flying fields. Many engines are available today. The new power source has been proven strong and reliable. World Championships have been held and the winning models were powered by jet engines. It seems that the ducted fan will be replaced soon. The growing interest in this small turbo engine is also reflected in the activities of the GTBA, the Gas Turbine Builders Association, which has approximately 1,700 members enrolled to date and which facilitates the exchange of ideas and practicalities.

The thrust figures have increased significantly. High tech materials are used in the area of the turbine wheels and bearings. By far, no other engine can give so much flight power to a model plane as a small gas turbine. Commercial engines offer thrusts of 100N or more. Electronic starters and control units become more and more standard. Therefore I have paid special attention to the constantly increasing number of production turbines now on the market and have revised and updated the description of these power plants.

In my eyes, the rapid development has only been possible because of an open information exchange by amateurs and home builders. Many commercial engines include the knowledge of many amateurs and their construction is in many ways very alike to the Microturbine, KJ-66 or its predecessors. In this second edition I have also improved the building instructions to achieve an easier construction with a solid performance.

At this point I wish to thank very sincerely all those who have helped me with tips and ideas, and especially Jesús Artés de Arcos, Otto Bruhn, Alfred Kittelberger, Ridi Reichstetter, Tom Wilkinson and John G. Wright.

Thomas Kamps, April 2002

Contents

Introduction

How do jet engines work?

Gas turbines have long since claimed a secure place for themselves in our world. Amongst the most obvious examples are the innumerable aircraft which day after day fly above us, trailing their wakes of condensation across the sky, but that's not all: gas turbines are at work where you might not know it: nowadays they are used more and more commonly in power stations, electricity generators, boat engines and much more.

Suddenly these engines are increasingly being used to propel models, and that is why we need to understand how they work. Unfortunately it is much more difficult to explain how a gas turbine works than to elucidate what is probably the most important energy machine of our time: the piston engine. There the immense pressure caused by explosive combustion moves a piston running inside a cylinder.

The principle is clear and comprehensible. Alas, it is just impossible to explain in so few words how a gas turbine works. Here we find spinning rotors and wheels, gas flow and energy conversion, but don't let that worry you - once we have made a little headway in explaining the basic principles, the jet engine will soon give up its mysterious secrets.

The open gas turbine process

Regardless of whether we are considering a shaft power turbine (designed to produce mechanical power) or a jet engine, we find the same working process at the core: it is termed the open gas turbine process. Air is sucked into the engine and compressed. The compressed air then flows through a combustion chamber in which it is heated to a high temperature.

In their hot state the gases are capable of performing more work than was put into them during the compression stage. Finally the air expands again as it is released into a turbine, to which it imparts a proportion of its power. This process sets the turbine spinning, which in turn drives the compressor to which it is connected by a shaft. The residual energy in the exhaust gas can now be exploited to serve the purpose of the engine. If the exhaust stream of the basic gas turbine is further accelerated by an exhaust cone the machine becomes a jet engine.

The resultant flow of hot gas produces a forwards-

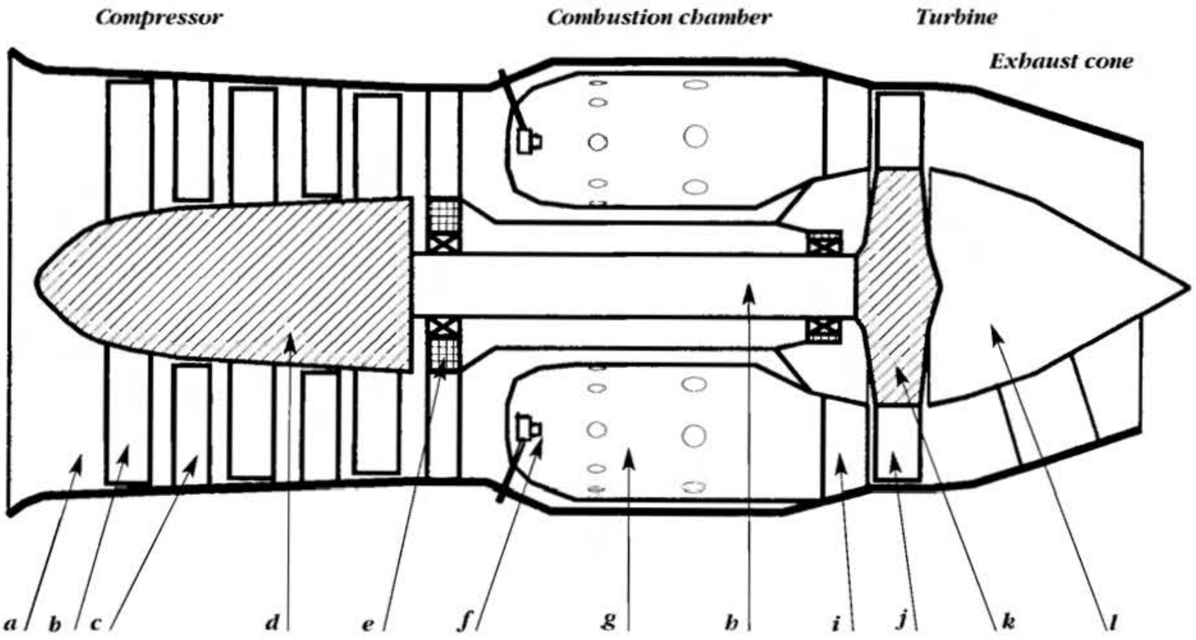
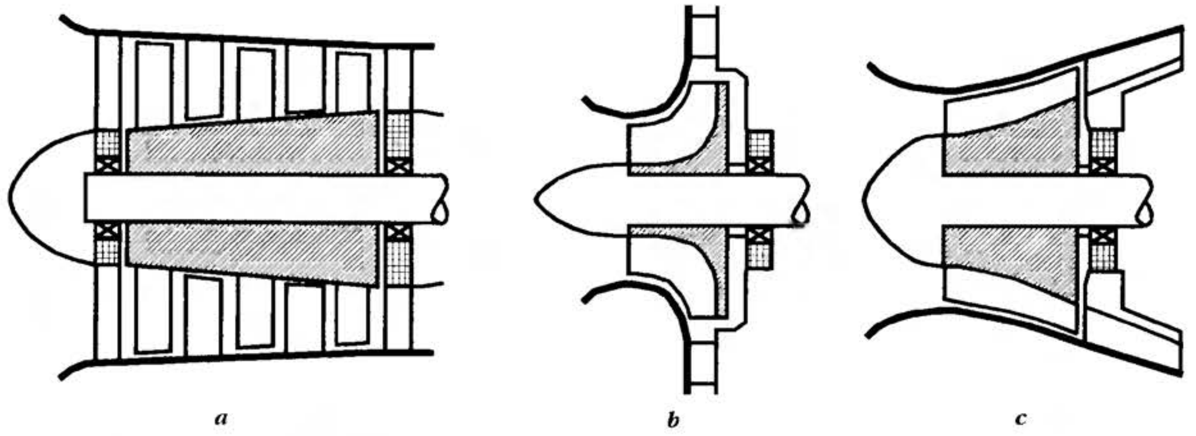


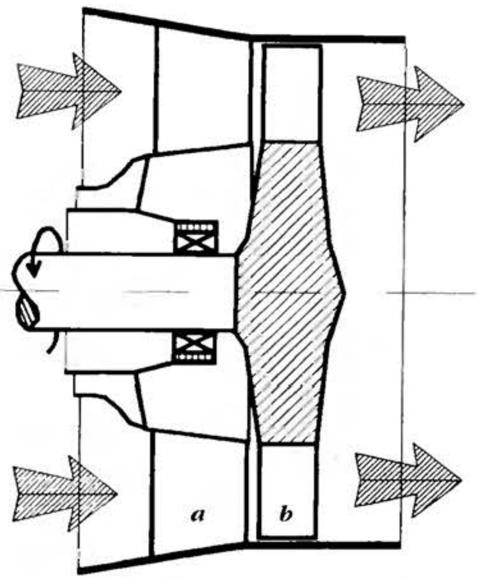
Diagram of a jet engine.
a) Air intake, b) Compressor blades, c) Ring of diffuser blades, d) Compressor rotor, e) Front bearing, f) Fuel injector nozzle, g) Combustion chamber, h) Shaft, i) Nozzle guide vanes, j) Turbine rotor blades, k) Turbine rotor, l) Tail cone.



Types of turbine compressor.
a) Axial compressor, b) Radial compressor, c) Diagonal compressor.

directed force, i.e. there is an equal and opposite reaction according to the familiar laws of physics.

The gas turbine is classed as a heat engine as is the piston engine familiar to model flyers, so it will be no surprise to find that both engines share certain basic features. The working medium is first compressed and then heated in a combustion chamber. In the piston engine the heating occurs by the combustion of a fuel - air mixture, the combustion occurring in an explosive form. The result is a tremendous rise in pressure inside the cylinder. In contrast, the analogous process inside the gas turbine is isobaric in nature, i.e. the pressure remains constant when the working gases flow through the combustion chamber. Thus in the case of the gas turbine the increase in usable power is not due to a rise in pressure in the combustion chamber. Quite the opposite: in practice we have to accept a loss of pressure of a few per



Single stage axial turbine.
a) Nozzle guide vanes, b) Rotating blades.

cent in order to achieve stable combustion. The sole purpose of the combustion chamber in a gas turbine is to heat air. As a result the gas turbine is not bound strictly to a specific fuel. In principle the engine could be made to work if an electric heating element were used instead of burning kerosene.

The crucial difference between the gas turbine and the piston engine is in the sequence of the processes within the engine. The piston engine completes the stages of its power cycle in sequence, one by one, whereas the gas turbine does everything at the same time. Air is constantly sucked in and compressed, heated and expanded again. It is this very constancy which constitutes the great advantage of the gas turbine. The individual processes run continuously and in separate spaces or areas of the engine.

Every gas turbine possesses a compressor and a turbine. These components are designed in the form of a continuous flow machine. In comparison with piston engines they offer the important advantage that they are able to produce great power in the smallest possible space. For example, a model engine's single turbine wheel, just 65 mm in diameter, can drive a compressor with a power absorption of more than 20 kW at full throttle. In full-size jet engines the power levels are astronomic - to the point where they are difficult to comprehend.

The compressor of a gas turbine is always some form of turbine machine; usually either an axial or a radial compressor. In the case of the axial type the gas flows parallel to the drive shaft, while the radial type hurls the gas outwards perpendicular to the shaft. A third type - the diagonal compressor - is used rarely, but it is still worthy of mention. As is easy to see, this represents a hybrid of the two other types. The air arrives in the axial direction and is pushed on in a broadly axial direction, the diameter of the flow increasing steadily. The axial compressor is broadly similar to the fan of an impeller (ducted fan). A compressor may consist of several stages, each stage consisting of a rotating compressor wheel and a fixed diffuser wheel, also known as the stator. The rotor and stator are always fitted with a particular number of vanes or blades. The air is initially accelerated as it flows through the stages, then slowed down again slightly. As a result of this process a proportion of the air's kinetic energy is converted into pressure energy in each stage. Multi-stage axial compressors are standard for full-size gas turbines. Modern jet engines have extremely complex compressors consisting of up to 17 stages and even more. The result is an increase in pressure of up to 30 times.

The radial compressor is much simpler in construction and therefore much more suitable for model engines. The air flows into the wheel in the axial direction and is then flung outward by centrifugal force. On its own this device is known as a centrifugal compressor. Once again a single stage consists of a rotor and a stator, although the pressure increase per stage is much higher than with an axial compressor stage. As a result gas turbines with radial compressors can often manage with only one stage.

Additional advantages of the radial compressor are its robust nature and its inherent reliability. The disadvantage is the large frontal area of the machine. Gas turbines with a radial compressor are therefore always somewhat bulky.

The second continuous flow machine in the gas turbine is the actual turbine. This can be visualised as a compressor "in reverse". The turbine converts pressure energy into the shaft power which is required to drive the compressor. Since the hot gases contain much more energy than the compressor absorbs, the system is self-sustaining. If the final temperature after the combustion chamber – what is known as the combustion gas temperature – is high enough, additional power can be extracted from it.

Like the compressor, the turbine itself may consist of one or more stages. When the air reaches the turbine stage it first flows through the stator which converts part of the pressure energy into kinetic energy. As the gases pass through the fixed stator they are accelerated in the direction of rotation of the rotor. The gas is accelerated once more within the vanes of the rotor, but this time in the opposite direction. The net result is a powerful peripheral force acting on all the rotor blades, and taking the form of a propulsive torque. This peripheral force arises from the recoil which the rotor blades experience. As the exhaust gases flow through at high speed they are accelerated in the direction opposite to that of rotation. On the other hand the twisting motion produced by the nozzle guide vane system produces an impulse force in the rotor blades, varying according to the design of the turbine stage.

Like the compressor, the power turbine can be constructed in axial or radial form. The first successful gas turbine designed by Pabst von Ohain (1937) was fitted with a radial turbine. In the course of time the radial turbine has been superseded almost entirely by the axial type. Even by the 50s the radial turbine only survived occasionally in low-power shaft power engines. However, for model jet engines this type of turbine could still be of interest.

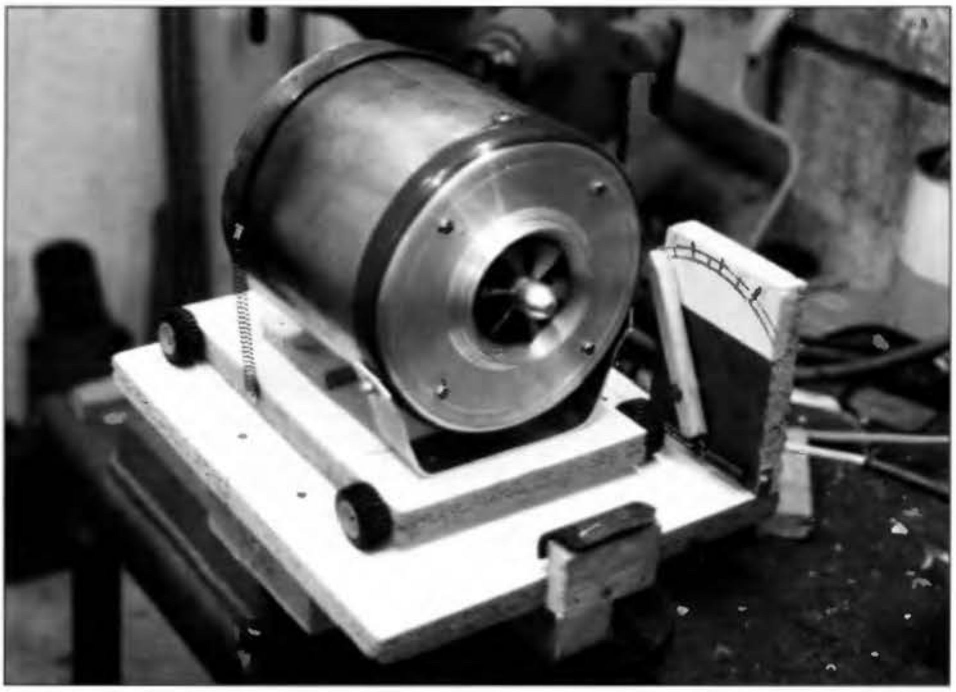
The question of efficiency

We will now consider the processes inside the gas turbine somewhat more closely. If we adopt the process described here, the engine can only function if the turbine produces sufficient power to drive the compressor.

Unfortunately turbines and compressors are not zero-loss machines. In each stage friction and turbulence absorb part of the energy and waste it as heat. To minimise friction losses there must be a gap between the rotor blades and the housing to avoid any danger of fouling. This clearance then allows a proportion of the gas simply to slip past the rotor.

To counter this problem and still keep the engine running it is essential to keep the temperature of the gas – and therefore its power capacity – high enough to compensate for the losses. However, the permissible gas temperature is not infinitely high. The maximum temperature is limited by the strength of the materials used in the engine, especially where the modeller does not have access to heat-resistant steels. The only way out of this dilemma is to strive for maximum possible efficiency of the compressor and turbine. This is one of the most difficult problems for the modeller to tackle, since the laws of physics have been drawn up to thwart the experimenter. The smaller we make the compressor and turbine, the less efficient, in general terms, they become.

Already recognisably a model jet engine, this design produced 5 Newtons of thrust at a maximum speed of 35,000 rpm. The fuel – pure diesel – was vaporised in a copper tube and burned in a reverse flow combustion chamber.



Simply reducing the size of a gas turbine and building it to model scale does not help, as it is impossible to reduce the size of the gas molecules in the air at the same time. It is the air molecules which are responsible for the inferior aerodynamic characteristics of small jet engine blades compared with large ones. It is the same problem that we encounter with very small model aircraft wings - which is what the blades really are. This was the reason why we modellers were so pleased when it proved possible to make a model jet engine run at all.

The first engine which I constructed refused to run until the air diffuser system in the compressor region had been reworked, and even then the engine's running qualities were very unsatisfactory. In subsequent experiments I used the housing of a commercial turbocharger in an effort to improve compressor efficiency. The experimental engine based on this component worked at the first attempt. The compressor and diffuser system were taken from an exhaust gas turbocharger designed for a lorry engine, and the air supplied by the compressor was ducted to the gas-heated combustion chamber by means of spiral tubing. The turbine was a home-made axial device with a rotor formed from thin sheet metal. Initially the engine's efficiency was so poor that the system could only just keep itself running. At the same time the temperature of the gas was so high that the turbine rotor glowed bright orange. Residual energy for thrust was virtually non-existent. When the throttle was opened the spiral hose inflated itself horribly, and the compressed air whistled out from many a leak.

Experimental engine: first run October 1990, maximum speed: 19,000 rpm, pressure ratio: 1.04, fuel: propane gas.

Since then I (and others) have produced a series of usable model jet engines. The efficiency of the stages has been improved to the point where the gas temperature can be held down to a sensible level. However, the relatively poor rotor efficiency still manifests itself in the engines' high fuel consumption: specific consumption is about 2-3 times that of comparable full-size engines and about 8 times the consumption of modern by-pass engines.

The development history of the jet engine

Since they were invented jet engines have been the subject of continuous development, and have evolved and changed to an enormous extent. The dual requirements of higher performance and better fuel consumption have resulted in an endless stream of new designs.

Clear trends can now be perceived: higher and higher combustion gas temperatures (above 1500° C) and pressure ratios mostly in the range 10 to 30. This is the only way in which maximum power can be combined with efficient exploitation of fuel. Turbine blades capable of surviving under such conditions are extremely sophisticated high-tech products. The simple form of the turbojet - what we might call the pure jet engine - has been almost entirely sidelined. In its place we find extremely complex engines, most of them multi-shaft by-pass and turbo-fan designs. There must be many modellers who would like to design their own model jet engines, but they will find no help at all in this type of prototype. On the contrary: modern jet engines with all their sophistication do an effective job of scaring modellers off. If you are one of those wonder-modellers who is capable of producing a miniature version of such an engine at model scale you will undoubtedly be feted as a master mechanical engineer, but it is extremely unlikely that you will be able to persuade your engine to run.

The jet-minded modeller really has no alternative but to concentrate on the essentials of the matter: the open gas turbine process. The first question we have to tackle is this: can a jet engine function at all if we do not achieve a particular minimum pressure ratio or a particular gas temperature? Fortunately the answer is yes; theory promises that a gas turbine will function even if the gas temperature is kept down to a value which we can comfortably handle. Prospects are also good when we consider pressure ratios; in fact, any minuscule excess pressure is theoretically sufficient to keep a gas turbine running.

Supporting evidence for this theory is found in early gas turbines. The first examples were extremely simple in design, but they did work. The thermodynamic data, pressure ratio and combustion gas temperature of these engines are within regions which we can certainly achieve with model jet engines. In short, if we are looking for full-size jet engines which might encourage us in our quest for successful model gas turbines, we should go right back to the original developments.

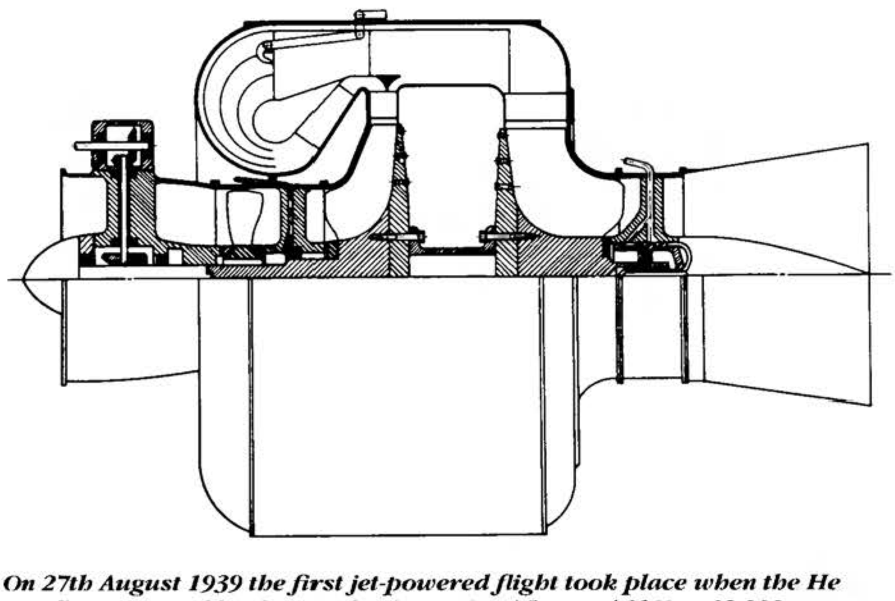
It all started in the 1930s

The history of jet engines begins in the late 1930s. The German physicist Hans-Joachim Pabst von Ohain and the Englishman Frank Whittle developed the first engines independently of each other and almost exactly at the same time. Von Ohain had been experimenting with the new propulsive technology since 1933. His first experimental engine, termed the S1, was completed as far back as 1935. From today's point of view this machine had more in common with a washing machine drum than a jet engine, and indeed it could not run independently. Ernst Heinkel, who recognised the significance of Ohain's work, allowed him to continue his experiments in the Heinkel works. About a year later, in March 1937, von Ohain's S2 engine ran autonomously for the first time. Only one month later Frank Whittle's engine was also running. Two years later the S2's successor - the He S3 B - had been developed to the point where it was capable of propelling an aircraft.

Von Ohain's engine is notable for its simplicity and functional nature. He used a radial compressor and a radial turbine, both with an initial diameter of 600 mm. An axial compressor stage was fitted in front of the radial compressor in an effort to increase the pressure ratio. The rotor, i.e. all the wheels and the shaft, was mounted on ballraces; one each between the axial and radial compressor stages and one behind the turbine. The maximum rotational speed of the S2 engine was 10,000 rpm at which point it produced a constant thrust of 1,270 Newtons. The exact thermo-dynamic data for this experimental engine are not available, but calculations show that the compressor could only have produced an excess pressure of around 0.8 to 1 bar.

It proved necessary to carry out a tremendous amount of experimental work in order to optimise the combustion chamber. Initially von Ohain used a short-cut, in so far as gaseous hydrogen was used as the fuel. This gas forms a combustible mixture when mixed with air in almost any proportion. Later a number of tubes were fitted, running through the combustion chamber. Petrol was pumped into the engine and vaporised in these tubes, so that it was in a more or less gaseous stage when it reached the combustion chamber.

Similar problems afflict today's model jet engines, and the burning of liquid fuel still presents us with serious difficulties.



On 27th August 1939 the first jet-powered flight took place when the He 178 flew powered by the He S3 B jet engine. Thrust: 4.9kN at 13,000 rpm, throughput: 12 kg/s, diameter: 1.2m, mass: 360 kg. (from: Leist, Encyclopedia of jet engines [German]).

Model jet engines which are capable of running on diesel or kerosene usually exploit the technique of pre-vaporisation. This technique was tried at the time, but in spite of its simplicity it was not successful. Today it has become a useful technique for model jet engines once again.

The robust jet engines of the 1950s

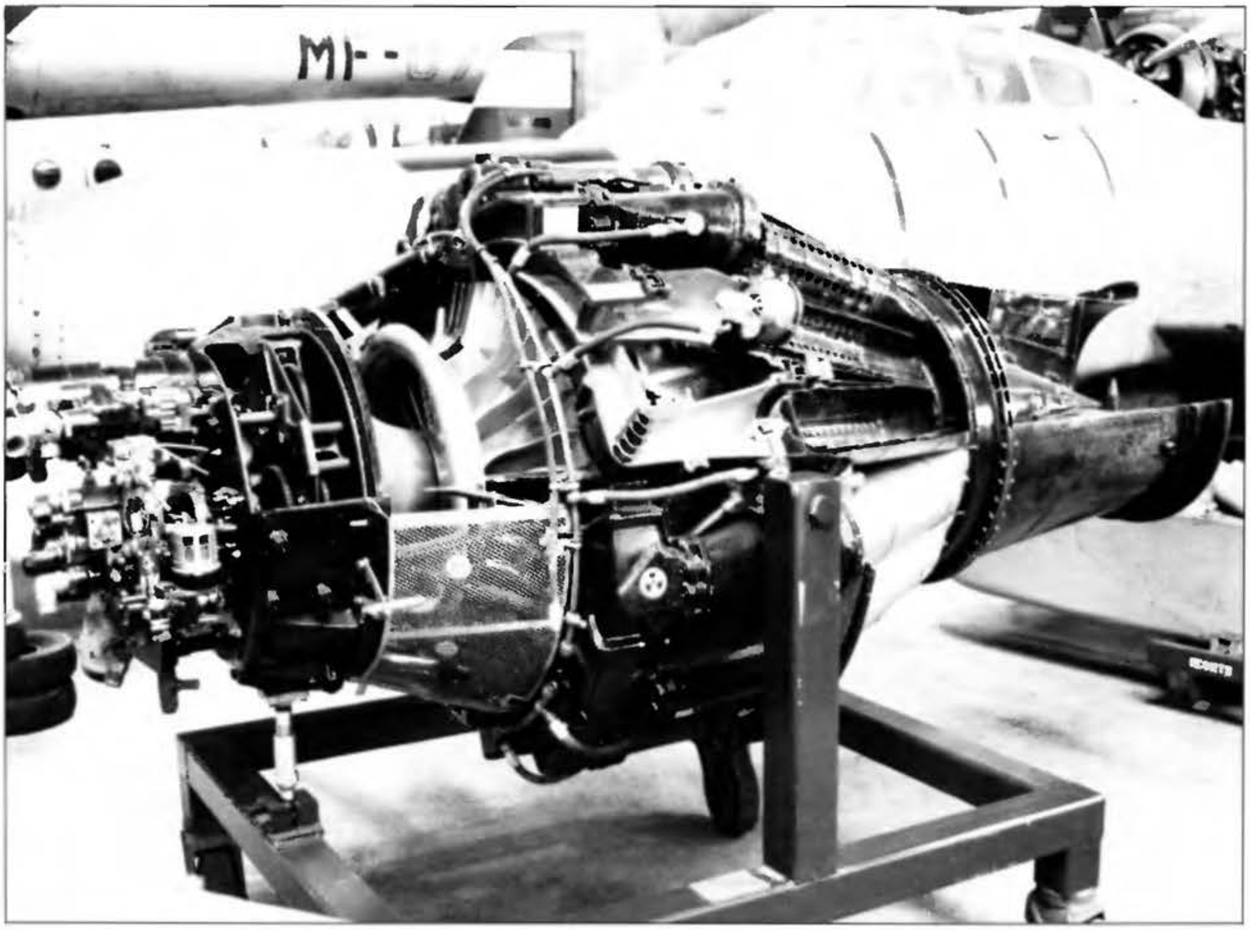
In the course of time more and more companies turned to the development of this type of engine. Amongst the best-known manufacturers at that time were Allison, General Electrics, Pratt & Whitney, Bristol, de Havilland, Rolls-Royce and Turbomeca, and these companies produced numerous variants on the gas turbine theme. Initially many engines were based on Frank Whittle's general design. The primary feature of these engines is their twin-flute radial compressor and single-stage axial turbine. The compressor wheel features vanes on the front and rear faces, which means that double the quantity of air can be moved. A gigantic diffuser system is usually connected to the rotor, ending in convoluted ducts running to the individual combustion chambers. An axial turbine is used. This type of engine is very clumsy and bulky, and its great frontal area makes it a poor contender for use in high-speed jet aircraft.

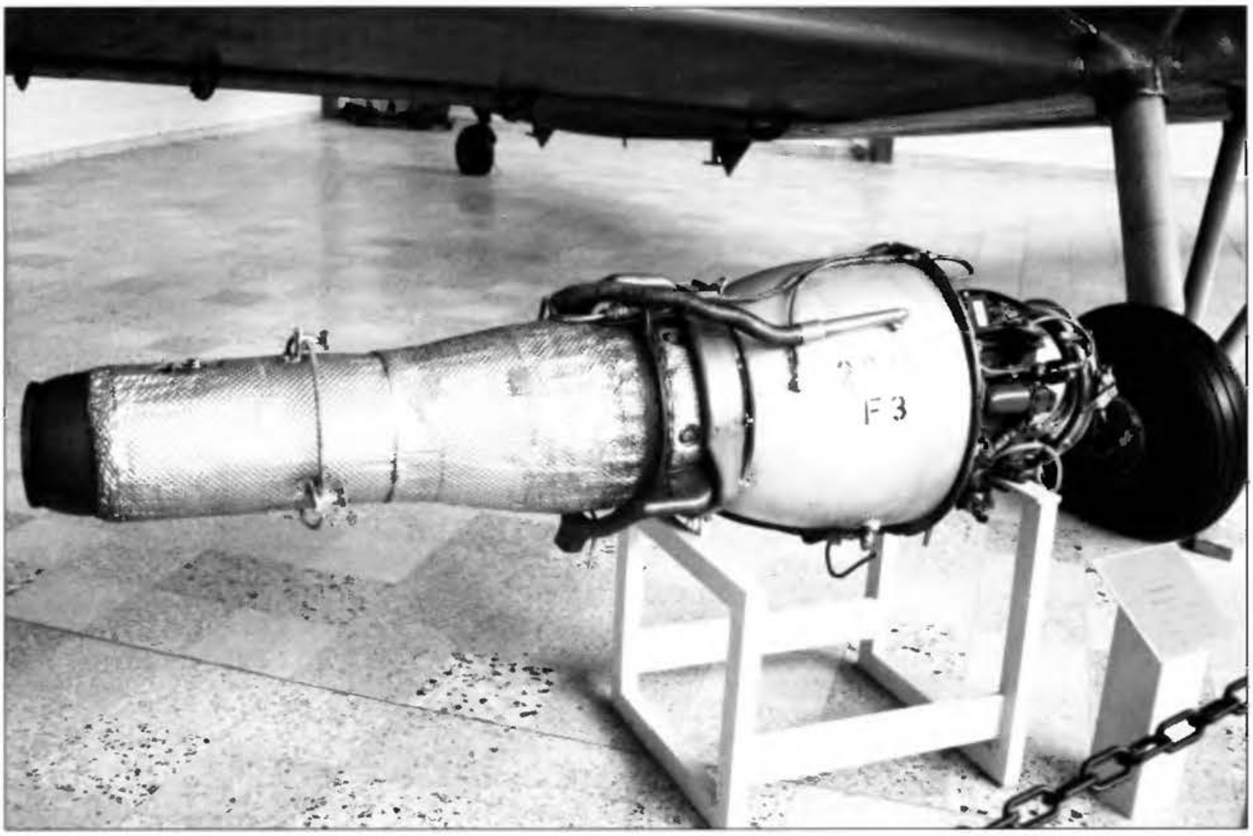
Nevertheless the Whittle design was very popular because of its simplicity and reliability. In many countries it was the starting point for further developments, and numerous variants were produced. These jet engines were used to propel many famous aircraft types. Thanks to the engine types' widespread application we find examples in most museums and exhibitions of aircraft technology. The technology is of particular interest to us because we can clearly see in it the elementary principles of the jet engine. The basic layout, i.e. radial compressor combined with axial turbine, is often used nowadays in model jet engines.

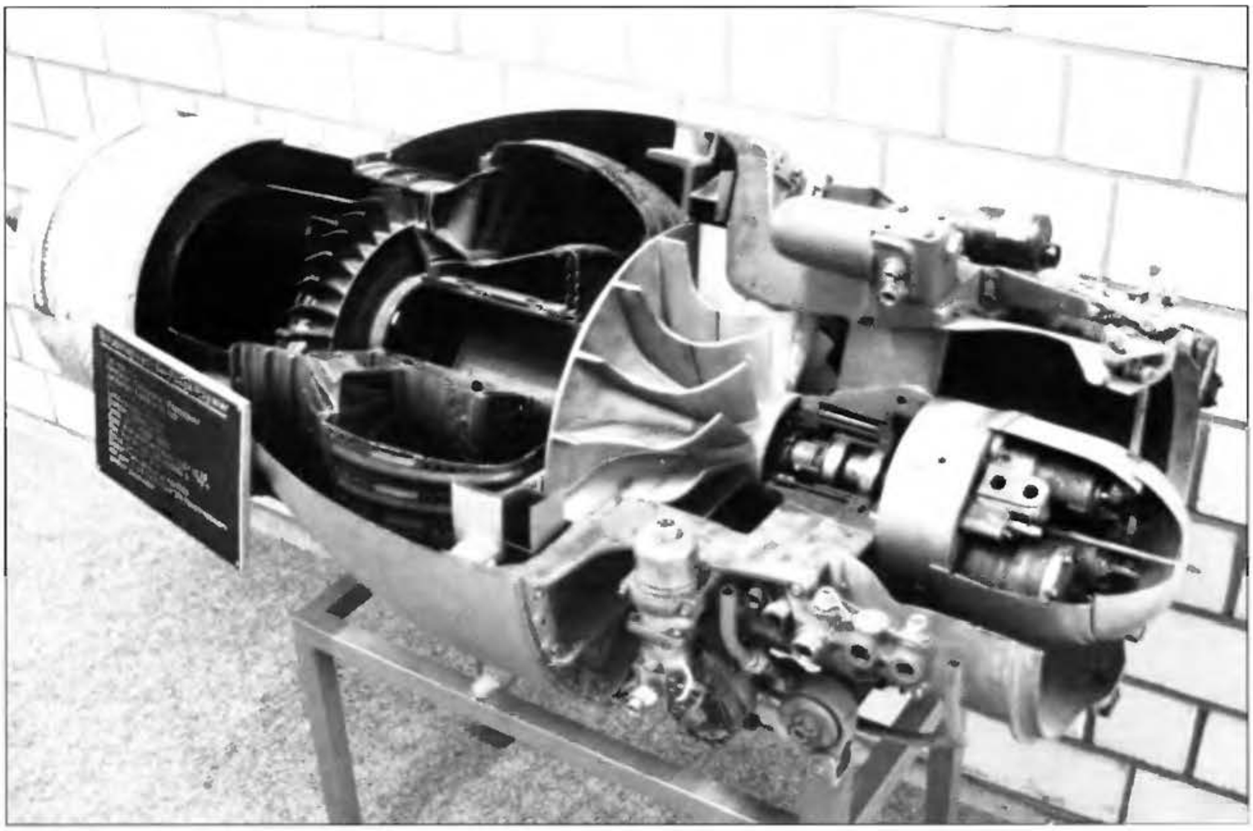
Another very successful family of engines was developed by the French firm Turbomeca. The company was founded in 1938 with the aim of manufacturing air compressors for supercharging piston engines. The development of small gas turbines began in 1941, and the first approved jet engine of the series was known as the Pimene, which produced 1,080 Newtons of thrust. The Palas and Marbore types followed in 1951 and 1952 respectively. At the same time shaft power engines were derived from the basic design by adding a further turbine stage. Probably the best known representative is the Artouste which was used in numerous helicopters, including the Alouette.

All these engine types were based on a radial compressor and an axial turbine. The design of the compressor gives important clues to the would-be designer of

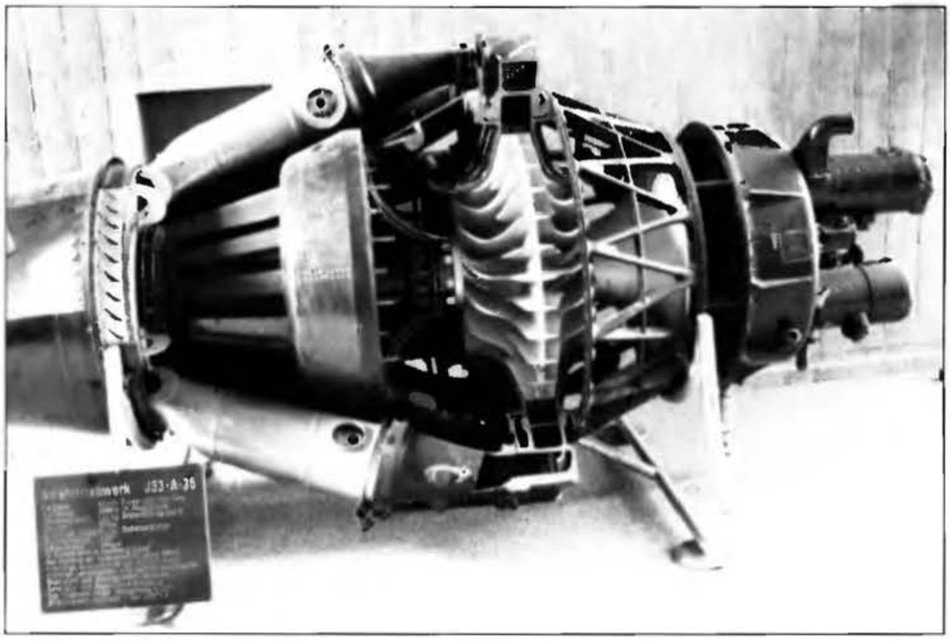
Allison J33-A-35 – Manufacturer: Allison Division, Indianapolis, USA, thrust: 20.5 kN at 11,750 rpm, throughput 39.5 kg/s, pressure ratio: 4.25, exhaust gas temperature: 686° C, mass: 826 kg, 14 individual combustion chambers. Used in Lockheed F80 Shooting Star and Lockheed T33.



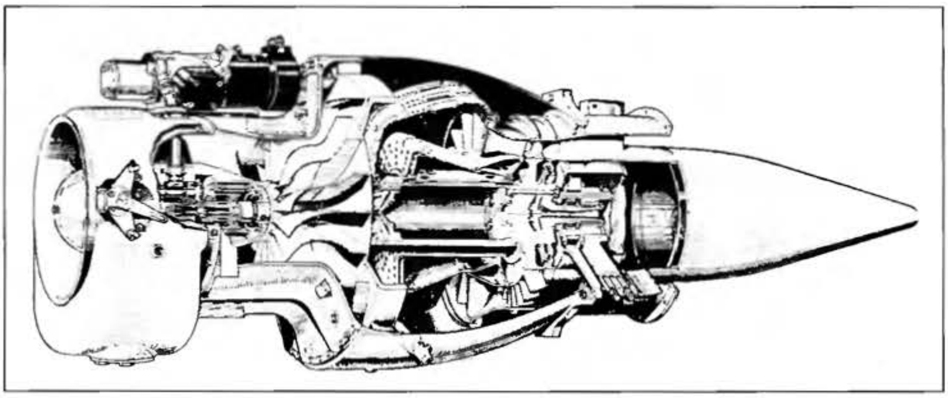




Examples of the Turbomeca Marbore II can be found in many museums. Continuous thrust: 3.1 kN at 21,000 rpm, maximum thrust: 3.9 kN at 22,600 rpm (limited to 15 minutes), pressure ratio: 4, mass: 146 kg, length: 1.566 m, diameter: 567 mm.



The Allison J33-A-35 is a typical representative of the Whittle school of design, here with the double-fluted compressor clearly visible. Each combustion chamber is assigned to one duct of the compressor diffuser system.



Perspective cut-away drawing of the Marbore II (from: Leist, Encyclopedia of jet engines [German]).

model jet engines. In order to keep the frontal area of the engine small the designers employed an ultra low-profile compressor diffuser system. The diffuser vanes were arranged in two rings - one radial, directly aft of the compressor wheel, and one axial at the periphery of the diffuser system, after the direction of the airflow had already been deflected. This neat trick allowed the company to build relatively slim engines which were very robust. The same general type of diffuser system is also used successfully in model jet engines.

Prototypes for model jet engines

Old jet engines can certainly give us ideas for small model versions, but there is no point in talking of actual prototypes. To my knowledge, fully working jet engines small enough to be used to propel a standard model aircraft did not exist until the late 80s. It is true that amateurs made many attempts at constructing engines to model scale, but any success they achieved was of short duration. Of course, very small professionally built gas turbines do exist, and the modeller can draw inspiration from them. This type of miniature engine is often utilised where high levels of propulsive power must be combined with low weight and compactness. For example, a portable fire-fighting water jet has been built powered by a miniature gas turbine made by the company of Kloeckner-Humboldt-Deutz. Most of the engines of this type are based on radial compressors and some of them even use radial turbines.

Drone engines and APUs (Auxiliary Power Units)

Small jet engines are often used in unmanned aircraft (drones), which are usually designed for a short flight duration and are subsequently disposed of after being used once. For this reason the engines are also designed for a short life. The main design criteria for these units are low weight and, above all, minimum possible cost.

A typical single-use engine of this type is the Williams WR 2 made by Williams Research Corp., Walled Lake, USA, which was used in the Canadair C189 reconnaissance drone. Fuel is injected via fine openings in the rotating engine shaft, which acts as a centrifugal pump. The compressor and turbine rotors are each manufactured in one piece using a precision casting process. This little engine's rotational speed and gas temperature are very high, with the result that it achieves an excellent pressure ratio and efflux velocity, comparable to the performance values for full-size engines of similar design.

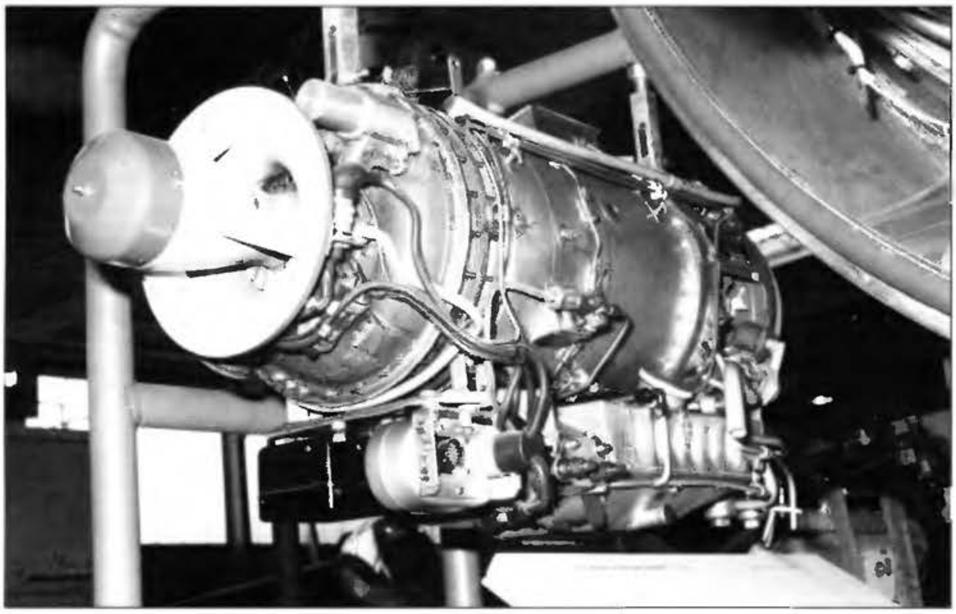
At the same time the stresses due to temperature and centrifugal force rise to such levels that the turbine wheel can only survive for a few minutes.

The most common application for professionally built small gas turbines is the APU, or Auxiliary Power Unit. These are supplementary aircraft engines which provide additional power when required. Small shaft power engines are used to drive electrical generators or hydraulic systems. Often these gas turbines can also supply compressed air in order to start the main engines.

The KHD T112 is a typical APU. Other examples are the T212 air pump and the T312 used in the Tornado. These engines were developed and built at Oberursel near Frankfurt. The rotors are almost of model size, and the compressor consists of one axial stage and one radial stage. The combustion chamber is designed as a reverse flow type in order to save space. After the combustion chamber comes a two-stage axial turbine. The axial compressor stage is particularly noteworthy, as the blades of this "trans-sonic" wheel run at supersonic speed at full load. These blades prove that it is possible to design very small axial compressors capable of achieving high levels of efficiency. In technical terms the engines of this type are very highly refined power plants, and any amateur attempt at emulating them would certainly be doomed to failure. Even so, it is obvious that much smaller gas turbines could have been made if a need for them had arisen.

In the meantime KHD has been taken over by BMW and Rolls-Royce. Even today the new company of BMW Rolls-Royce GmbH continues to work on full-size engines and small gas turbines.

Williams WR2, built 1962, thrust: 550 Newtons, speed: 60,000 rpm, throughput: 1 kg/s, pressure ratio: 4.1, diameter: 274 mm, mass: 13.6 kg, a generator is built into the intake opening.

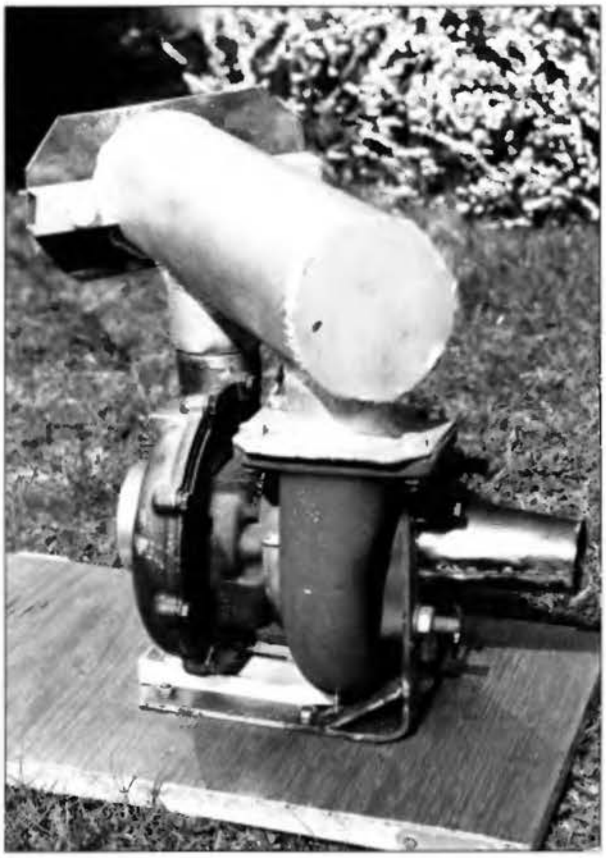


KHD T112, built 1963, length: 789 mm, diameter: 368 mm, throughput: 0.86 kg/s, pressure ratio: 4.96, speed: 64,000 rpm, 104 kW shaft power, mass: 34.1 kg, a starter is fitted in the air intake.

Hyper-charging

There are other sources of ideas for the modeller interested in miniature jet engines. Another area which at first sight has nothing to do with jet engines can, in fact, give us some interesting food for thought. Indeed, this is an area where some important components can even be used directly in our model jet engine. What we are talking about is exhaust turbochargers. A turbocharger is basically a compressor which is used to feed pre-compressed air to a piston engine. This technique increases the engine's air throughput so that it can burn more fuel and produce more power. The engine's exhaust gases flow through the turbocharger and drive the compressor via its turbine stage. Therefore inside every turbocharger there are a turbine and a compressor.

A disadvantage of exhaust turbo-charging is the delayed response of the turbocharger. If the driver suddenly opens the throttle from idle the charger pressure is very low, and therefore requires a certain amount of time to get up to speed. This accounts for what drivers of turbocharged cars know as turbo-lag. In modern turbochargers the inertia of the rotor is so low that turbo-lag is barely perceptible. One very neat solution to this problem is the bi-turbo, where two small chargers, with



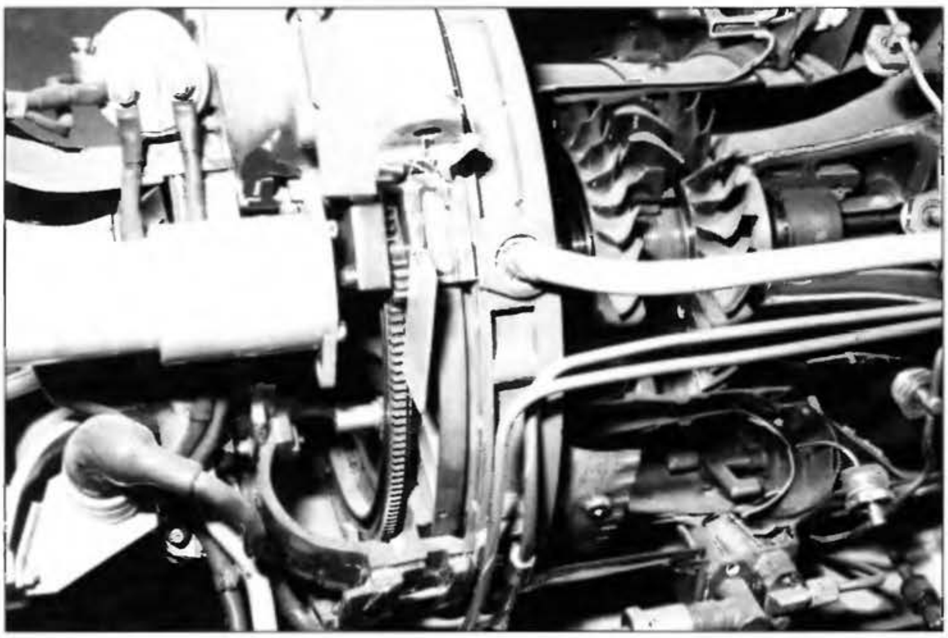
Experimental gas turbine based on a turbocharger.

correspondingly short response time, are used instead of one larger one.

For special purposes a further alternative is available which can be used to shorten the response time of a turbocharger to zero - this technique is known as hypercharging and it exploits the fact that a turbocharger is already almost a gas turbine. The housing of the charger accommodates a turbo-compressor and a turbine. The throughput of the turbine stage is accurately matched to that of the compressor, for the mass of the exhaust which the engine emits is exactly the same as the mass of fresh air it ingests. The mass of the fuel fed to the engine is so small that it can be ignored. The exhaust gas turbocharger is therefore almost a gas turbine; all it lacks is a combustion chamber.

In the case of a hypercharger the turbocharger is connected to a combustion chamber. When the main engine is idling, the valves leading to the combustion chamber are open, and fuel is injected and burned. The turbocharger is temporarily converted into a gas turbine by this

Internal view of the KHD T112 showing the two axial turbine stages and the reverse flow combustion chamber. The turbine rotors are 100 mm and 130 mm in diameter – almost model size already.



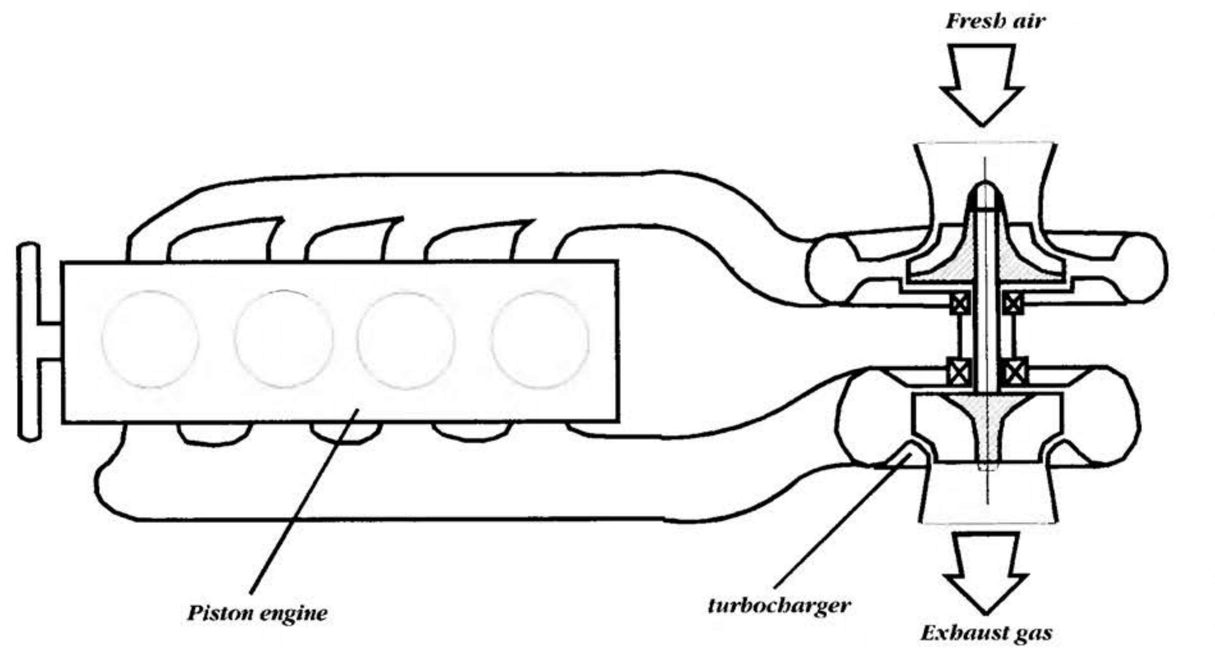


Diagram of a turbo-engine.

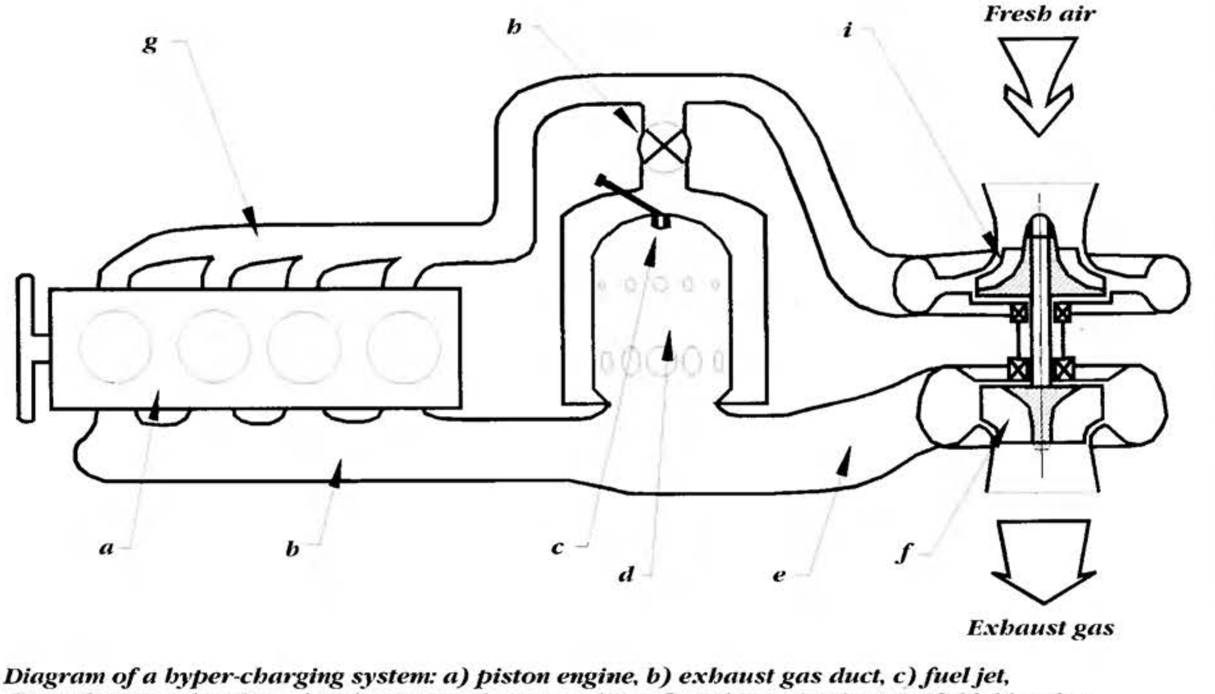


Diagram of a hyper-charging system: a) piston engine, b) exhaust gas duct, c) fuel jet, d) combustion chamber, e) exhaust gas duct to turbine, f) turbine, g) inlet manifold, h) valve, i) turbocharger compressor.

means, and therefore maintains a high rotational speed. The main engine now has high charger pressure available at any time, with zero lag, and the net result is that the engine can produce high torque even at low engine speeds.

Hyper-charging represents highly specialised technology and is seldom used. Its main application is to provide brief increases in power in diesel engines. For example, the BKS process developed by MTU (Motoren-und Turbinen-Union, Munich) for military tank engines exploits this technology.

The vital point of all this is that the modeller can exploit exhaust gas turbochargers as a source of parts for model jet engines. The efficiency levels achieved by turbocharger compressors and turbines are sufficiently high to enable a small gas turbine to run; and this applies to very small units too, as shown by the performance graphs of a turbo-engine. At full throttle turbocharger pressure rises far above exhaust pressure. You might think that this indicates a rise in gas pressure inside the combustion engine, but this is not so. This is what happens: simply heating the gases is sufficient to drive the turbocharger. It would also run if the engine were removed and a simple combustion chamber were installed between compressor and turbine.

I constructed just such an engine for experimental purposes, based on a scrapped lorry turbocharger with a rotor diameter of 76 mm. The combustion chamber consisted of a tin can, and the engine was run on propane gas. It is only really possible to start this monstrous creation using a vacuum cleaner fan. Even when the flame is burning in the combustion chamber some patience is called for, since the engine will not run until the oil in the bearings has reached its operating temperature and the rotor system floats on the film of lubricant. When the engine is running, lubricating oil is pumped into the turbocharger bearings from an oil tank connected to combustion chamber pressure.

If you are interested in trying this out, please bear in mind that this crude object is nevertheless a fully functional gas turbine with all its inherent characteristics, and that it must therefore be handled with appropriate caution.

For safety's sake you should keep to a maximum compressor pressure of 0.3 bar – which equates to a rotational speed of around 50,000 rpm in this case. The turbine wheel can be observed with the help of a mirror and the gas supply throttled back if it starts glowing more brightly than dull red. Liquid fuels such as petrol or diesel should not be used, again in the interests of safety, since liquid fuel tends to collect in the compressor housing if it is not burned immediately.

When the engine is run up to speed this fuel is then disturbed and burned. If this occurs the engine may then accelerate uncontrollably and run up to dangerously high speeds.

Frank Whittle encountered similar problems during his first experiments in April 1937. It is reported that Whittle opened the fuel valve of his WU (Whittle Unit) from an initial speed of 2,300 rpm. Immediately the engine ran out of control, accelerating very quickly and emitting a deafening wailing noise, whereupon everyone except Whittle himself immediately ran for cover.

The reason for this unexpected behaviour was leaking fuel lines in the combustion chamber. Even before the engine was ignited, pools of kerosene formed and immediately caught light, leading to uncontrollable combustion and very high gas temperatures.

Early model jet engines

Many amateurs have made brave attempts at building model jet engines, but until recently the success rate has been modest. A good few engines have been constructed using admirable manual skill and hundreds of hours of tender loving care, but even so they are destined for a quiet life in a collector's showcase. In some cases the reasons for failure can be seen just by glancing at the engine.

All those turbine designs which have come to my notice, and which one can believe might have run, have one feature in common: they implement the basic physical working principle using the simplest possible means. In virtually every case the air is compressed using a single-stage radial compressor, and the turbine section also employs only a single wheel.

Nevertheless, a number of modellers have actually succeeded in making very small engines which were capable of running, and have used them to propel model aircraft. The next section deals briefly with several different model jet engine types. Many of them are not in use today any more. New powerful successors supplanted them, but especially here we can see the different approaches the constructors chose to reach their target, a real working model jet engine.

Max Dreher's Baby Mamba

Whether this is really a model jet engine depends on your point of view. The engine is several magnitudes smaller than a normal aviation engine, but is still a touch too large for modelling use. The Baby Mamba, or more accurately the TJD-76C, was developed and built in the mid 50s by Dreher Engineering (USA). The whole engine has a mass of 6.5 kg, its diameter is 151 mm, overall length 416 mm. The Baby Mamba produces a thrust of 200 Newtons which can be increased to 240 Newtons for brief periods, at which point the rotor speed is 96,000 rpm. Originally the Baby Mamba was designed as an auxiliary power source for gliders and as a power plant for lightweight drones. One feature of this engine worth mentioning is its unconventional compressor design. The Baby Mamba is one of the few engines which utilise a diagonal compressor. This type of compressor generates a pressure ratio of 2.8 from a single stage. Of course, this is slightly lower than can be obtained with a radial compressor at the same peripheral speed, but the diagonal compressor makes up for this with a much smaller frontal area. For this reason the Baby Mamba is an extremely slim aircraft engine. Unfortunately the engine is too complex to be copied at true model scale. The turbine and combustion chamber are made of heat-resistant nickel-based alloys, and these materials are difficult for the modeller to obtain. The design of the compressor also calls for too much expertise from the experimenter. The distribution rights to the Baby Mamba are owned by Franz Kavan, but the engine is of no significance for model applications.

The Swedish PAL System and its successor Turbomin

Back in 1982 three Swedes succeeded in building a working model jet engine. The name of the design is derived from the Initials of the constructors: Prisel, Alme and Lyrsell. The core of the engine is the rotor of a Garret turbocharger, consisting of a radial compressor and a radial turbine. The actual engine is built around the standard rotor. One notable feature of this engine is the design of the combustion chamber, which is annular and arranged around the exhaust cone. As a result it can be made as long as the designer wishes since it does not have to fit between compressor and turbine. Reports state that the engine has produced a thrust of 120 Newtons at a rotational speed of 105,000 rpm at full throttle. The PAL jet engine is 460 mm long, 150 mm in diameter and has a mass of 4 kg. Type JP4 kerosene was used as fuel. Although these figures are good, the PAL system was not adopted for model flying; at least, not during the period in which it was developed.

Since that time the Swedish firm of Turbomin has produced another version of the engine which reflects further development work. The basic design, with its characteristically large reverse-flow combustion chamber, has been retained, and this means that it is possible to use actual full-size fuel of the JET A1 type of kerosene. Fuel enters the combustion chamber via five injector nozzles, derived from the atomiser nozzles used in an oil fired burner. At full throttle the Turbomin consumes 330 ml of kerosene per minute at an injector pressure of 10 bar, and develops a thrust of 75 Newtons. The maximum rotational speed is 100,000 rpm, and the pressure ratio is 2.1. The starting procedure is ingenious: initially fuel is fed to the engine by a separate fuel pump in the pit box. However, the kerosene only reaches the combustion chamber through one of the five atomiser nozzles, where it is ignited by a high-voltage spark plug. Only at this point does the actual injector pump start running, taking over the fuel supply system completely. The rotor is run up to speed using compressed air applied directly to the compressor wheel. All in all the Turbomin TN 75 is a very solid jet engine. Great emphasis has been placed on the simplicity of the design, and expensive high-tech components have been largely avoided in the interests of low price, even though this has limited its potential performance. For example, the ballraces used are simple standard bearings, and the rotor system is a modified unit from a Garrett turbocharger. In actual use in the field, the turbine is impressively simple to handle. Maintenance work can and should be carried out by the customer, including bearing replacement. For the highly stressed rear turbine bearing the estimated exchange interval is 100 flights. The TN 75 weighs 3 kg including the fuel pump. The diameter is 148 mm, the length 425 mm. This makes the engine one of the heavier types currently available, and quite a large model is required to accommodate it.

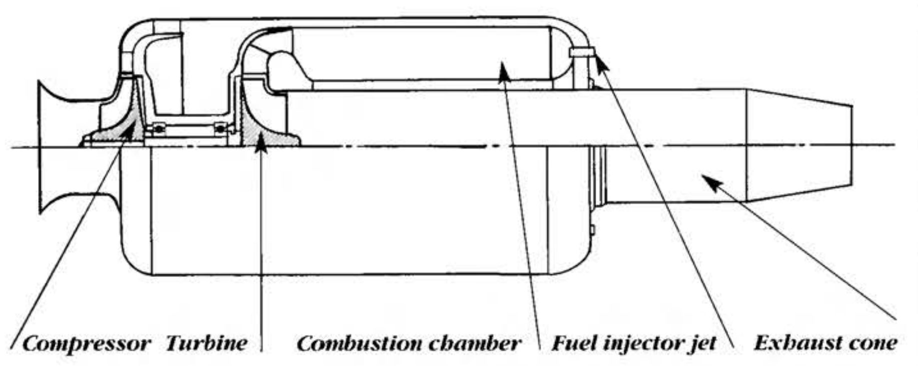


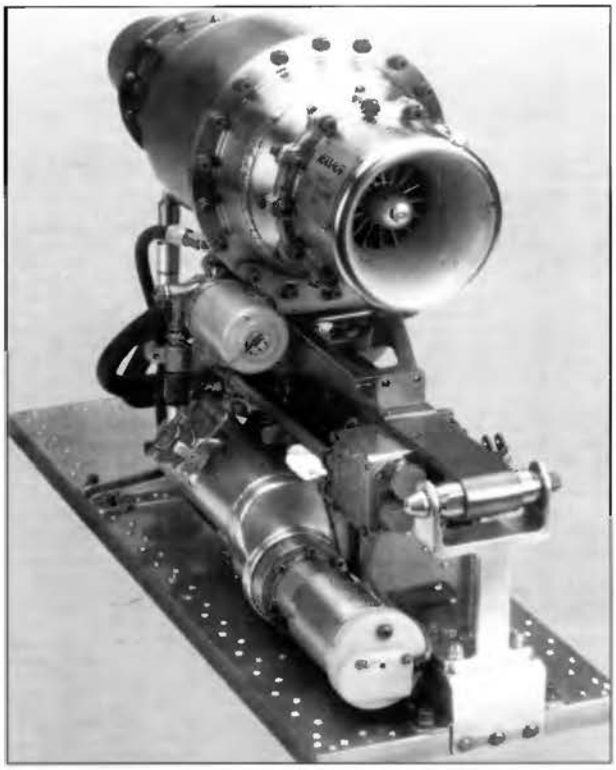
Diagram of the PAL engine.

Kurt Schreckling's FD series

In my opinion the FD engines (FD = Feuer-Dosen - gas canister) represent the most notable achievement to date in the area of model jet engines. Kurt Schreckling was the first modeller successfully to construct very small, lightweight jet engines using amateur means. His starting point was not full-size jet engines; instead he

The compressor wheel made of high-quality plywood, reinforced with carbon fibre. (Photo: Schreckling)

The Baby Mamba – an eye-catching picture on the Kavan catalogue.



took the fundamental principles of the gas turbine as his reference point and worked "from the ground up".

The focal point of his consideration was this: what was the best way of making small rotors in order to achieve maximum possible efficiency? The outcome was a radial compressor with many ingenious features: a rotor with substantially retro-curved blades and a cover plate. This is a type of construction widely used in industrial fans, but probably never before used in a jet engine. The cover plate over the blades almost completely avoids the gap losses which are critical in small engines. A further advantage of this type of compressor is its non-temperamental behaviour. Whether the rotor is required to move a large or small quantity of gas, the unit's efficiency usually stays at a high level. The only drawback is the rotor's slightly lower maximum rotational speed compared with a wheel not fitted with a cover plate.

The compressor is driven by an axial turbine. This is made of 2.5 mm thick sheet metal. The blade profile is worked from the solid using a mini-grinder. Before Kurt Schreckling completed his first working engine he carried out many experiments with compressors and turbines. He found that the efficiency of each stage was so good that the engine was bound to work - at least, according to theory. The first engine that he persuaded to run was an experimental unit which was not recognisable externally as a gas turbine.

The FD 2: the first airworthy model jet engine powered by normal filling station fuels. (Photo: Schreckling)

The FD 3, here installed in the "Rutonius" model jet aircraft.

The next-but-one version - the FD 2 - was already such an improvement that it proved capable of propelling a model aircraft. This early engine could already run reliably on liquid fuel: a mixture of diesel and about 15% petrol. The engine's compressor wheel was made of plywood as in his initial experimental work, but in this case it was wrapped with carbon fibre to reinforce the rotor and the cover plate. This construction has proved strong enough to withstand peripheral speeds of more than 300 m/s without failing.

The engine was developed further to produce the FD 3 and finally a production version in kit-form. All the engines in the series feature a compressor wheel built as described, although the production version is fitted with a compressor wheel cast in aluminium alloy. Another characteristic feature of the FD series is the fuel vaporisation system. It seems likely that it was this system together with the combustion chamber that absorbed most of the designer's experimental labours. The vaporiser itself consists of a coiled tube about one and a half metres long, located inside the combustion chamber. A gear pump pushes liquid fuel into the hot vaporiser where the fuel, still under pressure, is partially vaporised. As pressure falls off more fuel vaporises in the injection openings leading into the combustion chamber.

The kit version of the FD 3 is produced by the Austrian firm of Schneider-Sanchez.

The residue of the fuel, still in liquid form, is injected into the combustion chamber in fine particles where it burns successfully. Using this technique the designer was successful in creating engines which would run on Standard "Filling Station" fuels. This is an important development, as model jet engines will only become widespread if they are easy to operate. FD engines do not need propane gas, which, although it does burn cleanly and easily, is a safety risk in a model aircraft.

The thermodynamic data of the FD engines are as unusual as the overall design. The pressure ratio is very low, reaching a value of only 1.5 at full throttle. As a result the whole engine can be of very lightweight construction. The sealing of the housing presents no major problems. The exhaust temperature is in the range 600°C to 650°C - values at which ordinary 316 stainless steel can still - just - be used as turbine material if rotational speeds are kept to moderate levels. The jet efflux speed

Rutonius, presented by its builder, Kurt Schreckling.

This modified FD 3/64 features a compressor wheel machined from the solid. The builder decided not to fit a cover over the compressor.

is about 200 m/s, which is relatively low in comparison with full-size engines. As a direct result of this the engine is very quiet in operation. The familiar thunderous noise of full-size jet engines is primarily a function of their very high efflux speed, and the FD engines side-step this problem. The engine's thrust of 30 Newtons is high for an engine mass of about 750 g, and this is due to the considerable throughput.

The engine is 265 mm long and 110 mm in diameter. These figures make the FD 3 hard to beat in terms of thrust/weight ratio; even full-size jet engines do not always achieve such good values. In overall terms the FD 3 must be judged an effective model jet engine, and it has already proved its reliability and practicality in many models. Thanks to the constructional drawings produced by Kurt Schreckling many modellers have already produced their own versions, which have been made and flown in many parts of the world.

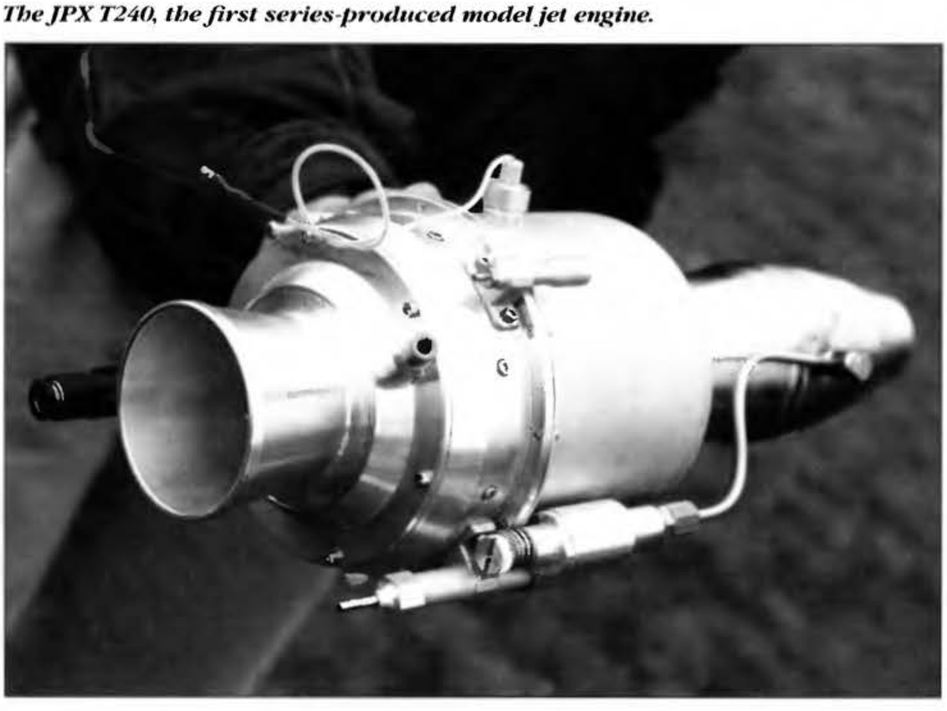
Turborec T240 from JPX

JPX, a company based in Vibraye in Northern France, was the first firm to produce a jet engine specially developed for model aircraft. The company's first turbine, the Turborec T240, was manufactured and marketed as far back as 1991. It is a small engine with a radial compressor and radial turbine. The design is based on development work carried out by the Frenchman Michel Serrier, who had worked on producing a practical model jet engine since the mid-80s. For his experiments he used the complete rotor of a small turbocharger of 60 mm diameter. In taking this approach he started with the advantage of a complete, professionally manufactured rotor system. The compressor wheel and turbine wheel are accurately matched to each other in terms of throughput and are of good efficiency. In addition the turbine wheel is made of high-strength, heat-resistant materials and can withstand very high loads in terms of temperature and rotational speed.

The entire rotor is surrounded by a specially made housing. In contrast to a turbocharger this design employs rings of guide vanes. The compressor diffuser system is similar to that of the Turbomeca Marbore, i.e. it features one radial ring and one axial ring of guide vanes, milled from aluminium alloy. The individual vanes are machined from the solid on CNC milling machines. The combustion chamber was designed to run on propane gas only, although that does not apply in the latest models. The liquid gas first flows through a ring welded onto the hot thrust nozzle. This arrangement represents a small heat exchanger, which partially vaporises the fuel. The propane eventually reaches the turbine's throttle, where a needle valve is used to control the gas flow, and with it the turbine's rotational speed. A second adjustable throttle limits the fuel flow to the combustion chamber. Using this technology the engine offers clean and almost complete combustion. For the same reason a fuel pump is not required since the gas is under pressure and readily flows into the engine. After the combustion chamber the hot gases flow into the nozzle guide vane system. This section is also different to a turbocharger because it features guide vanes. The hot gas, now at a temperature of around 750°C, eventually reaches the turbine wheel, where it gives up the major part of its energy. The remaining heat loss takes place in the high-volume thrust nozzle. The working gas finally leaves the engine after being accelerated to a speed of more than 300 m/s.

The T240 produces a thrust of around 45 Newtons at full throttle and a rotational speed of 122,000 rpm. The pressure ratio is around 2.15,

The JPX T240, the first series-produced model jet engine.



the exhaust temperature approximately 650°C. Further thermodynamic data has not yet been published by JPX, although calculations indicate a throughput of around 0.13 kg/s and an exhaust speed of 345 m/s. The combustion gas temperature is probably around 830°C. At these operating values the Turborec achieves a very commendable fuel consumption of around 135 g gas per minute. This corresponds to a volume of approximately 270 ml of liquid gas. The mass of the T240 is 1.7 kg, the length 335 mm, the maximum diameter 116 mm.

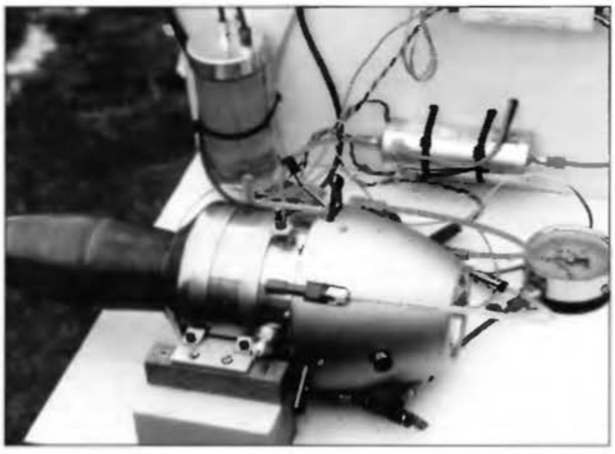
The JPX turbine on the test stand.

The engine has been the subject of a continuous programme of modification and development. Its direct successor, the T250P, offers increased thrust combined with lower engine mass. JPX quotes a continuous power rating for this engine of 49 Newtons at a speed of 118,000 rpm. The engine weighs 1.55 kg plus auxiliary equipment. The thrust of the turbine can be increased to a maximum of 59 Newtons for a brief period, for example, at take-off. Further development has resulted in a new, own-design rotor system, in which the compressor and turbine wheels are connected to each other by a large-diameter tubular shaft. The wheels are manufactured specifically for this engine. The turbine based on this work is the T260P, and its specified power output is 60 Newtons continuous thrust. Its mass remains at 1.7 kg. The other dimensions are largely the same as those of the original T240 version. These later engines also run on propane gas.

Handling the fuel (liquid propane gas) does require a cautious, circumspect approach. The only type of fuel tank which can be used is a pressure container, and this must be located close to the Centre of Gravity of the model aircraft. Without doubt propane gas represents a considerable fire hazard. If the model should catch fire, the tank represents a danger to everything in the immediate vicinity. For this reason a fire extinguisher is an absolutely essential component of the standard equipment - although this also applies to other types of jet engine. On the other hand propane gas is a clean fuel; the model never becomes soiled with spilt diesel or kerosene. A further advantage is the lack of problems in igniting the mixture in the combustion chamber.

In recent years great efforts have been made in converting the turbines to run on kerosene. On several occasions the company has announced series production of the "K" version designed for liquid fuel, and eventually this version did reach the model shops. The turbine employs a number of small injector nozzles which atomise the kerosene very finely. Some JPX owners have also converted their own engines to kerosene by replacing the standard combustion chamber with a kerosene-burning variant using hooked tubes (sticks). The various versions for Jet A1 fuel all produce the same thrust as the propane gas powered types. JPX turbines have proved their practicality at numerous flying events, and they been popular and successful in spite of their high purchase price. Several kit manufacturers have offered versions of their models that are specially designed for these engines. There have even been models which have were designed exclusively for the installation of the T240 or their successors. The importance of the JPX series later decreased from year to year. Other constructions with axial turbine wheels have proven faster to accelerate and more powerful. Also the use of liquid propane gas has always been a disadvantage compared to the easy to handle kerosene. Modellers using the Turborec need a considerable amount of auxiliary equipment: compressed air is needed to start the engine. This is fed through a nozzle to the compressor wheel,

The Sophia liquid fuelled engine is of very similar appearance to the JPX family.



The T250P supplies plenty of thrust when correctly installed in the fuselage.

which it sets in rotation. JPX has now stopped developing and producing this famous series.

Model jet engines to date

In recent years various turbines have been developed to the point where they are ready for series production, and are now available to the keen modeller. The thrust figures rose almost from year to year and have reached a level that is almost too high for many amateur pilots. Thrusts of 140 Newtons and more are widespread. Vertical climbs are easily possible if the model weight is low.

At the same time, manufacturers also realised the demand for even smaller engines. With higher rotational speeds it is even possible to build much smaller engines then described here in the building instructions. Compressor diameters of only 50 mm and below are used in commercial engines. These small units reach rotational speeds of 180,000 rpm and more. Apart from their main use - producing thrust to propel the aircraft - these very small engines have proven ideal for driving a second stage free turbine to deliver shaft power.

The general layout has become more and more similar nowadays. The designs follow the former amateur constructions, as they have proven reliable and powerful. All model jet engines use compressors from car or lorry turbochargers. The working turbine is a single stage axial type. The use of heat resistant alloys such as Inconel 713 or Nimonic types is standard today. The design of the combustion chamber has been taken over from the home-built engines. Pre vaporisation of kerosene in sticks from the rear is state of the art. Only AMT still use their own walking sticks type. Burning real kerosene in model size combustion chambers was formerly a significant problem. Nowadays most combustors work well with kerosene so that tanks with liquid propane gas are no longer required.

Automatic starters that spin the engine's rotor on command are also widely spread. These motors are located in the air inlet. When started, the inertia of the clutch presses an o-ring to the spinner of the compressor wheel. As long as the engine's shaft doesn't overtake the starter, the system is loosely coupled.

Mirroring developments in full-size engine building, the trend has been towards higher pressure ratios and gas temperatures. However, the rise has been modest, and the values are still a long way below those used in "full-size" aviation. As a result it is inevitable that fuel efficiency and power density remain inordinately low in comparison.

In general terms it is important to have a realistic understanding of the complexity of all the model jet engines currency available commercially. Extremely tight manufacturing tolerances are essential where all the revolving parts are concerned, otherwise there can be no guarantee of long, trouble-free operation. Some of the components used for the rotor, especially the radial compressor, are sourced from the motor car industry. These parts are dynamically balanced with great precision at the factory, and this ensures smooth running even at very high rotational speeds. Any attempt at improving the balance - unless you have expensive special equipment - or even dismantling the rotor assembly incorrectly, almost inevitably results in a worsening of rotor balance. Maintaining the engine in the amateurs modeller's workshop, as happens with small piston engines, is generally not possible. Most manufacturers state that a defective engine must be returned to the manufacturer, or an authorised service centre, for servicing, and there are good reasons for this.

The jet engine's control system is also complicated. Most commercial turbines are supplied with control units that automatically regulate the engine, based on crucial factors such as rotational speed or pressure, and exhaust gas temperature. The control unit's software includes a special program sequence for starting the engine, which ensures that the fuel flow is metered at the optimum rate, the propane gas for starting can enter and the glow plug is turned on for this moment. These facilities make engine operation much easier and also safer. Today many engines can be started and run completely via the remote control. During operation the rotational speed and the exhaust gas temperature (EGT) are permanently monitored and regulated.

It is especially important that the control unit takes into account the possibility of user error, and eliminates the dangers from such mistakes. Playing about with the throttle stick when controlling a piston engine does no harm, but repeating the experiment with an unregulated jet engine will wreck it in very short order. At one extreme the rotational speed of the turbine may fall below what we call the sustain speed, i.e. below the point at which the rotor is capable of accelerating under its own power. At this point the compressor and turbine are working at greatly reduced efficiency, and at the same time bearing friction has a much more serious influence. If you open the throttle in this state, any turbine will be damaged or even ruined in just a few seconds. Even more

	AMT Olympus	KH66	WREN MW54	JF-50 Bee
Engine diameter (mm)	130	112	87	80
Length (mm)	267	230	150	173
Compressor diameter (mm)	84	66	54	50
Turbine diameter (mm)	84	66	55	50
Engine weight (without fuel pump and ECU)	2475	930	800	800
Maximum rpm	108'000	115'000	160'000	180'000
Idle rpm	34'000	35'000	45'000	50'000
Thrust @ max rpm (Newton)	230	75	54	63
Pressure ratio	4.0	2.2	2.3	2.3
Fuel consumption (ml/min)	800	300	210	220
Mass flow (kg/s)	0.45	0.23	~0.18	~0.2

dangerous is the opposite extreme, which is the turbine's ability to run away uncontrollably. This is simply the result of feeding too much fuel to the engine, and allowing it to exceed its safe maximum rotational speed. The latter case is particularly hazardous and the control unit must prevent it happening with perfect reliability.

Any modeller who uses a jet engine must be fully aware of the special characteristics of these power plants and handle them cautiously and responsibly. However, model jet engines can be considered safe provided that you observe elementary safety precautions aimed at proper fuel metering and the avoidance of fire.

1.1. The J-450 by Sophia Precision

The overall design of the Japanese J-450 turbine is very similar to that of the French T 240: here again we find a rotor consisting of a radial compressor and radial turbine. The major difference between the two engines is the combustion chamber system: the J-450 uses a mixture of petrol and kerosene as fuel. Burning this mixture in such a small combustion chamber presents many problems. In contrast to propane gas, the liquid fuel has to be very finely atomised or vaporised. For this engine Sophia Precision decided to take the route of direct injection through small atomiser jets, using an injector pressure of around 10 bar at full throttle. The high pressure is produced by a powerful electric gear pump, which sucks the fuel mixture from a tank and forces it into the engine. Of course, the turbine could also be run on pure kerosene, but to achieve reliable ignition of the mixture in the combustion chamber the flash point of the fuel must be very low. To achieve this the kerosene is mixed with gasoline, which is highly volatile and therefore a serious fire hazard. Initially it was necessary to preheat the J-450 with a hot air gun for several minutes if weather conditions were cool; only then was the spark plug projecting inside the combustion chamber capable of igniting the fuel.

However, these problems had been solved. The engine is designed to produce a continuous thrust of around 55 Newtons, but it can provide up to 60 Newtons if required. Its maximum pressure ratio is 2.4 at a rotational speed of 130,000 rpm, and these figures clearly exceed those of the Turborec T240. The Sophia Precision J-450 weighs 1.8 kg without the fuel pump. The engine did not feature a speed limiter, and was sold without a regulator. As with the JPX turbines, compressed air from a bottle is required for starting. A 10-litre steel bottle is sufficient for 10 to 15 starts. The modeller, who used the Sophia needed a lot of equipment and technical know how. The complicated handling and the progress with other designs made this turbine become more and more meaningless. Yet even today some examples can be found at jet meetings.

1.2. AMT – Advanced Micro Turbines

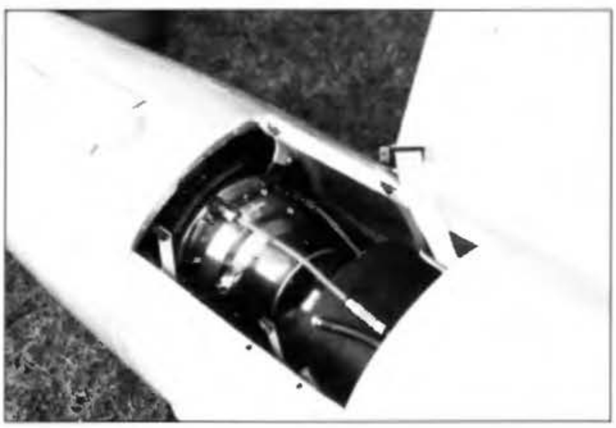
Really trend-setting engines have been designed in the Netherlands. Han Jenniskens and Bennie van de Goor started early in the 90s with their turbine constructions. Both were experienced pulse-jet builders and pilots and became real model jet pioneers. They have been the core of a team and have worked together for many years. Many calculations and experiments have taken place in 1990 and the following years. I have also been in contact with them and we exchanged many ideas.

The company of Advanced Micro Turbines (AMT) was later founded specifically to manufacture and market the engines. This philosophy has proved to offer many advantages: planning, development, testing and production are all carried out in-house, and this results in a turbine that incorporates many good ideas and a great wealth of experience. Their first engine, the Pegasus Mk-2 has been the most powerful production model jet engine for years.

In contrast to most other manufacturers, AMT decided on a genuine axial turbine from the outset; a type of turbine which is now absolutely standard in all full-size jet engines. With an axial turbine the working gas flows parallel to the shaft all the time it is passing through the rotor. The only component that is derived from a turbocharger is the radial compressor wheel.

The hot development-phase began in 1992 with a first

The Sophia Precision J-450 installed in an F86.



The AMT Olympus, Pegasus and Mercury family of engines.

Even the first prototype AMT Pegasus (Mk-1) produced a thrust of 100 N. The blade tips are moving at a speed of about 1500 km/hr at full throttle, and this demands enormous precision in manufacture. (Photo: AVIVA Press, Joop Wenstedt).

prototype. This power plant was fitted with an 84 mm diameter rotor, and after a short period of development it was already producing an impressive thrust of around 70 Newtons. Continual improvements in the area of the combustion chamber and the nozzle guide vane system increased this figure to a final value of 100 Newtons at a rotational speed of 95,000 rpm. In the course of the next few years this engine completed numerous test flights mounted on a Heinkel Salamander. The next prototype, the Pegasus Mk-3, reflected a further improvement in the technology. With a similar rotor, consisting of a Garrett compressor wheel and an axial turbine, the engine achieved a remarkable 150 Newtons of static thrust at a

The NGV systems and turbine wheels of the AMT Olympus and Mercury cast in Inconel 713.

pressure ratio of 3.5; a figure which lies in the range of full-size engines of similar design. This engine proved beyond all doubt the feasibility of an axial turbine in a model jet engine.

This level of power was considered no longer appropriate to the model aircraft application, so the production engine is slightly smaller. The production version of the Mk-3 features a 76 mm diameter compressor wheel, which is part of a high-throughput Garrett turbocharger. The diffuser system consists of two rings of vanes, through which air flows first radially and then axially. The compressor is driven by an axial turbine wheel, manufactured by a specialist company using a vacuum casting process. The material is a heavy-duty heat-resistant nickel-based alloy - the same material from which turbocharger components and gas turbine vanes are manufactured.

The combustion chamber of the Pegasus Mk-3 is designed to work with Jet A1 kerosene or a comparable fuel, injected by means of so-called sticks, or mixer tubes. These tubes extend into the combustion zone of the combustion chamber, where the fuel vaporises and mixes with the combustion air. The injection pressure required for this to work is very low. Much development work on optimising the combustion chamber has resulted in a simple, reliable system: fuel is burned very efficiently (i.e. completely) from a very low idle speed right up to full throttle. For starting it is necessary to pre-heat the combustion chamber using gas from a small cartridge, and the mixture is actually ignited using a glowplug.

The engine designers also invested some fresh thinking In the matter of the rotor bearings. They realised that the extreme rotational speeds encountered in a model jet engine actually called for a lubricant of very low viscosity. In fact, the viscosity of the kerosene fuel itself was sufficient to lubricate the bearings, and this made it possible to omit the oil tank generally used until then. Inside the engine a pipe guides a few percent of the fuel to the bearings. To ensure effective lubrication even when the kerosene fuel is above its boiling point, 4.5% of turbine oil is added to the fuel. The engine is fitted with hybrid bearings with silicon-nitride running surfaces.

The Pegasus is regulated by a special micro-processor controlled electronic unit. A sensor picks up the rotational speed of the rotor, while a thermo-element monitors the exhaust gas temperature in the thrust nozzle. The electronic unit then controls the injector pump on the basis of this data and the position of the throttle stick. The unit includes protection against over-revving, and also prevents the turbine running below the safe minimum rotational speed. The controller software provides a further program sequence to give reliable starting. The turbine is also stopped under computer control. Before the fuel supply is cut off, the engine is run to a rotational speed at which the exhaust gas temperature is at a minimum. This means that little heat is able to penetrate to the delicate bearings when the rotor is stationary and the flow of cooling air non-existent. Special software is also available to allow the transfer of current operational data from the controller to a Personal Computer via a serial link.

The Pegasus Mk-3 was rated at a continuous thrust of 100 Newtons, and thus represented the top end of the power spectrum of model jet engines for some years. The turbine's full throttle speed is 105,000 rpm. At this speed the pressure ratio is 3, the throughput 0.28 kg/s, and the efflux speed just on 360 m/s. With a specific consumption of 0,17 kg/N/h at full throttle, the engine is extremely frugal on fuel, but this still means that it consumes the substantial quantity of 350 ml of kerosene per minute. The Pegasus is extremely compact, with a diameter of 120 mm and a length of 270 mm, and weighs 2050 g including fuel pump and electronics. Many of these features that were first found in this engine are standard on others today.

Two further engines have been developed on the basis of this proven design. The first was an even more powerful variant, the Olympus, which is based on existing Pegasus components, but employing an 84 mm Garrett unit as compressor wheel. The turbine wheel was originally that of the Pegasus, but a larger diameter unit is now used. In this configuration the AMT Olympus produces 230 Newtons of thrust, which is well outside the spectrum of normal model applications. Hardly any model jet aircraft are designed to handle such levels of power. As a result it only forms a suitable power plant for the highly experienced and very safety-conscious modeller who wishes to build and fly really extraordinarily large models. Like the Pegasus, the Olympus turbine is also controlled by a sophisticated system of electronics. The mass of the engine is 2,400 g. Externally it is virtually identical to its smaller brother, although the diameter is a little larger at 130 mm. The thermodynamic data produced by the engine almost approach those of genuine drone engines: the pressure ratio reaches a value of 4, the exhaust gas temperature 650°C. At full throttle, which is no less than 108,000 rpm, the Olympus consumes 800 ml of kerosene per minute.

However, the latest development from AMT is more significant, as it is a smaller turbine: the Mercury. Here again, the design of the engine is basically the same as that of the Pegasus, but in terms of size and thrust it is a good match for most current model jet aircraft. One notable attribute is the turbine's modest external diameter, which is a deliberate design feature. The case diameter is only 100 mm, and the length just 225 mm. These small dimensions are only possible because the engine is based on a very small rotor. Nevertheless, the turbine produces an impressive thrust of 88 Newtons, and the secret to its high output is the high rotational speeds at which it runs: the full throttle speed is 150,000 rpm. The axial turbine wheel is another precision casting in Inconel 713. The Mercury achieves a pressure ratio of 2.8 at an exhaust gas temperature of 650°C, and fuel consumption is very low at around 360 ml per minute. Externally the smaller engine is very similar to its two larger brothers.

In the meantime the good team of Bennie and Han has unfortunately split up and two branches developed. They are AMT Netherlands and AMT USA. Both companies are legally independent, but now sell similar turbines.

1.3. The KJ 66

In recent years Schreckling has abandoned his original design. The latest turbine that is linked to his name is the KJ 66. This is a high-performance model jet engine that has become extremely well known since its introduction. The name is derived from the initials of the first names of the motor's manufacturers, Kurt Schreckling and Jesus Artés, who collaborated on the design of the new engine. The KJ 66 is externally similar to the original FD 3/64, which was designed by Kurt Schreckling, but that is all the two turbines have in common. Only the outer hous-

KJ 66 and Microturbine (left).

ing of the engine was retained for the new design. It is the case of a small gas container which can be bought as a camping accessory. The other internal parts have been entirely redesigned, and in general layout they correspond to the Micro-Turbine described in these building instructions.

The compressor is a proven turbocharger wheel with a diameter of 66 mm. This component is much more efficient than the wooden type previously used. The compressor diffuser takes the form of a machined aluminium part, whose vanes take the form of fat wedges. The axial turbine wheel is a precision-made fine cast item with 23 vanes that can tolerate extremely high rotational speeds. The wheel is cast in Spain in Inconel 713. It has been a co-operation between Jesus, Kurt and me to enable the wheel to fit the KJ and the Micro-Turbine as well. It is now also used in other engines of the same size.

The combustion chamber employs the now proven stick principle. The actual combustion chamber is very compact, so that a short shaft can be used. The shaft is carried in two ballraces that are mounted in an aluminium shaft tunnel; the bearings are preloaded by means of a spring.

The KJ 66 has a high maximum rotational speed. The use of a very strong turbine wheel makes it possible to run the jet engine safely at very high peripheral speeds. At 115,000 rpm the KJ 66 produces a thrust of 75 Newtons, and at the same time the weight of the engine is very low thanks to its use of thin sheet materials. The KJ 66 weighs around 950 g, depending on version, and

A KJ 66 built into a fuselage.

The German Behotec has internally a similar design to the KJ 66.

therefore offers an impressive thrust:weight ratio. With these figures the turbine is capable of providing plenty of thrust for virtually any model jet aircraft.

Further developments around the KJ 66 include an electronic control unit. Gaspar Espiell, a member of the team centred on Jesus Artés, has developed an engine governor which controls this (and other) model turbines very accurately. The electronic circuit monitors both exhaust gas temperature and compressor pressure, and maximum and minimum pressures can be entered to suit the specific application by means of a handheld data terminal. The KJ 66 has not been produced as a complete engine in the beginning. A set of plans and the most important parts, including the turbine wheel have been available. Meanwhile almost all parts can be bought from different vendors. This turbine-design has been copied many times and many of the current commercial turbines look like this turbine in many points.

1.4. The Artés-Turbines

Jesus Artés and his Spanish Team moved on in developing their own model engines. The original design of the KJ 66 was improved and new components were added. The JG-100 Eagle, a design of Jesus and Gaspar Espiell, had been the next turbine. The thrust had almost doubled and 150 Newtons were possible with this machine in a casing of only 108 mm diameter. This tremendous performance is possible by some changes,

The cast turbine wheel of the JF-series.

Jesus Artés with one of his JF-50 Bees.

especially by using larger compressor and turbine wheels. The new combustion chamber has 12 sticks and the compressor wheel has 16 blades with aggressive, almost upright ending blades. At full throttle it reaches a rotational speed of 132,000 rpm and a pressure ratio of 3.4.

The series version, now called JF-120 Super Eagle is produced in collaboration with Felipe Nieto in Mexico. The thrust is slightly lower and now reaches 135 Newton. The casing of the turbine is made of aluminium. Many details have been improved. Jesus spends much time in development and continues to experiment with new thrust cones, bearings, guide vanes and other parts.

Apart from the JF-120 other similar engines have been developed. One engine, called JF-100 Falcon, has a smaller casing of only 98 mm diameter but still delivers a thrust of 100 Newtons. A lot of time has been invested in building much smaller engines. The latest result, the JF-50 Bee is described at the end of the chapter. Beside the engines, Jesus delivers a lot of parts. Cast turbine wheels, nozzle guide vanes and shafts are available.

1.5. The Jet Cat model turbine

This model engine is an interesting unit, which incorporates several real innovations. The feature that immediately catches the eye is the electric starter motor which is integrated into the turbine's inlet opening. The essential control components are hidden away discreetly in the immediate vicinity of the inlet bell mouth. Everything is concealed, and the engine is very compact overall. In terms of turbine technology the JetCat P80 is very closely based on existing home-built engines: the proven 66 mm diameter

Jet Cat P120 mounted on a Kanaroo trainer

KKK turbocharger compressor is used, combined with a cast axial turbine.

The combustion chamber is equipped with six sticks in which the kerosene is pre-vaporised. Propane gas is used for ignition, fired by an electric glow-plug. Initially the two ceramic bearings were lubricated by a separate oil feed system, and the engine was supplied complete with an oil metering pump, but since then the manufacturers have changed to a maintenance-free fuel lubrication system. The front bearing is pre-loaded in the forward direction, as in the AMT engines. In purely visual terms the turbine is very neat and uncluttered, and makes an excellent impression.

The output power is quoted at 80 Newtons, which is a very high level, and ample for powering models with a take-off weight of 12 kg or more. The engine weighs just over 1.3 kg complete with all accessories. However, the real highlight of the system is the integral starter. Once the model's fuel tank has been filled and all batteries charged, all you have to do to start the engine is operate a switch on the transmitter the electronic circuit does the rest. First the starter is switched on; this engages with the compressor hub automatically and sets the rotor spin-

Typical is the electric starter of the Jet Cat.

Just like toys. Parts of Jesus' Nano Bee.

The JF-50 sectioned. the small engine is compact and stable.

ning. At the same time the gas valve opens, and the glowplug is switched on. A thermo-element reports ignition in the combustion chamber by detecting the rise in exhaust gas temperature. The electronic circuit responds by starting up the fuel pump, and the engine runs up to speed. The electric starter switches itself off, and the gas flow required for ignition is cut off automatically. From this point on the turbine is regulated using the functions now common to most modern engines. Maximum rotational speed and exhaust gas temperature are automatically limited.

The JetCat model turbine has already proved itself in many model aircraft: it is a very efficient and lightweight power plant, its compact external dimensions allow the engine to be fitted easily into most model jet aircraft. The set includes comprehensive instructions and mounting materials. The JetCat has been the first model turbine that has been distributed in regular model shops by Graupner. This fact must not imply that this power plant is something for a beginner. You also must be an experienced modeller to operate the system correctly, but, this precondition fulfilled and the system correctly installed, the model is simply carried to the take-off strip, where the entire starting procedure can be carried out with ease and convenience from the transmitter.

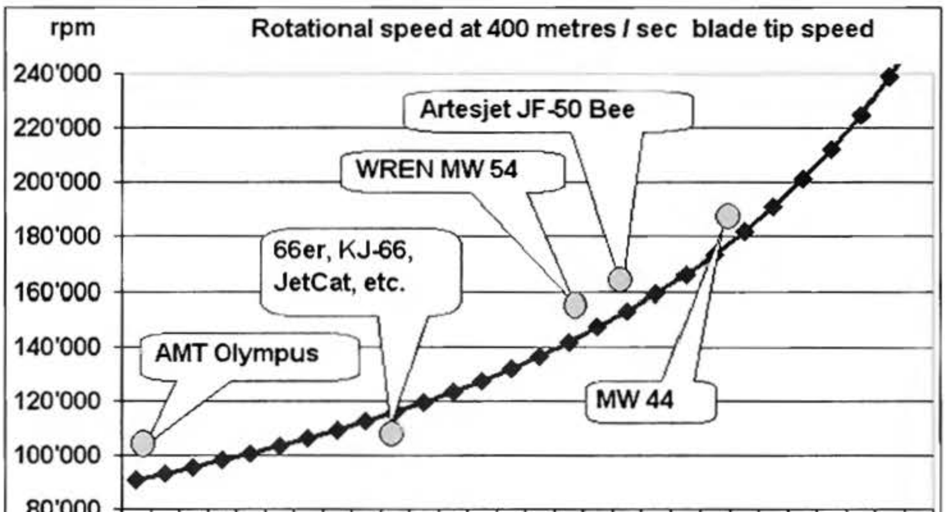
Also the original JetCat P80 got bigger brothers. A more powerful version P120, later a P160 and even P200 with 200 Newtons continuous thrust is available now. All engines look alike and they all carry the characteristic electric starter at their front.

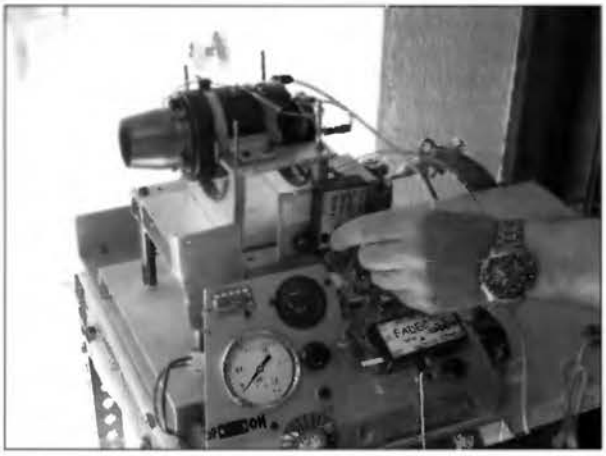
1.6. The smallest engines

Despite the tremendous inflation of thrust figures in recent years, much smaller engines have been developed. Fifty or sixty Newtons of thrust is more than enough to propel small airframes. New turbocharger developments from the car industry also help to enable new dimensions in small gas turbines. The car industry produces smaller and smaller cars with turbocharged engines. These turbochargers are so small, that they seem to be almost toys. The smallest compressor wheels have diameters of only 35 mm. The blades are cast with a thickness of just 0.4 mm. You could merely crush them with your fingers. Generally the number of blades are only 8 or 10 and they are greatly retro-curved. The efficiency of these wheels is almost as high as that of their bigger brothers. Wheels of 50 mm reach almost 80%. The availability of these parts makes very small and powerful engines possible.

The number of revolutions reaches new dimensions as well. Up to 180,000 rpm are necessary. This means no less then 3,000 revolutions per second. If perfectly balanced, you lose the feeling for these rotational speeds. At full throttle you just hear a powerful roaring and the rpm just becomes a number on the digital display. The shafts are fitted with hybrid bearings without cages. They are generally lubricated with fuel.

Relation between rotational speed and compressor diameter.





The Bee on the test bench. You don't realise the extreme rotational speed.

The MW 54 and its smaller brother the MW 44.

As with the maximum revolutions, idle speed also increases. It is typically around 50.000 rpm for the smallest engines. The small electric starters have to spin up extremely high to get the engine to run safely.

A typical example for a very small engine is Jesus' JF-50 Bee. The overall design is similar to that of its larger brothers. The outer diameter has been reduced to only 80 mm, the length is 173 mm. The JF-50 Bee reaches full throttle at 180,000 rpm and a thrust of 60 Newtons. If you hold this machine in your hands you realise that it is really only as big as a coffee-cup, but at the test bench it certainly earns high respect because of the really high performance. The Bee has an electric starter and is entirely digitally controlled. The weight is 800 g. Jesus has already developed an even much smaller engine. This Nano Bee is already working but is, at time of writing, still in an experimental stage. The Nano Bee has a wheel diameter of only 35 mm. The external diameter is only 58 mm. It fits into a beverage can.

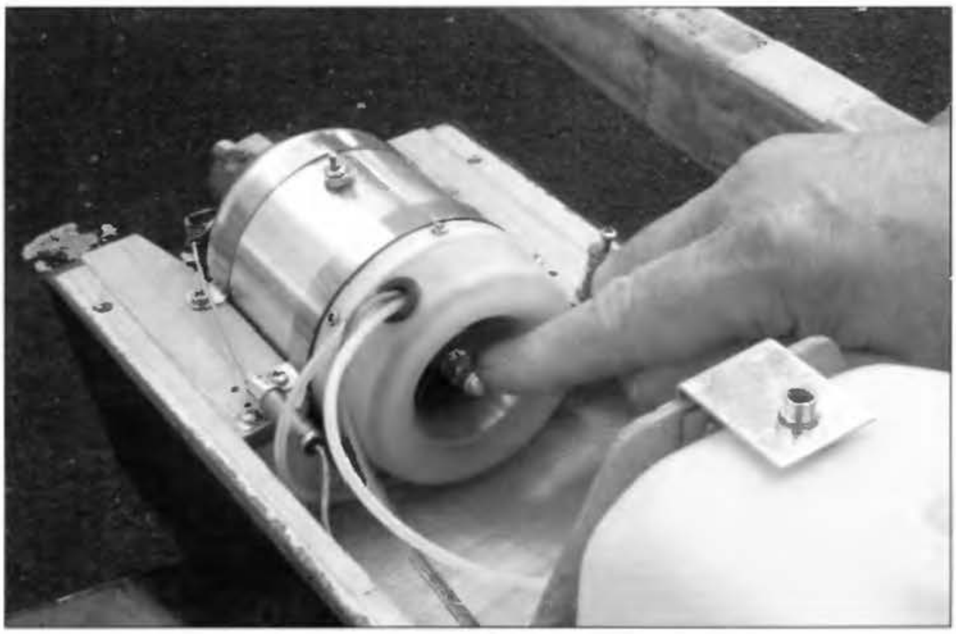
Another small turbine has been developed in England. John G. Wright and Mike Murphy have designed the MW 54, a small engine based on a turbocharger compressor. The name is also derived from the names of the builders and the diameter of the compressor. The engine uses a 54 mm Garret compressor wheel. The turbine wheel is exactly one millimetre larger. It is, as well as the NGV, a cast part made of the heat resistant material Inconel 713.

The MW 54 is very small and light. Its outer diameter is only 87 mm and the length is about 150 mm. The engine weighs just 650 g and although of such small dimensions the thrust reaches 54 Newton at about 160,000 rpm. Later developments led to an MW54 MK3 with an augmented thrust of 64 Newtons. With this normal sized models can be flown without any problems. The construction is also ideal for models with two or three engines. Also the fuel consumption is relatively low.

The construction of the combustion chamber is worth mentioning. Especially in small engines the complete combustion of the fuel is a serious problem. The combustor of the MW 54 has a length of only 47 mm. Within this distance combustion and mixing of secondary air must take place. John and Mike are using the proven sticks, but here they are formed like an 'S' and end at the inner diameter of the combustion chamber. Additionally small nozzles lead air into the chamber. That the concept works is proven by the low exhaust gas temperature of 370 °C without the exhaust nozzle. With the thrust nozzle mounted about 575 °C is reached.

Mike and John have also produced an even smaller version. The MW 44 is a fully developed series engine with a wheel diameter of only 44 mm. Its potential is about 32

The MW 44 built into a trainer. With the hand close to it you can imagine the extremely small size.



The MW 54 in turboprop configuration driving a big propeller.

Newtons and the weight is only 470 g. The rotor spins up to an amazing 190.000 rpm. The MW 44 and MW 54 are sold through WREN Turbines Ltd. Parts and complete kits for the MW54 are also available.

1.7. Turboprop and shaft power engines

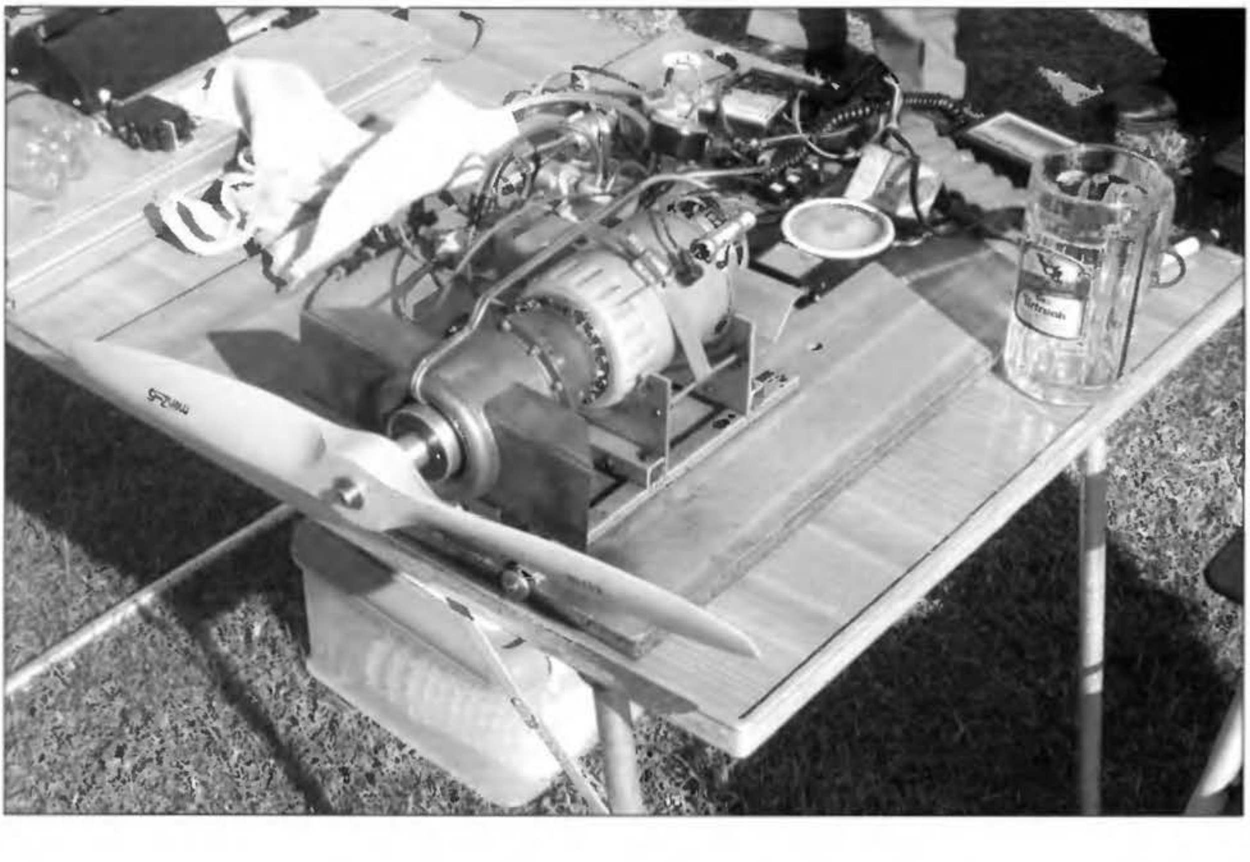
Apart from direct jet, other means can also be used to propel airframes. The gas jet of the engine delivers enough energy to produce plenty of shaft power. The most popular way is to use the exhaust gas jet to drive a secondary turbine stage. This design has important advantages. The second turbine stage acts as a clutch. The propeller can even be held stopped, while the core engine is spooling up. The second turbine stage has also got much lower rotational speeds. Constructing suitable gearboxes is by far easier then to couple the gears directly to the core engine's main shaft. The engines can be used to drive a propeller (turboprop) or to drive the rotor of a helicopter (shaft power engine).

Very small turbines are especially interesting for turboprop applications. Their power is generally sufficient for most applications and the fuel consumption is low. Building a shaft power engine, based on an AMT Olympus could theoretically deliver about 50 kW and therefore power a small car - too much for any model application.

One popular construction is based on the MW 54 core engine. This small turbine is used as core gas generator for the turboprop assembly. With a much bigger second turbine wheel instead of the thrust nozzle, up to 5 kW shaft power are reached. This assembly powered a model helicopter reliably already in 1999. In this shaft power version, the turbine is mounted against flight direction. The hot exhaust gases stream to the front, where the power turbine is located. A big propeller is then driven via a gearbox. The power can get so high, that some propellers can break at full throttle. The engine is available from WREN ready built as a kit.

Some turboprops have in the meantime become commercially available, but they can also be built from a plan. Here you can add a second turbine stage to an existing gas turbine or build a specially designed construction. Certainly the effort is higher than if you only try to build a normal jet engine. Kurt Schreckling did a lot of development in this field. His building instructions are also available in a Traplet Publications book. The title is: "The Model Turbo-Prop Engine".

Homebuilt turboprop in twin shaft configuration based on a very small core engine.



Chapter 1

The Component Parts of a Model Jet Engine

This section presents the most important components of a model jet engine - the compressor, combustion chamber and turbine - one by one. Details are provided on the principles and method of working of the parts, and also the methods of calculating the data for designing these essential components. The basic theory required is explained gradually and illustrated with the help of examples. The underlying formulae relating to each part are stated at the beginning of each section and discussed briefly where necessary. Only a small number of formulae are required overall to calculate the essential data for a jet engine, and you will also find that everything turns up again when we discuss the turbine. I would like to point out to you here that, although the theory presented in this book can certainly be used for the calculations relating to a model jet engine, the mathematics has naturally been simplified somewhat. Don't be concerned - the complete calculations concerning all the flow processes inside a model jet engine would fill several volumes, if it were possible at all. All this means is that there is plenty of scope for experimental work on the completed engine, using the modeller's favourite method of determining the best possible design and construction of the components. We shall start with the compressor, as all the other components are designed and adjusted to suit this part. The reason for this sequence of operations is that in this area the modeller can use a ready-made compressor wheel as used in turbochargers. As a result, selecting a particular compressor wheel determines the overall characteristics of the engine at a stroke.

Special features of small gas turbines

Model jet engines are not simply reduced-scale models of full-size engines. The basic method of working is the same, but there are special considerations which demand a different and usually simpler design. Any comparison between a real aircraft engine and a model jet engine initially throws up few similarities. Most modern gas turbines include features such as multi-stage compressors and turbines, blade cooling, complex regulatory and control machinery and so on, and these are simply not present in the model version. In our case everything depends on simplicity and functionality.

Combustion

The combustion chamber is one of the most critical components of the engine. Although it has no moving parts and its only task is to heat air by means of the combustion of fuel, there are considerable problems involved in optimising the design. The reason for these difficulties is the extremely short period which the air spends in the combustion chamber. On average this is only about 1/500 of a second. In this period the fuel and air have to be mixed, burned, and secondary air added to the mixture.

In this respect chemistry presents the modeller with serious problems. In fact the expansion speed of the flame front is severely limited. It is therefore essential to slow down the flow inside the combustion chamber to a huge extent, so that the gas speed in the combustion area (known as the primary zone) is very low. At high rotational speeds gas flow speeds up markedly, and the efficiency of combustion falls off quickly, i.e. fuel leaves the engine unburned. This can reach the extent that unburned fuel forms a plume of white smoke as it leaves the exhaust. At its worst the flame is simply blown out. However, the rate of flow in the combustion chamber can only be slowed down if its cross-sectional area is correspondingly large. Liquid fuels present a particular problem here, as combustion cannot take place until a combustible mixture is formed - a complex process in itself. The length of the combustion chamber plays an important role here. If the chamber is too short only a proportion of the fuel burns in the combustion chamber, and the flames then continue into the turbine stage. Even if the engine runs at all in such a state, this problem will always result in inefficient exploitation of fuel. Streams of hot gas, still burning, then produce local overheating in the turbine - what are known as hot spots. Poor combustion also has an unfavourable effect on the efficiency of the turbine. Exhaust temperatures rise to excessive levels although the compressor and turbine stages may actually be working efficiently. Viewed overall, it is clear that an efficient combustion chamber is a fundamentally essential feature of any practical model jet engine. Many industrial miniature gas turbines side-step the problem of miniaturising the combustion chamber. This is done by arranging a separate, large-volume combustion chamber adjacent to the rotor. A central fuel injection vaporiser jet in the middle of the flame pipe is then all that is required. Unfortunately this solution is very bulky, and cannot be used in a jet engine designed to propel model aircraft.

Rotor design

Turbine engines only produce high power at very high peripheral speeds. This applies to full-size jet engines and also to small ones, i.e. model jet engines. This inevitably means very high rotational speeds to take into account the smaller wheels. Our small engines often run at speeds in excess of 100,000 rpm, depending on the diameter of the rotor. These very high rotational speeds make particular demands on the modeller, as they require that the rotor system be made to extremely high levels of precision. Even very slight imbalance results in substantial centrifugal forces, which in turn lead to a slight elastic deformation (bending) of the shaft. The distortion in turn increases the imbalance, and

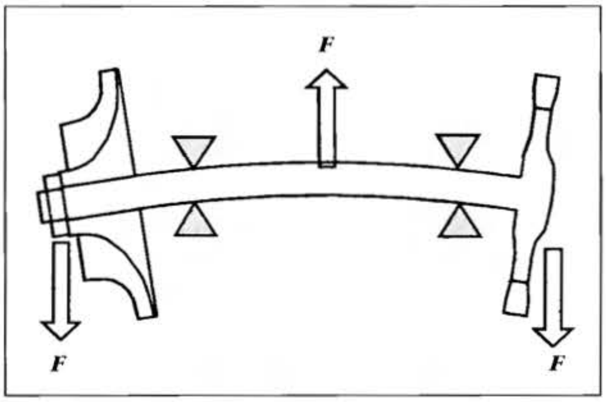


Diagram of dynamic bending of the engine's shaft as it approaches the critical rotational speed.

Rotor of a model jet engine (Mini-Turbine).

the centrifugal forces rise further. The only force which counters this effect is the shaft's natural resilience. As long as this is greater than the centrifugal force, the bending stays within relatively narrow limits. However, if rotational speed continues to rise we reach a point where the rotational frequency of the rotor is the same as the resonant frequency. At this point resonance sets in and any minute imbalance causes the rotor to bend and oscillate. The deformation in the shaft increases uncontrollably and the shaft is destroyed. However, before this happens, i.e. well below the critical rotational speed, the shaft may be so seriously distorted that it is permanently bent, and the bend may even be visible to the naked eye. If this occurs in a model jet engine the result is sudden, intense vibration at full throttle. As the engine runs down the damage will be obvious by the compressor shaft running out of true.

When you are running the gas turbine it is therefore essential to ensure that the rotational speed of the shaft remains significantly below the critical speed. The critical rotational frequency varies according to the shaft material, the mass and geometry of the rotor and the arrangement of the bearings.

As a basic rule we can state that, the longer the shaft, the lower the maximum permissible rotational speed. At model sizes, for example, lengthening the shaft by a single centimetre reduces the rotational speed strength by up to about 20%. For the same reason there are limits on the length of the combustion chamber, as it has to fit between the compressor and the turbine.

The actual rotor bearings take the form of ballraces and, curiously enough, they generally present no problems. The only essential stricture here is that the bearings must be lubricated and cooled adequately. Provided that this is the case, then you can safely exceed the nominal maximum speed stated by the bearing manufacturer by up to three times. Heat-resistant steels such as basic stainless steel are extraordinarily poor conductors of heat, and it is only this circumstance which enables us to keep turbine bearings at a low temperature. Although the temperature of the turbine blades reaches more than 600° C, the bearings, located only a few centimetres away, stay relatively cool. However, this is only true if the correct amount of air is ducted to the bearings for cooling. If very high rotational speeds are required we recommend that the bearings be pre-loaded usually to a minimum value. Specialist literature from bearing manufacturers should be studied on this point.

Gap losses

There must be a slight gap between the compressor and turbine wheels and their housing to provide clearance for the moving parts. Naturally it is essential to keep this "escape route" as small as possible, otherwise gas will flow past the blades instead of through them. The width of the gap is primarily dictated by the potential thermal loading. When the engine is started up from cold the turbine blades almost instantaneously reach the same temperature as the gas, but the surrounding housing takes a little time to warm up. The clearance must therefore be great enough to avoid the turbine blades touching the housing as they expand more quickly. The reverse case must also be considered: when the engine stops running the housing cools quickly, and could foul the spinning rotor blades which are still hot.

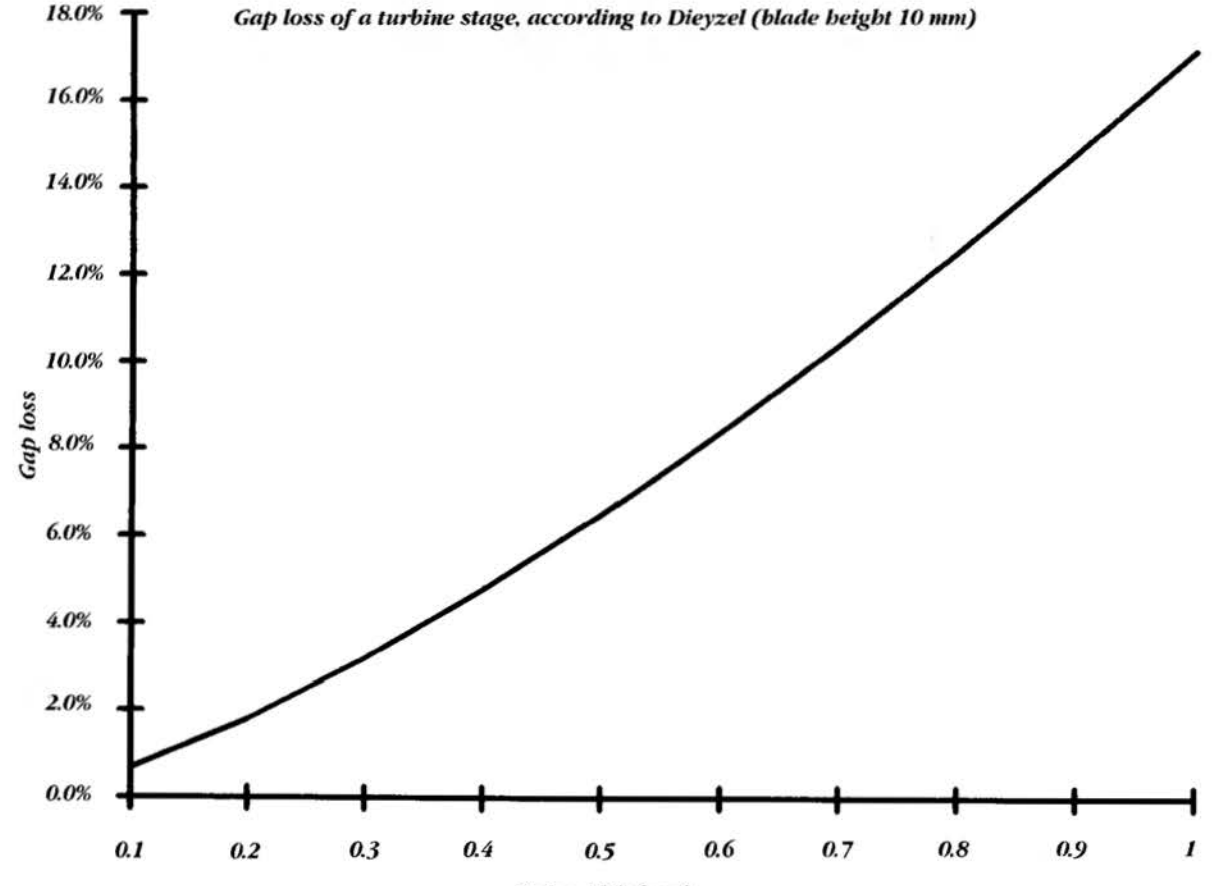
In industrial gas turbines the gap is 2 to 3 thousands of the rotor diameter. For example, the turbine clearance of the Turbomeca Artouste, with a rotor diameter of 220 mm, is only 0.4 mm. This narrow gap did occasionally cause the engine to stop when the housing touched the blades and jammed the rotor.

In practical terms such tight clearances are not feasible for model jet engines. Extreme accuracy in the workshop might make this possible, but in any case uneven temperature distribution in the exhaust gas is virtually unavoidable, and this would tend to cause heat distortion in the turbine shrouding system. Fouling of the turbine would then be inevitable. For model jet engines we must therefore accept a gap of 5 thousands of the rotor diameter and learn to live with the inevitable losses. The distance between the rotor blades and the housing of a model jet engine will typically lie in the range 0.3 - 0.5 mm, depending on the turbine diameter. These values are easily within the scope of the amateur. However, any further widening of the gap will result in a significant drop in efficiency. With a gap of one millimetre the engine will not run at all. Similar rules apply to the compressor area, although our experience shows that a small radial compressor with a gap of 0.4 mm is still quite efficient. Gap losses can be avoided almost completely by using what are known as enclosed rotor wheels. These wheels feature a plate which covers the compressor blades to form enclosed ducts. The disadvantage is the slightly lower rotational speed strength of these wheels.

Conclusions relating to the model jet engine

In designing a model jet engine the aim of the exercise is to exploit the basic principles of the gas turbine, as already described, using the simplest possible means. This straightforward aim presents plenty of problems in itself, which means that the modeller can certainly spare himself any thoughts of technical refinement. It is safe to assume that afterburners, multi-shaft rotor systems and by-pass engines will not find many advocates in the model arena. The obvious choice for the model jet engine's compressor is the radial type. With a single stage this sort of wheel can provide an acceptable pressure ratio. The axial compressor generally used in full-size jet engines unfortunately presents a multitude of problems at model scale. Calculations show that a gas turbine could function with a single-stage axial compressor, but in practice such an engine would only develop as much thrust as a good-quality heat gun. The low pressure ratio would give a very low efflux speed, and fuel consumption would be unacceptably high.

To obtain a pressure similar to that of a single stage radial compressor an axial compressor would require at least three stages, and the construction of a multi-stage compressor is enormously complicated. The stator housing would have to be made in two halves with an exactly circular internal cross-section. It would no longer be possible to support the rotor on only two bearings, as this would dictate a very low critical rotational speed.



Gap losses at the turbine stage of a model jet engine.

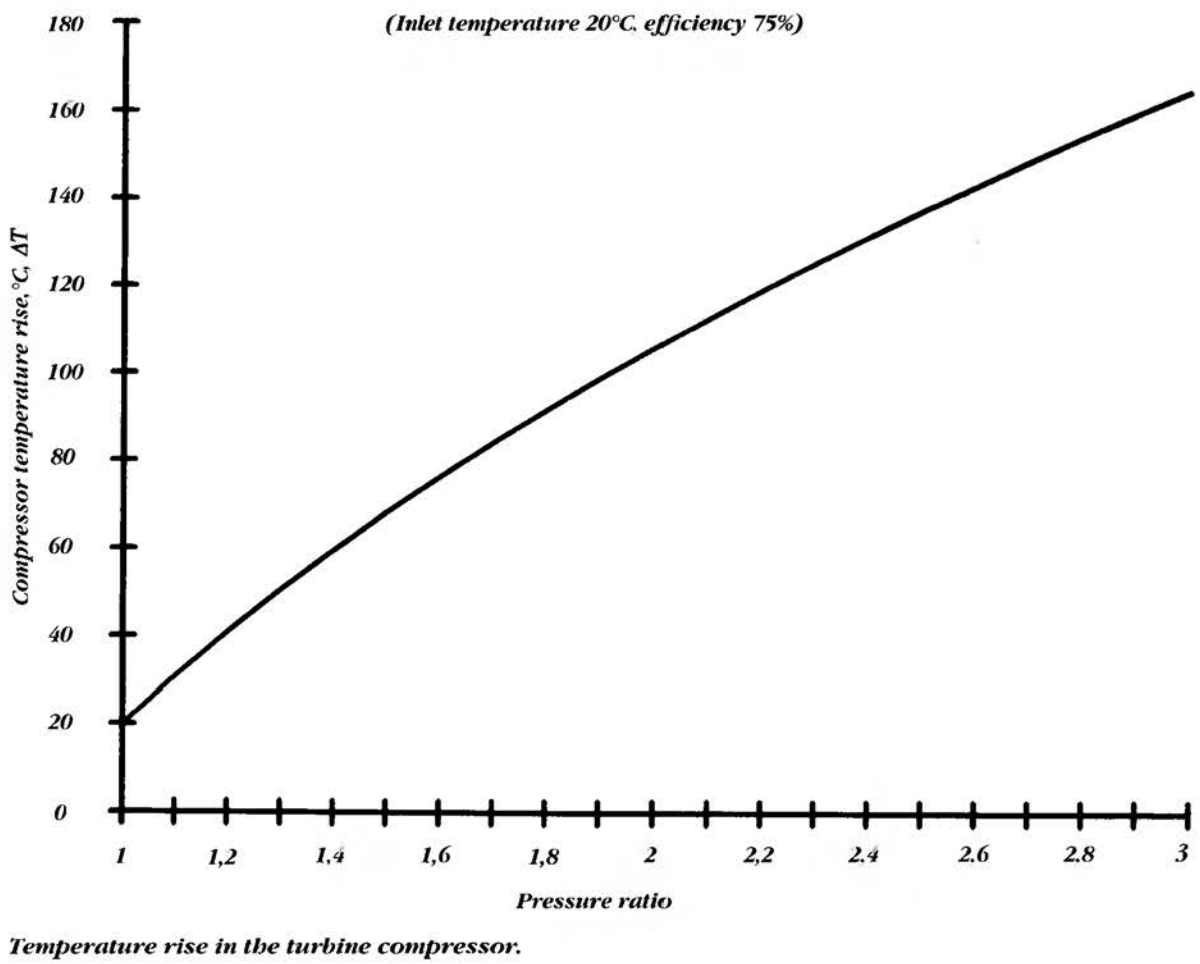
MODEL JET ENGINES COMPARED WITH INDUSTRIAL AIRCRAFT ENGINES

Engine	FD3	Micro-Turbine	T 250P	Marbore	CF6-80C
Firm/Constructor	Schreckling	Kamps	JPX	Turbomeca	GE, MTU, SNECMA
First Run	1990	1993	1995	1952	1983
				Fouga CM 170 "Magister"	Airbus A 330 Boeing 747
Thrust (Newtons)	30	50	59	3,900	262,500
Mass (Kg)	0.75	1.14	1.55	146	4,066
Pressure Ratio	1.5	2	2.15	4.1	32
Turbine					
Intake temperature (°C)	ca.700	ca.650	ca.740	780	1.280
Specific Thrust (N/kg)	40	44	38	27	65
Consumption (kg/min.)	0.16	0.166	0.177	7.6	158
Specific Consumption (kg/N/h)	0.32	0.2	0.18	0.117	0.036

Nevertheless, in theory this type of compressor might have possible applications in the model scene.

Once the type of compressor has been selected, the layout of the turbine stage is already fixed to some extent. A single-stage turbine is quite adequate, and both axial and radial turbines are feasible.

Single-stage compressors and turbines take up little space, but the same does not apply to the combustion chamber, and that is why model jet engines do not look at all like their full-size cousins from the outside. In fact, the relative proportions are more or less reversed. In a full-size jet engine the combustion chamber constitutes a short section between compressor and turbine, but it is usually the largest component in the model version. There are further differences in terms of specific power. Model-size compressors and turbines are less efficient than industrial aircraft engines. If the engine is to run at all, the turbine must extract most of the available energy



Temperature rise in the turbine compressor.

from the exhaust flow. As a result only a relatively small residue of energy is left to produce thrust. This fact, coupled with the low pressure ratios which can be achieved in model jet engines, has the effect that only 3 to 8 per cent of the energy contained in the fuel is turned into thrust. Nevertheless, since these small engines are low in mass they achieve thrust:weight ratios comparable to those of their full-size friends. The drawback is fuel consumption: the model pilot who wishes to use this type of engine in a model must allow for the installation of a very large fuel tank.

The compressor

The purpose of the compressor is to compress the air drawn into the engine. The basic principle of all compressors is the same: it converts kinetic energy into pressure energy. To achieve this the air drawn into the compressor is first accelerated to high speed and then decelerated; this action converts the speed of the gas into pressure. If a radial compressor is used, centrifugal force provides a further increase in air pressure. During this process the temperature of the medium rises at the same time as the gas pressure rises. This effect will be familiar to anybody who has pumped up a tyre with an ordinary hand-operated pump.

The work done is stored in the gas leaving the compressor. In technical terms this is an increase in the enthalpy ("heat content of a substance per unit mass") of the air. In theory the rise in enthalpy corresponds to the specific power of the compressor, although in practice we have to make allowance for the inevitable losses.

$$\Delta h = T \times c_p(\pi^{0.286} - 1)$$

- Δh = Enthalpy increase (J/kg)
- T = Inlet temperature in ° Kelvin
- c_p = Specific thermal capacity of air, 1000 (J/kg/K)
- π = Pressure ratio of the compressor, i.e. final pressure/inlet pressure

The exponent in the formula (0.286) is derived from the polytropic coefficient n. In the case of an uncooled compressor (known as adiabatic compression) n = 1.4. The exponent used in the formula is (n-1)/n = 0.28571, or 0.286 when rounded up. This value (or its reciprocal 3.5) crops up again, and again in all thermal calculations.

The input power which the compressor requires for its work can be calculated as follows:

$$P = \dot{m} \times \Delta h / \eta$$

$\dot{m}$ is the compressor throughput in kg air per second.

η is the efficiency of the compressor. In the model sphere it varies within the range 0.65 to 0.78.

The lower the coefficient, the more energy is converted uselessly into heat, and the greater the temperature increase ΔT in the compressor.

$$\Delta T = \frac{\Delta h}{c_p \times \eta} = \frac{T}{\eta}(\pi^{0.286} - 1)$$

One of the most important equations used in calculating the compressor – and in fact the entire engine – is what is known as the continuity equation. It can be used virtually everywhere and fortunately it is extremely simple. It states that the volume of gas which flows in one second through a known cross-sectional area A at a known speed c is the product of A and c. Logically the volume which flows doubles if we double the cross-sectional area or the speed. One value which is always of interest is the throughput, i.e. the mass of gas which flows per second, and to calculate this we multiply the volumetric flow by the density of the gas.

This gives us the classic continuity equation:

$$\dot{m} = c \times A \times \rho$$

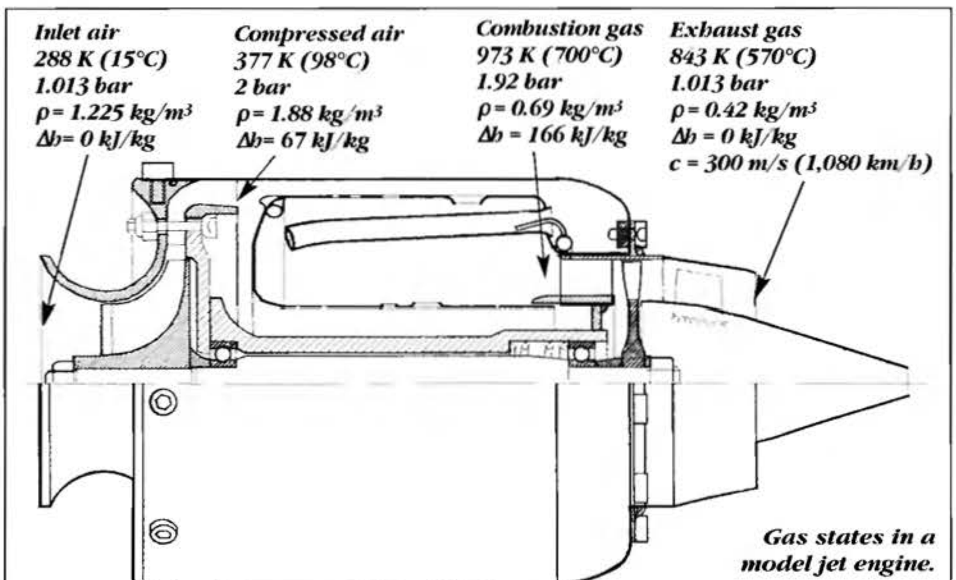
- $\dot{m}$ = Throughput (kg/s)
- c = Speed (m/s)
- A = Flow cross-section (m^2
- ρ = Gas density in the cross-section (kg/m^3)

When using this equation it is important to keep to the correct units of measurement. We can exploit the fact that the throughput in a model jet engine is virtually constant at all points. We can ignore the mass of the fuel supplied to the engine since it represents only about 1.7% of the air throughput.

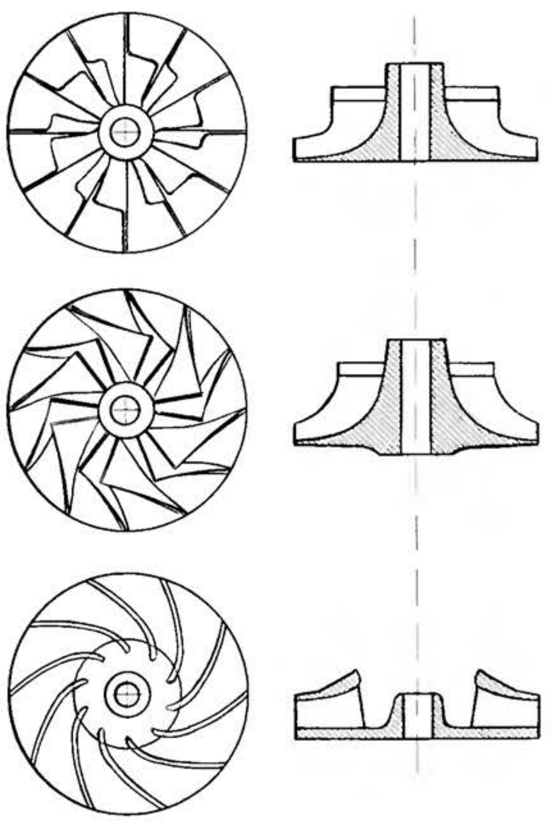
We can now find the flow speed for any cross-section provided that we know the throughput and the gas state. To calculate gas density we only need the pressure and temperature of the gas.

$$\rho = p/(R \times T)$$

- p = Absolute pressure of the gas in Pascal (N/m^2) (1 bar = 100,000 Pa)



Gas states in a model jet engine.



Types of radial compressor (top to bottom): wheel with radially tipped blades; wheel with slightly retro-curved blades; enclosed wheel with greatly retro-curved blades.

T = Absolute gas temperature in ° Kelvin
R = Gas constant for air and for combustion products produced in the engine (287 [J/kg/K])
ρ = Gas density in kg/m³

The radial compressor

For a model jet engine this type of compressor appears to be "made to measure". The radial compressor is extremely robust and straightforward in construction. Because of these advantages it is still used today where it would be possible to replace it with the more effective axial compressor.

The radial compressor can be built in various configurations which exhibit widely varying characteristics, although the two main categories are those with a cover plate, and those without. The former type features a plate covering the blades, designed to avoid gap losses. The resultant compressor is an "enclosed wheel" type. A second important feature is the curvature of the blades, whereby the crucial point is the angle of the blades at the wheel exit. We have to differentiate between wheels with radial blades and those with retro-curved blades.

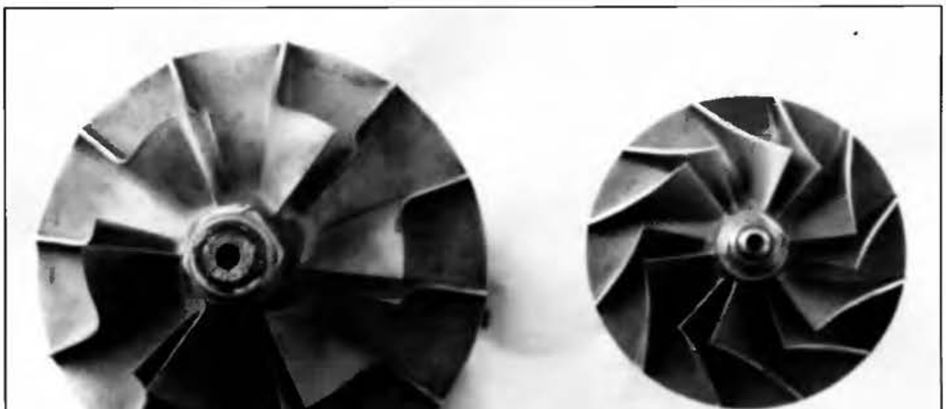
Practical experiments have shown that all these wheel forms are suitable for model jet engines. Regardless of the precise type of radial wheel, the air drawn in flows in the direction of the rotational axis. Once inside the wheel the gas follows the blade ducts and is pushed outwards in the radial direction under the influence of centrifugal force. Finally the air leaves the wheel and flows at high speed into the adjacent compressor diffuser system. Here the gas is slowed in the widening ducts and the residual kinetic energy is converted into pressure. The overall pressure rise in the stage is distributed over the wheel and the diffuser system. The reaction level r of the compressor stage can be defined in general terms as follows:

$$r = Y_{Wheel} : Y_{Stage}$$

Y_{Wheel} and Y_{Stage} are the values for the work which is done on the air in the wheel and in the overall stage respectively. The unit of measurement here is J/kg.

The distribution of the two components is determined by the type of blade form used in the wheel. Radially tipped blades supply a reaction value of 0.5. With substantial retro-curvature this value is much higher, which means that most of the energy conversion takes place inside the wheel.

Compressor wheels of 95 mm and 66 mm diameter. The former is already slightly too large for normal model use.



The increase in pressure in a radial compressor varies according to the deflection of the gases in the direction of the peripheral motion. Peripheral speed is not a constant in a radial compressor, and this is the crucial advantage of this type of unit. At the air inlet the wheel diameter is small, and the peripheral speed therefore correspondingly low. In contrast, maximum peripheral speed is reached at the wheel outlet. The overall deflection is therefore considerable. The work done can be calculated as:

$Y_{th} = u_2 \times c_{2u} - u_1 \times c_{1u}$
u_1 = Peripheral speed at the wheel inlet
u_2 = Peripheral speed at the wheel outlet
c_{2u}, c_{1u} = Gas speed in the peripheral direction at the wheel inlet and outlet

For our purposes we can simplify the formula even further. If the compressor consists of a single radial stage, then the gas flows into the compressor without any twisting motion. This means that the airflow is perpendicular to the peripheral direction at the wheel inlet. As a result the inflow speed has no component in the rotational direction. The expression $u_1 \times c_{1u}$ becomes equal to zero, and the following formula applies:

$Y_{th} = u_2 \times c_{2u}$; [m/s × m/s = m²/s² = J/kg]

The net result is that we only need to consider the flow conditions at the wheel outlet. At this point we use a velocity diagram to clarify matters. In a velocity diagram the individual flow components are drawn as vectors. The vector arrow shows the direction of flow, while the length of the arrow shows the magnitude of the speed. In the resultant velocity diagram you can use trigonometry to obtain the values you want. This gives you an alternative method of determining all the vital flow angles: either by calculation or by consulting graphs.

All the speeds at the wheel inlet and outlet are given the suffix numbers 1 or 2 in order to differentiate them clearly. We will consider the absolute speed of the gas c, the relative speed w and the peripheral speed u. The absolute speed is the gas speed at a particular, fixed point of observation. In contrast, the term relative speed applies to those components which relate to the blades which are in motion. If we could hitch a ride on the compressor wheel, the measured flow would be the relative component. In the wheel we obtain the absolute speed by vector addition of relative and peripheral speed. A further important speed component is what is known as the radial component c_m. The radial speed is the component of the absolute speed in a direction perpendicular to the peripheral direction. The magnitude of c_m determines the throughput of the compressor.

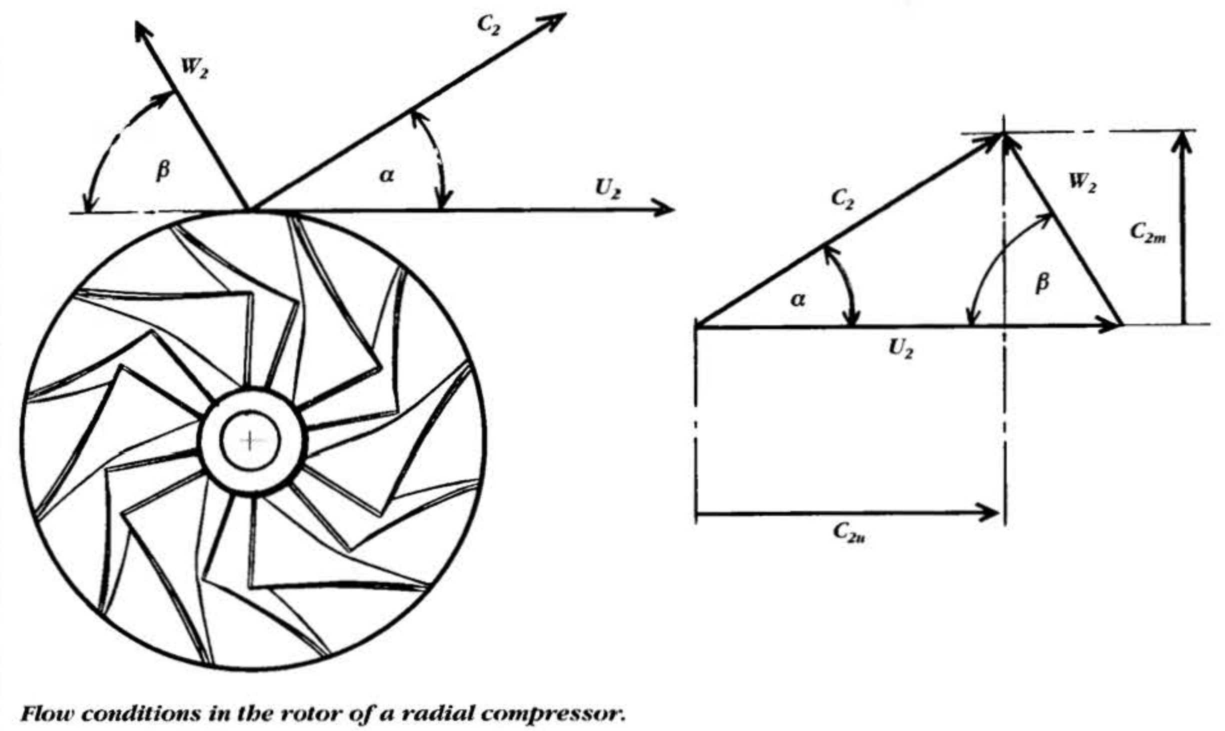
The work done is determined by the components u_2 and c_{2u}. If we assume a constant rotational speed and thus a given peripheral speed the rise in pressure varies only according to c_{2u}. The steeper the blade angle β_2, the larger this component becomes. Wheels with radially tipped blades – $\beta_2 = 90°$ – therefore provide the highest pressure. In this special case c_{2u} is always the same as u_2, which means that the work done is:

$Y_{th} = u_2^2$

For certain special applications compressor wheels with forward curved blades are used, but they are of no interest to us here. The conclusion that wheels with radially tipped blades are the best solution for model jet engines because of their high pressure is not correct. The velocity diagram shows that the absolute speed c_2, i.e. the speed at which the air leaves the wheel, is still very high.

A large proportion of the pressure gain takes place in the diffuser system of the compressor, where the residual kinetic energy in the gas is reduced. Unfortunately the compressor diffuser system inevitably involves significant losses at model scale.

In contrast, wheels with retro-curved blades convert a larger proportion of the energy within the wheel itself, i.e. the reaction level is greater than 0.5. The speed at which the gases flow into the diffuser system is slightly lower because the curvature of the blades is opposed to



Flow conditions in the rotor of a radial compressor.

the peripheral direction. In our experience the compressor is more efficient overall if the wheel is fitted with retro-curved blades.

In practice the pressure ratios which these compressors achieve is not as high as the theoretically possible levels. There are two reasons for this: when air is flowing through the compressor losses occur which reduce the work performed. In addition, the gas does not follow accurately the path dictated by the blades. The deflection in the air in the peripheral direction is lower than predicted by theoretical calculations. This effect is known as blade slip. If we wish to move away from the theoretical situation and find out exactly how much air is moved and with what level of efficiency, we have to take into account the reduced performance factor μ and the internal efficiency η.

Determining the parameters μ and η is very difficult, and they are usually found experimentally. For this reason a different method is used to calculate the basic data for a model jet engine compressor.

The calculations relating to a radial compressor are carried out using non-dimensional values. These allow us to establish all the important data relatively simply by observing easily measurable magnitudes. The parameters which define the characteristics of a compressor are its throughput and pressure gain. For compressor pressure we define a pressure value ψ as follows:

$$\psi = \frac{2 \times Y}{u_2^{\,2}};[\frac{m^2/s^2}{m^2/s^2}]$$

The peripheral component c_{2u} of the absolute speed is not included in the definition. The compressor's pressure value remains largely constant over a broad range of rotational speeds.

Provided that we know the pressure value, we can determine the work done, and from it the pressure ratio relative to the peripheral speed u_2. The peripheral speed in turn can be calculated from the rotational speed.

For ordinary day-to-day operation of a model jet engine the reverse of this procedure is also useful: instead of measuring rotational speed by some complex method, all we do is measure the pressure, which can be done using simple means.

The second non-dimensional value relates to the throughput of the radial compressor. The supply value or throughflow value defines the radial component c_m, from which we can calculate the throughput with reference to the peripheral speed u_2. For our purposes the supply value ϕ can be defined as follows:

$$\varphi = \frac{c_{2m}}{u_2};[\frac{m/s}{m/s}]$$

Definitions of the supply value vary across the specialist literature; it may be defined as the gas flow at the inlet or outlet of the wheel. In this book we relate it deliberately to the compressor wheel outlet. We should also note that the radial speed at the wheel outlet is not distributed evenly, and hence c_m should be considered as an average speed. The throughput achieved by the compressor can be found from the continuity equation as follows:

$$\dot{m} = A \times c_m \times \rho = A \times \varphi \times u_2 \times \rho$$

A is the cross-sectional area of the compressor outlet. It is calculated from the expression $d_2 \times \pi \times b_2$, where d_2 is the wheel diameter and b_2 the blade height at the outlet.

ρ is the density of the air immediately it leaves the wheel. A sample calculation for the supply value is included in the section on diffusers.

Typical calculation for a radial compressor

From all this theory it is possible to derive a few simple formulae which are genuinely helpful at the design stage of a model jet engine project. The actual work done is assumed to be equal to the gain in enthalpy. Using this information the pressure value for a particular wheel can be calculated as follows:

$$\psi = \frac{2 \times c_p \times T \times (\pi^{0.286} - 1)}{u_2^{\,2}}$$

Let us assume that a model jet engine, running at a measured rotational speed of 56,000 rpm, achieves an excess pressure in the housing of 0.24 bar. The wheel diameter is 66 mm, the air temperature 17° C and air pressure 1000 mbar.

The pressure value can now be calculated from this data is as follows:

$$\psi = \frac{2 \times 1000\,J/kg/K \times 290K \times (1.24^{0.286}) - 1}{(0.066\,m \times 3,146 \times 56000.1/min/60s/min)^2}$$

The units cancel each other out ($1J = kg.m^2/s^2$). This calculated value is typical for model jet engines with slightly retro-curved blades. Another home-built engine with a turbocharger compressor and radially tipped blades produces a pressure value of around 1.16. Large compressors in jet engines achieve better values due to the number of blades (usually higher) and the consequent improvement in the reduced performance factor. For example, the Turbomeca Marboré achieves a pressure value of 1.35 in its basic form.

If the compressor blades feature greater retro-curvature, the specific pumping performance is lower; in the case of Kurt Schreckling's FD 3 the value of ψ is around 0.86, although it varies according to wheel design and construction.

When a model jet engine is running the pressure value only varies within narrow limits. It is certainly permissible to calculate rotational speed from the measured pressure ratio, and vice versa. The pressure ratio can be calculated from the formula:

$$\pi = (\frac{\psi \times u_2^{\,2}}{2c_p \times T} + 1)^{3.5}$$

According to this formula the pressure ratio of the engine amounts to about 1.044 when running at an idle speed of 25.000 rpm (corresponding to a peripheral speed of 86 m/s).

This corresponds to a water column of 44 cm and agrees very closely with the actual values.

Working the other way round, we can determine the peripheral speed and from that the rotational speed from the pressure value and the pressure ratio.

$$u = \sqrt{\left(\frac{2 \times c_p \times T \times (\pi^{0.286} - 1)}{\psi'}\right)}$$

The engine we are using as an example produces a thrust of 30 Newtons on the test bench. The pressure above atmospheric in the engine is then 0.91 bar. Normal conditions apply, i.e. an air temperature of 15° C = 288 K and an air pressure of 1.013 hPa. The pressure ratio is therefore equal to (1.013 + 0.91)/1.013 = 1.898.

$$u = \sqrt{\left(\frac{2 \times 1000\mathrm{J/kg/{}^0K} \times 288\mathrm{K} \times (1.898^{0.286} - 1)}{0.98}\right)}$$

$$u = \sqrt{(118220\mathrm{m^2/s^2})} = 344\ \mathrm{m/s}$$

The rotational speed can be calculated from the stated peripheral speed as follows:

$$n = \frac{60\mathrm{s/min} \times u}{d_2 \times \pi} = \frac{60\mathrm{s/min} \times 344\mathrm{m/s}}{0.066\mathrm{m} \times 3.14159} = 99{,}495\mathrm{rpm}$$

Turbocharger compressors

For the modeller the compressors incorporated in turbochargers are an ideal starting point for the construction of a model jet engine. They take the form of small radial wheels which have been refined to a high level through innumerable experiments carried out by experts. The strength of these wheels is so great that we need not worry about it even at very high rotational speeds. The specifications quote failure speeds of more than 600 m/s at the periphery, which are well beyond any model application. Other components in the model jet engine, such as the shaft and the turbine wheel, have much lower rotational speed limits. Nevertheless the high speeds necessarily involve certain hazards. There is no place for carelessness when the modeller is working with such high-speed rotating parts. The wheels must not be modified in any way, and especially not weakened in the hub area. They must be securely attached. For this reason a left-hand thread fixing is essential for a right-hand rotation wheel. The compressor wheels of turbochargers are usually cast in aluminium alloy using a high-quality casting process; a technique which allows the production of extraordinarily complex curves and twists. The design of this type of wheel could never be calculated using amateur means, far less actually made. Modern turbocharger wheels achieve efficiency levels which approach to within a few percentage points those of the radial compressors in industrially produced full-size gas turbines. Overall these components offer by far the most promising start for building a really powerful model jet engine.

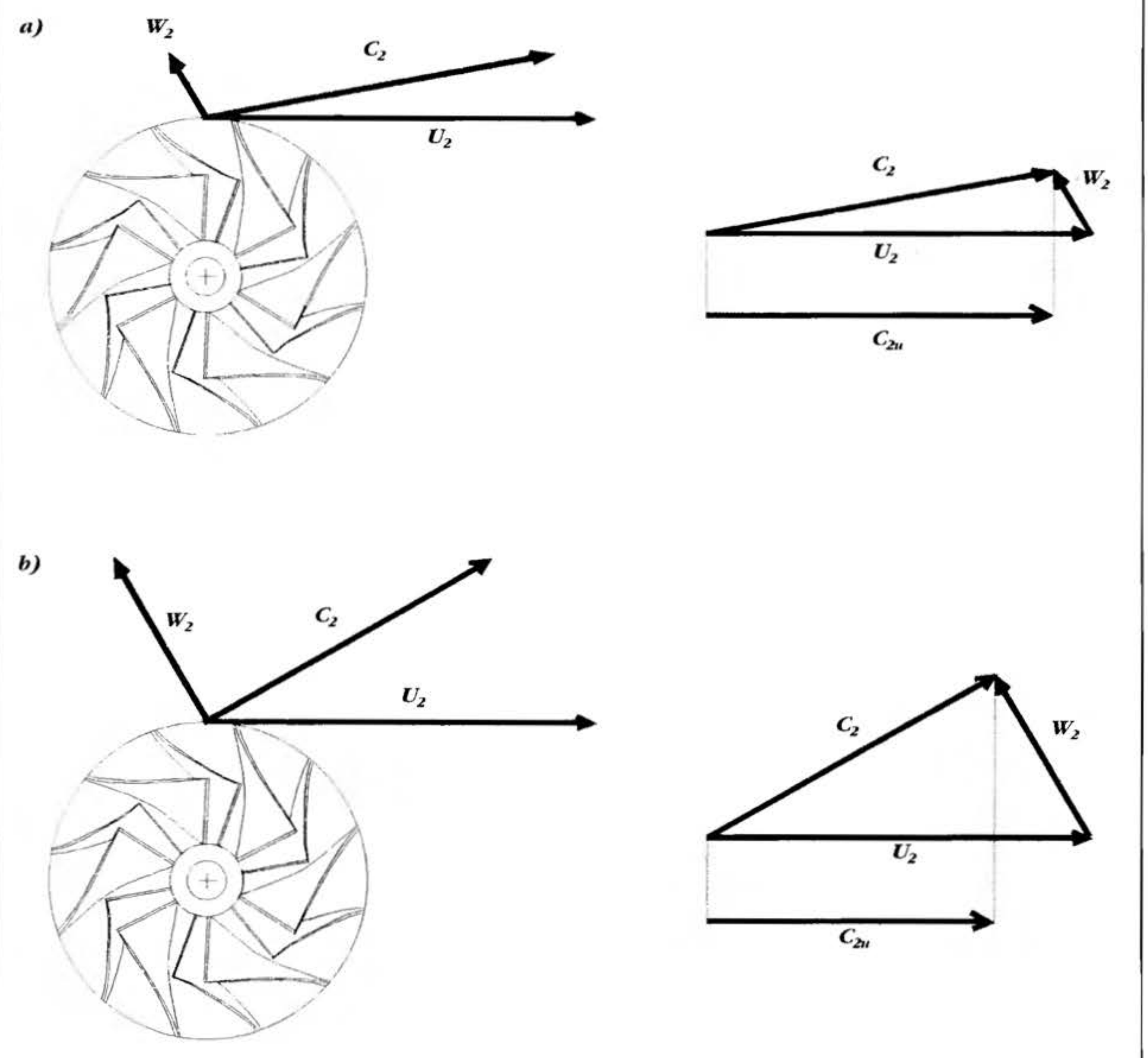
As supplied turbocharger compressors are accurately dynamically balanced and can be installed directly in the model jet engine. Bear in mind the usual rule on size: the bigger, the better. Good wheels of around 60 mm diameter achieve efficiencies between 70 and 75%, while larger versions approach 80%.

In recent decades turbocharger compressors have been the subject of considerable development. Early examples virtually without exception featured radially tipped blades, since these types are easy to manufacture and supply high pressure levels. However, they only work at reasonable efficiency in a narrowly defined range of throughputs. If the engine connected to the turbocharger requires more air, the compressor's effectiveness diminishes significantly. For a model jet engine this narrow operating range is not necessarily disastrous, since the throughput of the turbine stage is also limited to a relatively narrow range. In fact, many full-size jet engines use wheels with radially tipped blades. The proviso with this type of blade is that the throughput of the model jet engine has to be matched very accurately to the compressor, otherwise good results will never be obtained. The characteristics of the compressor wheel must be borne in mind when you are operating a model jet engine. When the throttle is opened the throughput of the turbine stage falls for a moment, with the result that the compressor simply goes on strike if you advance the throttle too quickly.

Nowadays compressor wheels with retro-curved

Turbocharger compressor from a diesel engine. Large wheels such as the one shown are often machined from solid.

Small turbocharger from a lorry diesel engine. The wheel has a diameter of 76 mm and features radially tipped blades. Wheels of this type were the starting point for several experiments. The model jet engine based on it eventually produced a thrust of 40 N at 81,000 rpm.



Behaviour of a radial compressor at a) low throughput and b) high throughput.

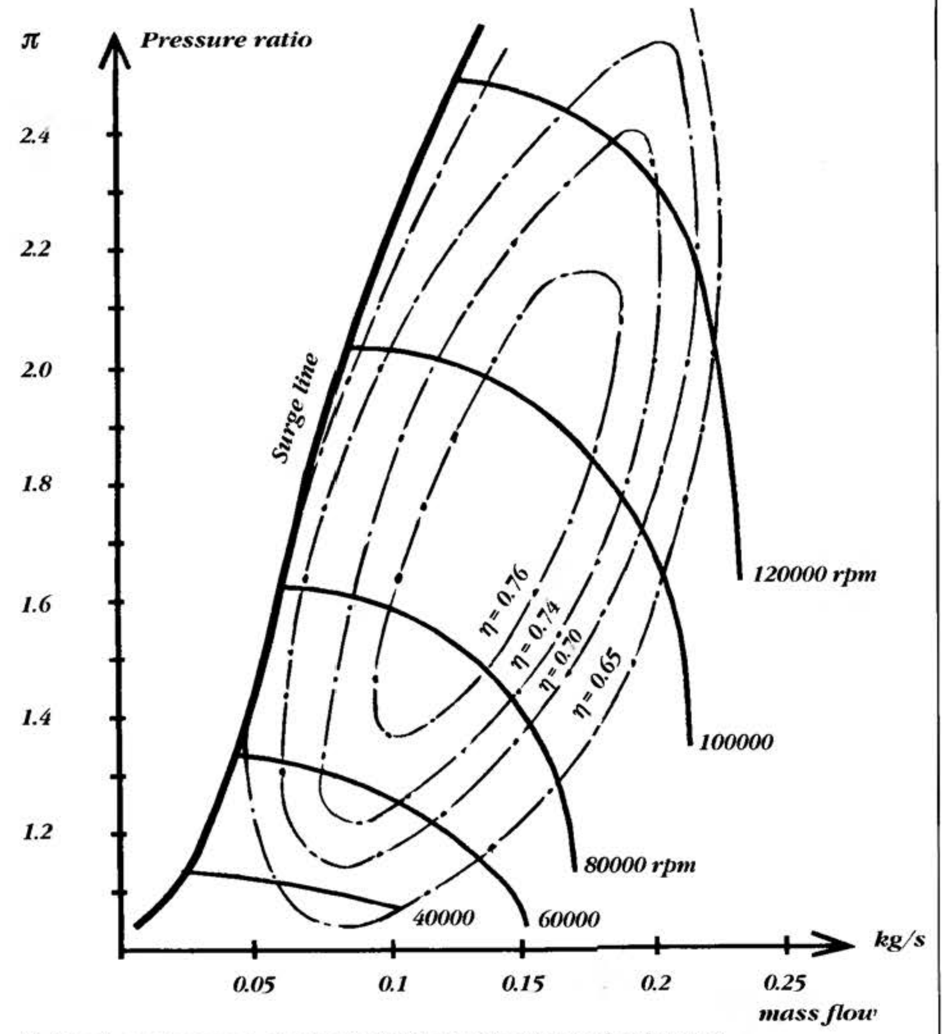
blades have superseded all others. These wheels are manufactured in large numbers and in numerous variants. Usually the blade tip angle β_2 is between 60 and 75°. This type of compressor has the advantage that the flow through the blade ducts possesses a component opposite to the peripheral direction. Thus the specific work done varies according to the rotational speed and the throughput of the wheel.

When small volumes of air are moved, the relative speed w_2 in the blade ducts is low. The component of the absolute speed c_{2u} in the peripheral direction is then almost as great as the peripheral speed u_2. In this situation the specific work done $Y_{th} = u \times c_{2u}$ is of a similar order to that of a compressor with radially tipped blades.

As throughput rises, and the gas speed in the blade ducts becomes high, the component c_{2u} becomes smaller since the air between the blades flows in a slightly backwards direction, opposite to the direction of rotation. As a result the pressure supplied by the compressor is now lower. If the turbine stage in the model jet engine is too large relative to the throughput, the compressor supplies more air at low pressure. If on the other hand the throughput of the turbine stage is too small, the pressure rises, and the volume of air moved falls. The overall result is that, within certain limits, this type of compressor adjusts itself automatically to a given turbine stage. If it is your aim to build a successful jet engine you will have much better prospects if you use a wheel with retro-curved blades. In practice this type of engine offers the extra advantage that it can be accelerated extraordinarily quickly, as the compressor works efficiently over a wide range of rotational speeds. This effect is particularly marked if the compressor blades feature significant retro-curvature, as used in Kurt Schreckling's FD 3, where the blade angle is only 45°. As a result the engine responds to the throttle almost as fast as a well adjusted piston engine.

Turbochargers of a useful size for model jet engines are used with a bladeless annular diffuser system.

As throughput varies, the flow direction in the diffuser system also changes. The effect is not dramatic with a bladeless annular diffuser provided that the angles are not too shallow. In contrast, the initial direction of flow is crucial with the bladed diffuser system used in a model jet engine. In consequence the operating range of the compressor in the model jet engine is slightly restricted compared to that of the turbocharger.



Typical compressor characteristic graph of a turbocharger compressor with retro-curved blades. Other characteristic graphs are illustrated in Gert Hack's book "Turbo cars, turbo-engines" from Motorbuchverlag, Stuttgart (German).

The compressor characteristic graph

The data for a compressor are usually presented in the form of a diagram: the characteristic graph, from which the essential data for the wheel can be read directly. A characteristic graph is a valuable but not absolutely essential tool when designing a model jet engine.

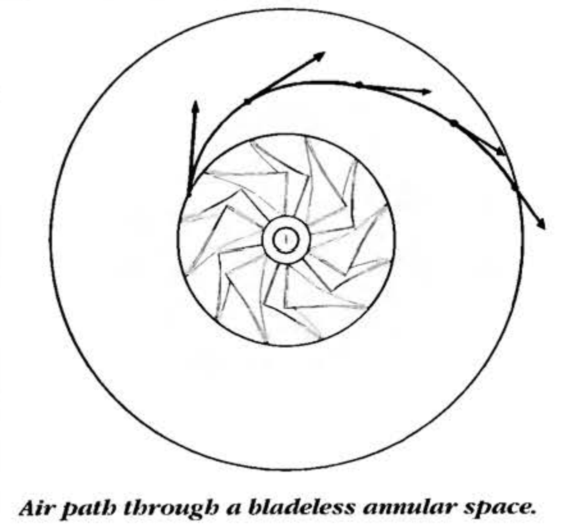
Usually the air throughput and/or the compressor flow are differentiated on the x-axis of the diagram. The pressure ratio is stated on the y-axis.

The characteristic lines in the diagram give the potential pressure and throughput for the stated constant rotational speeds. These curves always have a negative gradient, i.e. the more air the compressor supplies, the lower the pressure.

This basic fact also applies to wheels with radially tipped blades. The work done and thus the possible final pressure are exclusively dependent on peripheral speed, but in practice the reduced performance factor diminishes as throughput increases. When the pressure is great, the gas follows the path dictated by the blades less and less accurately, i.e. the actual specific work done is slightly lower.

"Island" traces on the graph indicate efficiency. Note that optimum efficiency is usually possible only within a narrow range. In designing a turbocharger the aim is to match the compressor's characteristics accurately to the piston engine to which the unit is attached, but the "best efficiency" position on the diagram is also a useful indicator for a model jet engine.

The compressor characteristic graph always applies to a particular atmospheric pressure and temperature. In different conditions – for example a high-pressure

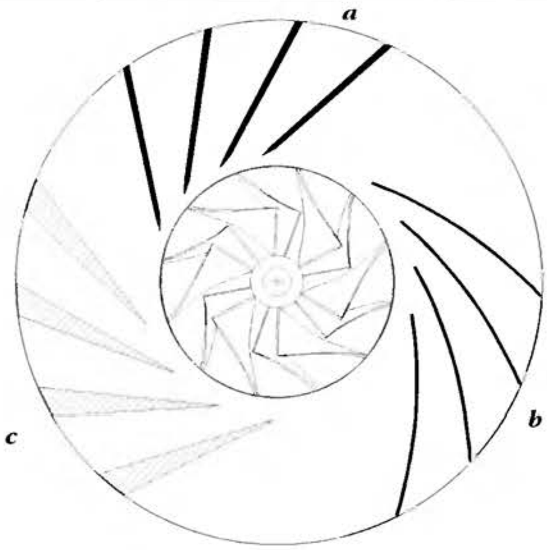


Air path through a bladeless annular space.

Turbocharger diffuser system. The height of the flow duct is reduced immediately behind the rotor wheel.

weather situation with very low temperatures – throughput and pressure rise significantly.

In the same way the characteristic diagram only applies in conjunction with a given diffuser system. If the compressor wheel is used with a different diffuser system important parameters may alter. The compressor characteristic graph of a turbocharger is not the same as the graph which would result if the same wheel were installed in a jet engine. The most significant changes would be in the optimum efficiency level and the position of what is known as the surge line.



Types of compressor diffuser system:
a) Straight diffuser blades,
b) Forward curved blades,
c) Wedge-shaped blade diffuser.

Diffuser wheels

In the compressor diffuser system the residual speed energy in the flow is converted into pressure energy. In this case the energy in the gas is proportional to the square of its speed. Therefore if we can halve the gas speed in the diffuser system we have already converted three-quarters of its energy. A particularly critical point here is the area immediately behind the rotor wheel, where flow speeds are still high. The diffuser system in this area must be matched very accurately to the rotor wheel. If a bladed diffuser system is used the diffuser blades must be designed in such a way that they start exactly in the direction of the flow. A variation in the flow angle of only a few degrees may mean that the model jet engine refuses to run. It goes without saying that obstacles to the gas, such as pipes and retaining bolts, must be kept away from this area.

The compressor diffuser, also known as the stator, can be built in any of several variants. In principle we can differentiate between bladed and non-bladed diffuser systems. In the specialist literature the latter is generally termed a bladeless annular space. This type is very easy to make and is efficient if designed carefully. The greatest advantage of the bladeless annular space is that the compressor as a whole has outstanding regulatory characteristics. Since there are no blades it is not possible for an incorrect choice of blade angle to result in flow breakaway.

The best solution for a model jet engine is a bladed diffuser system. However, the diffuser blades should not start immediately adjacent to the rotor, as at this point the flow speed is still very unevenly distributed. It is best if the flow has a chance to even itself out between the rotor wheel and the diffuser blades. If the angle of the gas flow from the rotor wheel is shallow, the diffuser blades can begin closer to the rotor wheel, as the air then follows a longer path to the diffuser blades. In the model jet engine the diffuser blades should start after a gap at 1.15–1.2 times the wheel diameter.

It clearly makes sense to place a small annular space in front of the diffuser blades. Although there are no blades at this point to force the air in a particular direction, as the diameter increases the gas flow slows down, and with this comes a rise in pressure. The cause of this is not, as you might imagine, the widening cross-section of the annular space as the diameter increases, but the effect of centrifugal force, directing the gas outward. The effect of this force is to increase the pressure of the medium as the diameter rises. However, according to Bernoulli's law the total energy in the flow is always constant. Where pressure rises, speed must fall, because no new energy is added in the diffuser system. The spiral law derived from this states that the product of the radius in the diffuser system and the speed in the peripheral direction is constant.

Spiral law, or Vortex law $r \times c_u$ = Constant

This physical fact of life plays an important role in ordinary daily life as well as in the model jet engine. The spiral law is obvious if, for example, we stir a cup of tea, where the speed is highest close to the centre. In contrast, the pressure is highest at the edge, as we can tell from the height of the fluid.

The speed is inversely proportional to the diameter of the diffuser system. This indicates the disadvantage of the bladeless annular space. If we are aiming at efficient pressure conversion we need a large diameter diffuser. Widening the flow duct does not help. Quite the opposite: this would result in flow breakdown in the diffuser, which would involve substantial losses.

The air flowing through the diffuser describes a spiral path from the end of the rotor wheel to the end of the diffuser. The angle of the gas flow at an imaginary tangent is constant at every point on the path, and follows the outflow angle of the rotor wheel. In mathematical terms the flow path describes a logarithmic spiral, whereby the outflow angle of the gas from the rotor wheel determines the length of the path. The greater this angle, the faster the gas reaches a large diameter and a high pressure. The friction losses which arise in this process are also proportional to the length of the path. If we combine a compressor wheel with a very shallow outflow angle and a bladeless diffuser, we obtain a very long flow path and correspondingly low efficiency.

For this reason modern compressors, especially in turbochargers, utilise bladeless diffuser systems whose channel becomes narrower away from the centre. This means that the cross-sectional area does not become larger, and the air is forced to a larger diameter by a short route, incurring low losses. Unfortunately this trick does not help us reduce the external dimensions of the diffuser system. Thus for a model jet engine a bladeless diffuser alone appears to be an unpromising solution. One of our primary considerations in designing a model jet engine must be the diameter of the unit. If we are to keep the frontal area of the engine as compact as possible, the diffuser apparatus must be as small as possible. The air can only be deflected towards the combustion chamber without incurring severe losses once it has given up most of its energy. Here again the spiral law plays a role: the centrifugal forces which arise in the deflection process tend to accelerate the flow on the inside of the curve, producing new losses.

If we were to use a bladeless annular space alone we would have to make the diameter of the engine at least twice the diameter of the compressor wheel if we wanted sensible efficiency levels. An extra problem is that this type of diffuser cannot eliminate the twisting motion of the gases. When the air flows towards the centre of the engine in the direction of the combustion chamber, the spiral law again dictates that the peripheral component of the flow c_u would increase as the radius falls. In consequence gas pressure would then diminish again. To counter this effect diffuser blades would certainly be needed at the periphery of the diffuser system to eliminate the residual spiral motion.

In a bladed diffuser system the situation is different. The diffuser blades form individual flow ducts, widening towards the periphery. The peripheral components of the gas and the twisting motion no longer have to be taken into account, and the only thing that interests us is the flow within the individual channels. The crucial point here is the expansion angle of the blades. Unfortunately we are restricted in our choice of angle, as there is a danger of flow breakdown. The specialist literature recommends expansion angles between 8 and 10° where the flow is slow. For our application, however, the angles can be slightly larger to take into account the extremely small dimensions of our engine. The reason for this is the influence of the boundary layer which becomes narrower as the width of the blade ducts rises. However, if we choose an expansion angle significantly above these values, the flow tends to break away from the blades, with resultant severe losses. In contrast, smaller angles produce pressure conversion at too low a rate, with the result that the gas flows through the channels for a long time at high speed, producing severe friction losses.

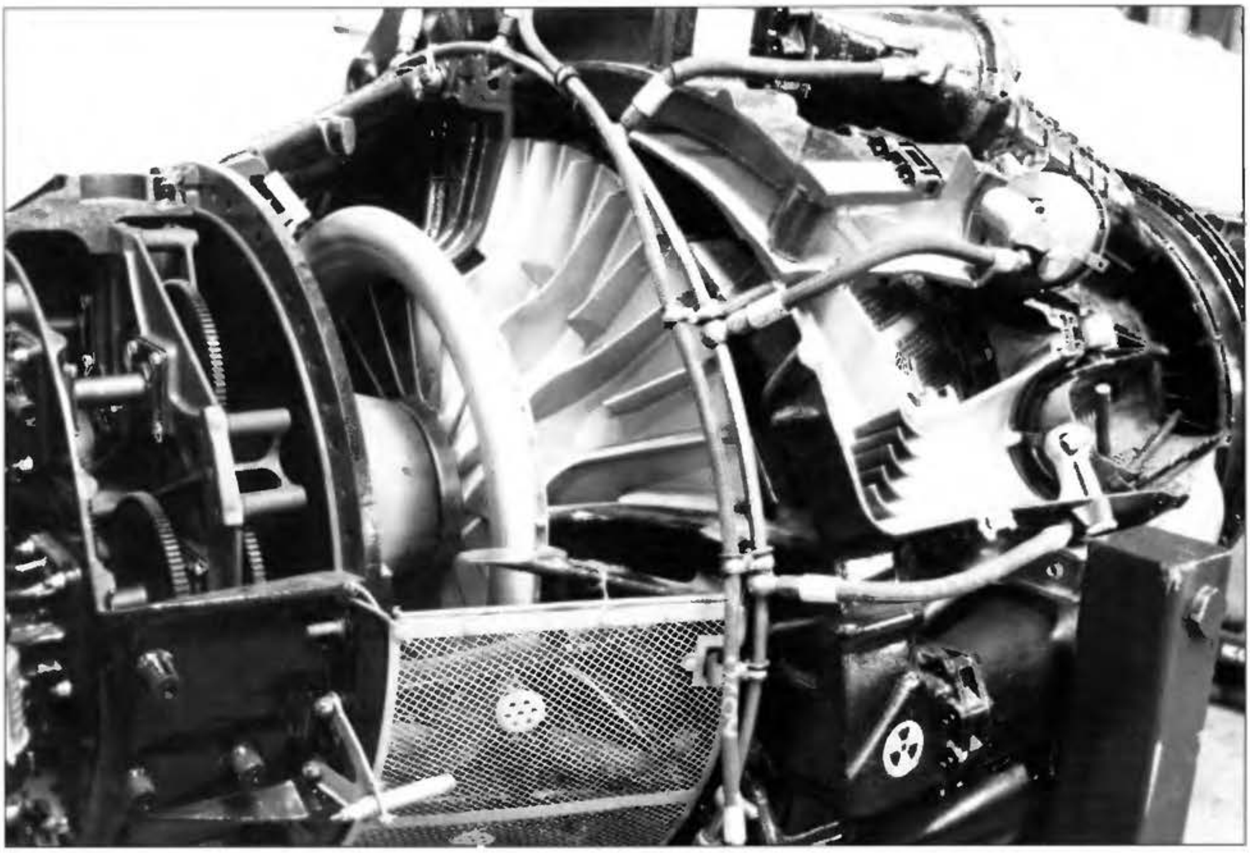
You can give your imagination free rein in the matter of the blade configuration in the diffuser. Some types of guide vane are curved in the direction of rotation of the compressor, others in the opposite direction. Another popular design is the wedge blade diffuser. The blades grow wider towards the periphery to form thick wedges, thick enough to accommodate fixing bolts. This alone is an excellent reason for the practical modeller to opt for a bladed diffuser wheel, as the bolts required to retain the compressor cover can be faired into the diffuser blades without spoiling the gas flow.

If we select blades of constant thickness then the expansion angle between two adjacent blades is calculated as follows:

ε = 360°/z
ε = Expansion angle
z = Number of blades

If we aim for an expansion angle of 15° then we have to construct a diffuser system with 24 blades. For smaller expansion angles even more blades would be required. However, more blades also mean more friction and thus greater losses.

For this reason it is better to use blades which are curved slightly forwards, forming gently widening ducts. In general terms the pressure conversion takes place much faster than in the bladeless annular space already described. If the compressor is designed carefully it is now possible to build a model jet engine of relatively small overall diameter. Nevertheless we should not be too parsimonious with the overall diameter of the diffuser system; a good starting point is a housing diameter at least 1.6 times the diameter of the compressor rotor.



The gigantic diffuser system of the Allison J33-A-35 features 14 very low-profile diffuser ducts. Note the bladeless space arranged between the rotor wheel and the diffuser blades.

The blade-free annular space was used successfully in the first home-built gas turbines. An axial diffuser system is fitted at the periphery.

Any smaller than this, and the efficiency of the system suffers directly, usually in the form of excessive exhaust gas temperature.

Example of calculating the diffuser system

We will assume that the core of the compressor is a typical turbocharger wheel with retro-curved blades. The calculation is based on geometrical data, but also takes into account our own experimental findings. In my experience these values can be carried over to other turbocharger rotors of similar design.

This means that the prospective engine builder can calculate the values for a compressor for his jet engine with reasonable accuracy even if he does not have access to the characteristic graph of the turbocharger.

The rotor wheel we will consider here is 66 mm in diameter and has 12 blades, ending at an angle of about 65°. The blade height is 5 mm at the wheel outlet. The nominal rotational speed of the compressor has been chosen to keep the stresses arising in the model jet engine within reasonable limits. In this respect the maximum rotational speed primarily depends on the turbine wheel, which is subject to severe thermal loads. If a suitable blade form is used in combination with high-alloy nickel-chromium steels peripheral rotor speeds of more than 300 m/s are acceptable, even with amateur means. If high-temperature materials are used this value can be pushed further. The nominal rotational speed is therefore assumed to be 100,000 rpm. This corresponds to a peripheral speed of: If the value for this parameter turns out to be higher or lower than assumed, efficiency should not suffer significantly. In fact the compressor gives good results even when the model jet engine is idling.

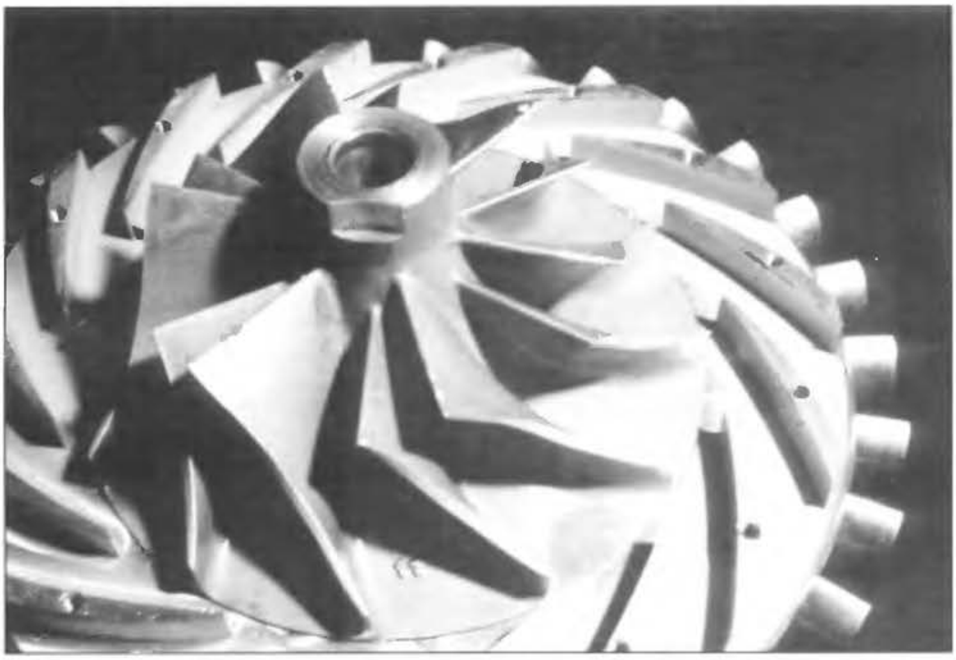
Forward-curved compressor diffuser blades in combination with turbocharger rotor wheels have produced the best results to date.

$$u = \frac{n \times d_2 \times \pi}{60} = \frac{100000 \times 1\,/\,\text{min} \times 0.066\text{m} \times 3.14}{60\text{s}\,/\,\text{min}} = 346\text{m}\,/\text{s}$$

The peripheral speeds may sound astronomically high. At its periphery the rotor is turning at a speed of almost 1,250 km/hr. However, it would still not be correct to state that the air in the compressor is flowing at supersonic speed. When the gas reaches the end of the rotor wheel it has already been compressed to half its volume, i.e. pressure and temperature are already much higher. As a result the speed of sound in the medium itself rises. Even at a peripheral speed of more than 450 m/s the sound barrier cannot be exceeded within the model jet engine.

From the compressor characteristic graph we can see that the compressor runs at maximum efficiency at the engine's nominal rotational speed if the throughput is

Here the diffuser blades are divided into a ring of radial blades and a ring of axial blades.



0.135 to 0.175 kg/s. Since the thrust of the model jet engine rises in proportion to the throughput, it makes sense for us to aim at the highest possible value here.

Against this requirement we have to set the need for the engine to possess a broad operating range and good, docile control characteristics. We therefore aim to set up the diffuser system for a throughput of 0.16 kg/s. Finally we extract the pressure ratio from the characteristic graph. At 100,000 rpm and a throughput of 0.16 kg/s this is around 1.88. Standard temperature and pressure prevail, i.e. a temperature of 15° C and atmospheric pressure of 1,013 hPa.

Now the purpose of our calculations is to obtain an overall view of the flow conditions at the wheel outlet and the diffuser inlet. Because of the high pressure ratio the effect of air compressibility must also be taken into account. We will assume half of the possible pressure rise has already taken place in the compressor wheel. Admittedly this assumption is a simplification, but my experimental findings to date show that this is reasonably accurate. We can now calculate the pressure ratio after the rotor wheel as follows:

$$\sqrt{1.88} = 1.37$$

If we assume an efficiency of 74% and an inlet temperature of 288 K (15° C) the air temperature rises by:

$$\Delta T = \frac{288K}{0.74}.(1.37^{0.286} - 1) = 37K$$

to 325 K or 52° C. At the same time gas density rises to:

$$\rho = \frac{1.37 \times 101300Pa}{325K.287J/Kg/K} = 1.488 \text{ kg/m}^3$$

With the help of the continuity equation we can calculate the radial speed c_m. The cross-sectional area A is the annular cross-section at the periphery of the rotor.

$$c_m = \frac{0 \times 16kg/s}{1.488kg/m^3 \times 3.14 \times 0.066m \times 0.005m} = 104m/s$$

As a by-product of this calculation we can find the supply value at the nominal point: $c_m/u_2 = 104/346 = 0.3$. This value is typical for turbocharger wheels, as shown by the characteristic graphs for similar rotors. If you possess a retro-curved compressor rotor but lack the characteristic graph, you can assume this value. Wheels with radially tipped blades generally produce lower supply values. In the author's experience you can assume a value in the range 0.25 to 0.27.

Once we know the peripheral speed u_2, the known radial speed cm and the blade tip angle β_2, we can calculate the overall speed vector as follows:

$$c_{2u} = u_2 - (c_{2m} / \tan(\beta_2)) = 346 - (104 / \tan(65°))$$
$$= 298m/s$$

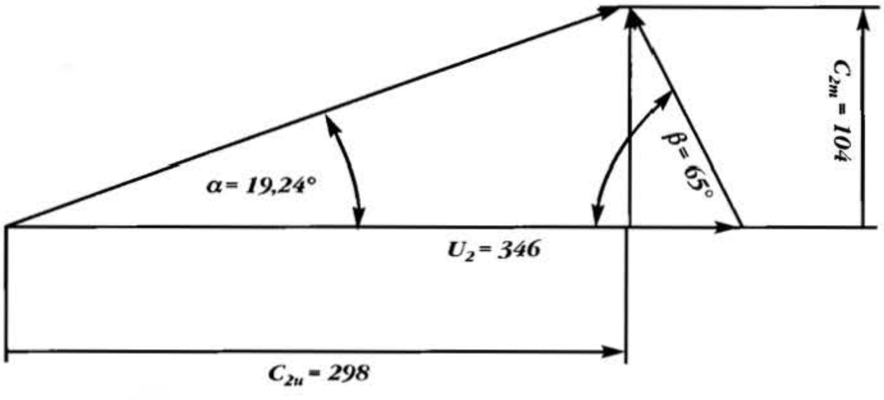
The final calculation is to define the outflow angle α, found from the equation $\tan(\alpha) = c_m/c_{2u} = 104/298 = 0.349$. Thus at the periphery of the wheel the gas leaves the rotor at an angle α of 19.24° to an imaginary tangent. This angle is a constant – even after the gas has flowed through a bladeless annular space of constant width. This indicates that the adjacent diffuser blades should be set at an angle of about 19°. Depending on the thickness of the blades up to 2° may be added to this figure to take into account the effective reduction in cross-section.

For compressor wheels with radially tipped blades calculating the guide vane angle is a simpler matter: the equation is $\tan(\beta_2) = \phi°$). For optimum efficiency the gas flow should be at a much shallower angle. The calculated value is 15°, which should again be corrected to 17° to allow for the narrowing of the blades. One of the author's model jet engines has a guide vane angle of 20° and radially tipped compressor blades, and it actually tends to surge at full throttle.

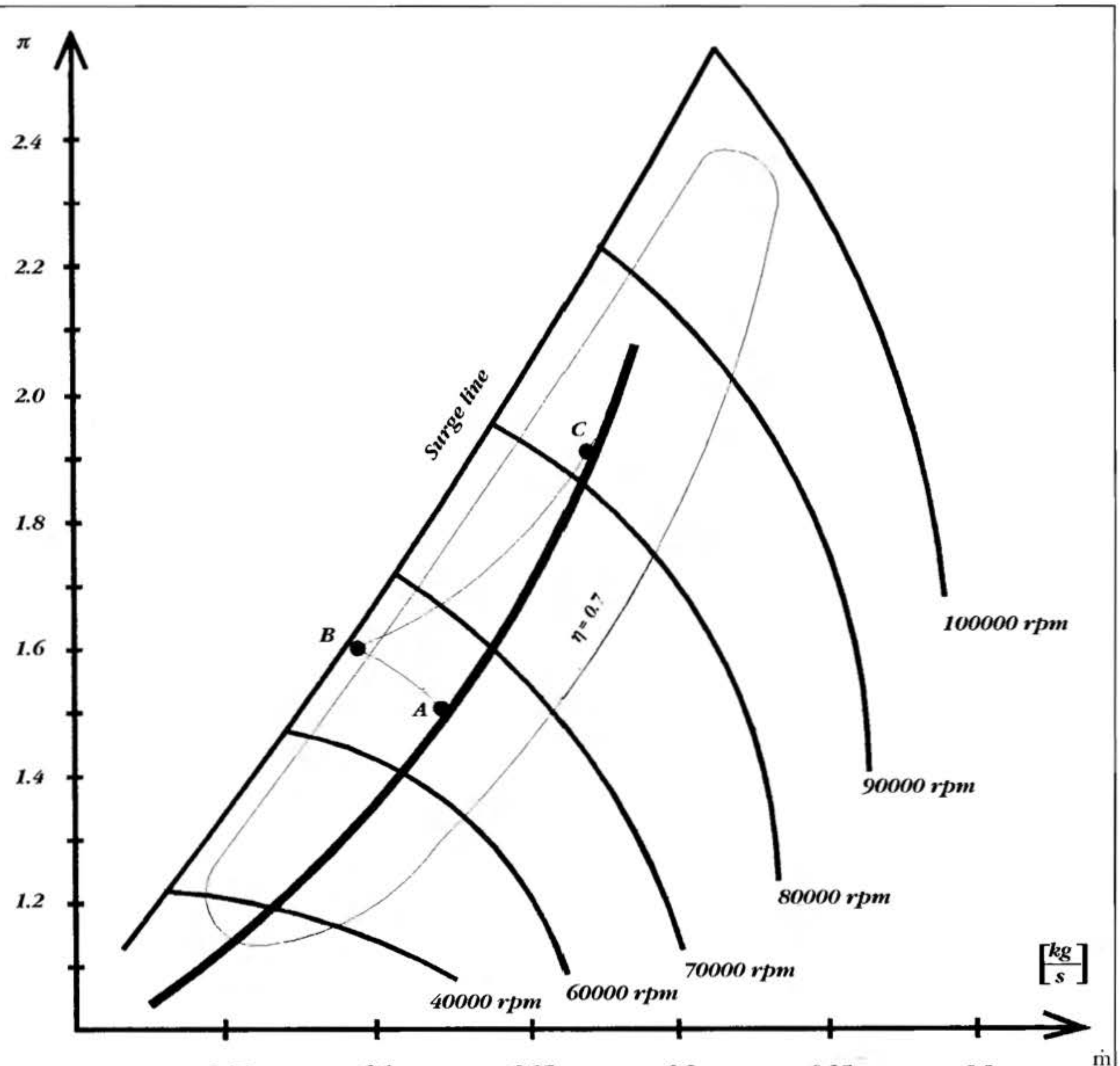
The surge limit

The "surge limit" of a compressor refers to a tendency to supply the working medium cyclically instead of constantly. This may sound innocuous, but in the world of full-size engines it is viewed with great alarm, since the usual result is more or less severe damage to the engine. In the case of model engines the results are not so dramatic, but even so the thoughtless experimenter could damage the compressor of his engine by needlessly exceeding the surge limit.

Compressor surge has a very simple cause. Consider a compressor running at constant rotational speed in a jet engine and conveying a particular quantity of air. If we restrict the throughput of the engine, perhaps by using too small a turbine wheel (due to mistakes in the calculations), then the compressor will push less air through, but at higher pressure. The compressor can therefore compensate for minor inaccuracies in design.



The vector diagram for the calculated example.



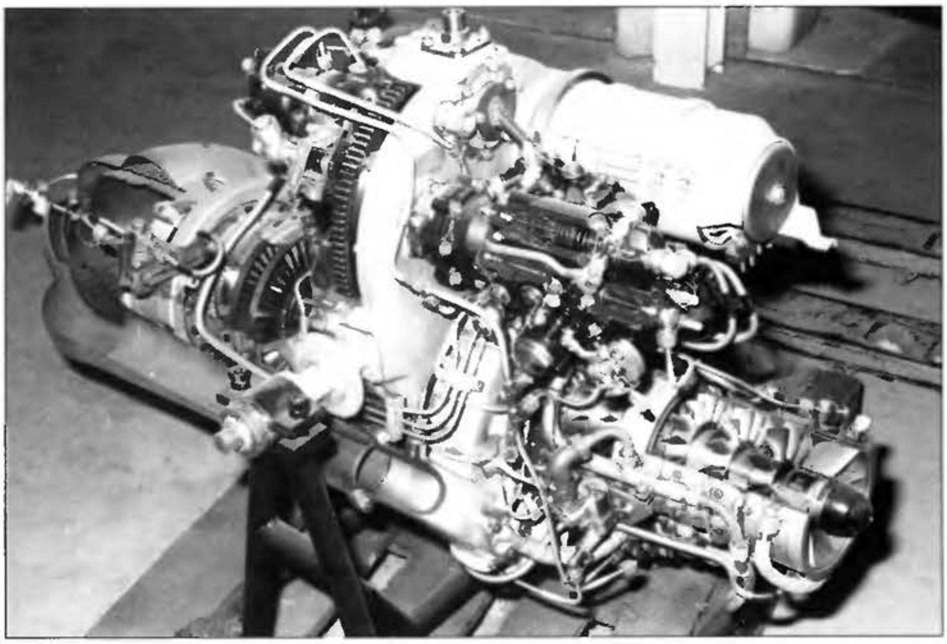
Explanation of compressor surging when the engine is accelerated. If the throttle is suddenly opened, e.g. starting from point A, throughput falls initially, and point B is reached. Only after a slight delay do rotational speed and throughput rise, and we reach the suction line C. If acceleration is even faster, point B could extend into the surge zone.

However, if the throughput is excessively restricted, the results are fatal. The outflow angle of the gas from the compressor wheel becomes too shallow. As a result the gas flows onto the blades of the diffuser system at such an angle that the airflow breaks away. If the compressor is fitted with a bladeless annular space the flow paths grow longer and the friction losses rise substantially. Overall the pressure in the compressor collapses. Suddenly the pressure supplied by the compressor is lower than the pressure of the gases which are already inside the engine, and the direction of flow reverses. This reverse flow continues until the housing pressure has been reduced, and the compressor starts to supply air again.

This process repeats itself at regular intervals, known as surge cycles. The frequency of the cycles varies according to the volume of the engine housing: the larger the engine's internal volume, the lower the frequency.

In a model jet engine the surge cycles follow on so quickly that all you hear is a loud, unmistakable growling sound. If this should happen it is essential to close the throttle immediately, since the engine will usually never clear the condition by itself. If you do not close the throttle the turbine wheel will overheat.

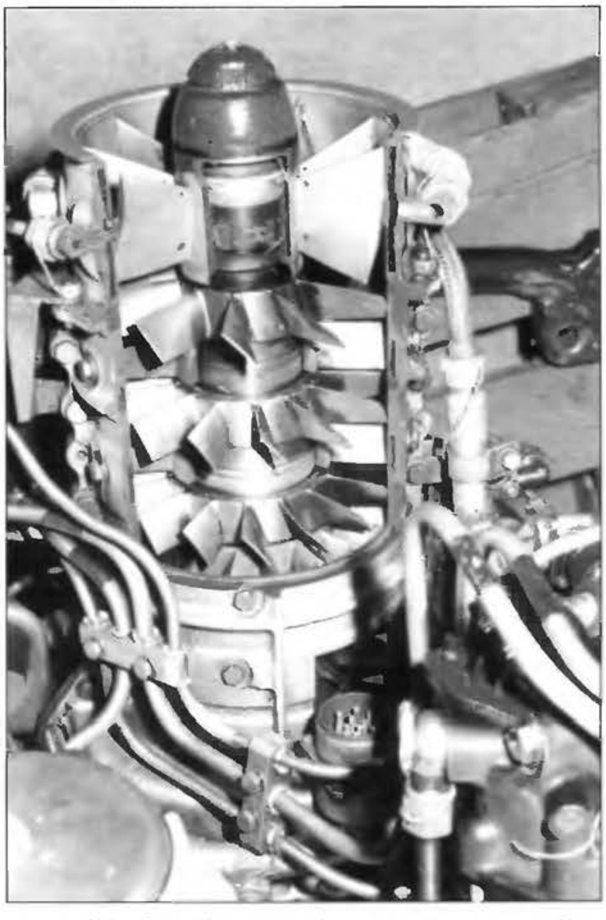
In full-size jet engines the oscillations resulting from the surge phenomenon usually cause damage to the blades, so the situation has to be avoided at all costs. Some axial compressors are fitted with variable compressor diffuser blades which adjust themselves in a fraction of a section to suit the prevailing flow angle. It is also



An example of a turbo shaft engine with a small axial compressor: Isotov GTD 350, built in 1960, USSR, air throughput: 2.19 kg/s, pressure ratio: 5.9, mass: 135 kg, speed 45,000 rpm, 295 kW shaft power.

possible to vent compressed air which causes the throughput to rise again, and keeps the engine a safe distance from the surge limit.

However, compressor surge can even occur under certain circumstances even if the turbine stage is designed to ensure that its throughput lies in the region of optimum compressor efficiency. When the throttle is opened from a particular rotational speed, the combustion gas temperature immediately rises. However, the inertia of the rotor causes the rotational speed of the engine to remain constant for a moment. The density of the gases, which are now at a higher temperature, falls, and the consequence is reduced mass throughput at the turbine stage. For a moment the turbine stage is suddenly working much closer to the compressor surge limit. Only then does the engine's rotor accelerate. Throughput rises, the combustion gas temperature falls and stabilises again close to the starting value. However, if we open the throttle too quickly, the throughput may momentarily fall to the point where the compressor starts to surge. If this should happen, it is essential to reduce the throttle setting immediately. The compressor surge limit is more critical in a model jet engine if the blade tip angle of the compressor rotor blades is large. Model jet engines with retro-curved blades are extremely resistant to surge. In contrast, types with radially tipped blades are very susceptible to surge when the throttle is opened. In this case the surge limit varies primarily according to the design of the diffuser system. If the blade angle is excessive, this type of compressor tends to surge even at full-throttle.



View of the first three axial compressor stages in the Isotov GTD 350. After the axial compressor comes one radial stage. The diameter of the wheels is only about 130 mm.

The axial compressor

To date I have not heard of any model jet engine with an axial compressor.

Nevertheless the axial compressor deserves attention, and I will deal with it briefly. I have deliberately simplified the theory, and concentrated on the most commonly used type. There is no reason why an axial compressor should not be used for a model jet engine, either alone or in combination with a radial compressor. Industrially produced small gas turbines often feature one or more axial stages in front of the radial compressor, and even at very small dimensions these compressors exhibit adequate efficiency levels. The smallest axial wheels have a diameter of around 90 mm and are fitted in front of radial compressors.

The advantage of the axial compressor is its great throughput combined with small frontal area.

The pressure rise in an axial stage is usually distributed in equal parts between the rotor blades and the diffuser blades, i.e. half of the work done is carried out in the rotor wheel itself. The so-called reaction level then can be defined as follows:

$$r = Y_{Wheel} : Y_{Stage} = 0{,}5$$

r = Reaction level of the stage
Y_{Wheel} = Work done by the rotor blades (J/kg)
Y_{Stage} = Work done by the stage overall (J/kg)

From this it follows that the rotor array and the diffuser array should utilise geometrically similar blade forms.

The air flows to the compressor rotor and strikes the rotor blades which are moving at a high peripheral speed. The blades are profiled in such a way that the flow is easily diverted in the direction of the shaft axis. The effective flow cross-section at the rotor inlet is smaller than at the rotor outlet because of the more acute angle of the flow relative to the periphery. In consequence the airflow slows down within the blades, and speed is converted into pressure in the now familiar way. This slight deflection in the direction of the periphery is responsible on its own for the pressure rise in the rotor wheel. If blades with a greater curvature were used the flow would inevitably break down, and a significant reduction in efficiency would result.

The flow deflection which constitutes the work done is the vectorial difference between the speed w_1 of the gas relative to the diffuser blades at the wheel inlet and w_2 at the wheel outlet. If we consider the absolute speeds of the gas, the difference in speed is naturally the same. In the compressor diffuser system a further, mirror-image speed change then takes place. The absolute speed at the rotor wheel outlet also represents the relative speed at the guide vane inlet. If we assume a reaction level of 0.5 the deviation in the rotor system and the guide system is of the same magnitude.

If we consider the speed vectors w_1 and w_2 it is obvious that w_2 is smaller, i.e. its vector arrow is shorter than that of w_2. The reduction in speed energy which this represents has been converted into pressure energy. The theoretical specific work done by the axial stage is:

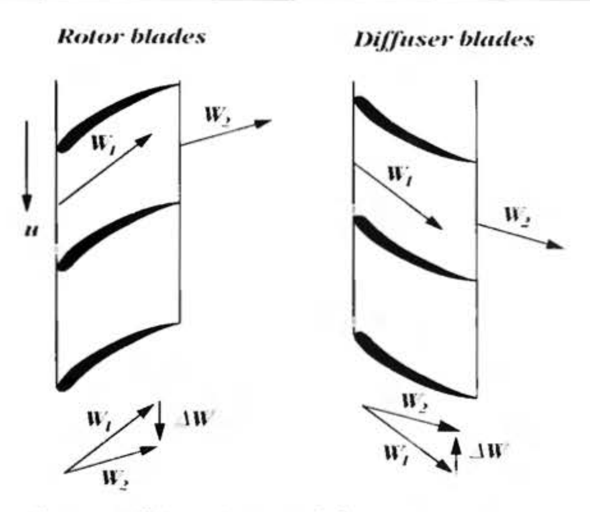
$$Y_{th} = u \times \Delta w$$

To move from theoretical calculations to the actual work done, we multiply Y_{th} by the reduced performance factor μ and the internal efficiency η. The reduced performance factor takes into account the fact that the gas does not keep exactly to the path dictated by the blades, as with the radial compressor, and that the deflection of the airflow within the blades is lower than calculated. The internal efficiency η reduces the specific work done by the magnitude of the losses which occur in the blades.

$$Y_{tat} = Y_{th} \times \mu \times \eta$$

Example calculation: axial compressor stage

Now we will calculate the essential characteristic data for an axial compressor at model scale. To simplify matters we will assume a number of typical figures relating to full-size compressors. If you like your mathematics a little more accurate, I recommend that you read the books by Dietzel and Bohl.



Flow conditions in an axial stage.

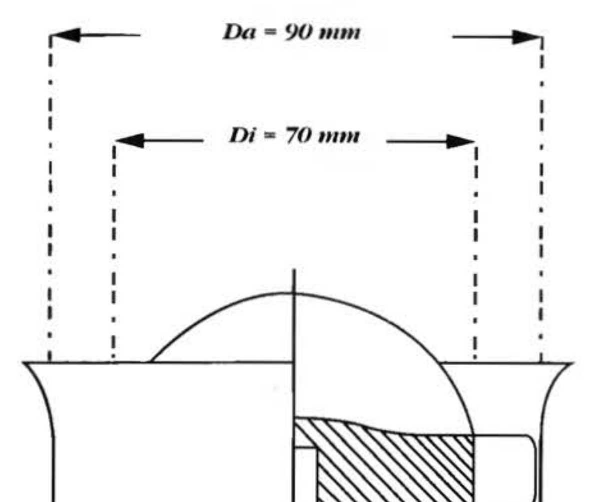


Diagram of an axial stage as calculated.

We will assume a compressor with a rotor diameter of 90 mm and a hub diameter of 70 mm. The blade profile might be such that the deviation Δw is one third of the peripheral speed. The strength of the rotor allows a maximum rotational speed of 60,000 rpm. Efficiency and reduced performance factor are both assumed to be 0.7 – on the optimistic side.

All calculations are based on the average stage diameter dm.

$$d_m = \frac{d_a + d_i}{2} = \frac{0.09m + 0.07m}{2} = 0.08m$$

The average peripheral speed is then:

$$u = \frac{n \times d_m \times \pi}{60} = \frac{60000 \times 1 / \min \times 0.08m.3,14}{60s / \min} = 250m / s$$

From these figures the deviation in the peripheral direction can be calculated to be 250/3 = 83 m/s with the blade profile we have assumed. The theoretical specific work done is thus:

$$Y_{th} = u \times \Delta w = 20750 \ m^2/s^2$$
$$= 20750 \ J/kg \ (J = kg \times m^2/s^2)$$

From the actual specific work done:

$$Y_{t_{at}} = Y_{th} \times \mu \times \eta = 10,169J / Kg$$

we can determine the pressure ratio of the stage. To this end we equate the work to the gain in enthalpy and resolve the formula according to the pressure ratio.

If the inlet temperature is 15° C (288 K) the pressure ratio works out at 1.129. The excess pressure after the compressor is therefore no better than 0.129 bar. This indicates that several compressor stages would be required in order to obtain an acceptable pressure ratio for a powerful model jet turbine. In each stage the pressure would rise by approximately 1.129 times.
The overall pressure ratio after n stages is thus:

$$\pi_{Overall} = (\pi_{Stage})^n$$

Therefore we would need

A fuel feed ring for propane gas proved adequate for initial engine experiments.

$$n = \frac{\ln 2}{\ln 1,129} = 5,7$$

or 6 stages, to obtain a pressure ratio of 2.
The notable feature here is the very high throughput of the axial compressor. Like the potential specific work done, this varies greatly according to the blade form. The steeper the blade angle, the greater the meridian component of the airflow. In this case the term means the speed component in the direction of the shaft axis. This speed component remains largely constant when air is flowing through the compressor. A typical value

Typical example of uneven combustion: some nozzle guide vanes are glowing brightly, others are almost cold.

might be $c_m = 0.6 \times u$. Based on this assumed value the compressor throughput can be estimated using the continuity equation:

$$\dot{m} = r \times c_m \times A = 1.225 kg / m^3 \times 0.6 \times 250 m/s \times 0.0025 m^2$$
$$= 0.46 kg/s$$

In spite of the blade height we have assumed of just 10 mm the throughput is clearly very substantial. The real question is whether this type of compressor could be made using amateur means. Naturally the crucial point is whether the efficiency that could be achieved is sufficient to allow the gas turbine to work. The other critical point is the matching of the compressor to the turbine. According to the specialist literature the airflow in the axial compressor breaks down immediately if the components are not accurately matched to each other.

The combustion chamber

Modellers do not generally give the combustion chamber the attention it deserves; if you believe that the main problems for a model-sized jet engine are the compressor, turbine and bearings, you are wrong. The real problem area is the combustion chamber. Optimising the performance of the combustion chamber is not simply a matter of pushing fuel consumption down as low as possible, or of preventing flames roaring out of the turbine. No, a good combustion chamber is the basic pre-condition if your jet engine is to function at all. These are the main reasons:

If combustion is uneven the inflowing air is not heated to full temperature in certain areas of the combustion chamber. The enthalpy of this portion of the air only rises slightly, and in consequence does little work when flowing through the turbine stage. To compensate for this deficit the rest of the air must become that much hotter when it flows through the turbine. This uneven temperature distribution results in uneven speed distribution in the turbine nozzle guide vanes and thus poor overall efficiency. In the worst case this simply means that the model jet engine will not run at all.

Even if combustion is consistent there can be problems. The task of the combustion chamber is to heat the pressurised air. The hot air can then perform more work when it is decompressed than was required to compress it. However, if the air is heated during the decompression process the effect is largely nullified. This means that combustion must be restricted to the confines of the combustion chamber to the greatest possible extent. If the flames are too long and extend into the turbine area the gases continue to be heated. This is not desirable, as it causes the overall exhaust gas temperature to rise to the point where the turbine overheats.

For these reasons we have to strive to keep combustion of the fuel as far as possible completely confined within the engine. It is an unfortunate fact that model jet engines trailing a long wake of fire are fit only for the showcase. Building a model jet engine combustion chamber that works really well is the work of Sisyphus (King of Corinth, condemned to roll a huge rock ceaselessly up a hill). Many parameters have an important influence on combustion, amongst them the fuel in use, the injection method and the air throughput. I have even come across a case where an engine was re-assembled after being dismantled, only to find that the flame configuration in the combustion chamber was completely different despite the fact that no deliberate changes had been made to the engine.

Unfortunately it can be very difficult to pin down the cause of problems which arise with the combustion chamber. The only solution to this dilemma is to carry out systematic experiments and test different designs. However, an extremely usable combustion chamber has now been developed after many experiments and with the help of much expert advice. The design exploits the technique of vaporisation which was developed in the early 50s by Armstrong-Siddeley and is still in widespread use today in small jet engines.

Design and function of the combustion chamber

In the combustion chamber the air supplied by the compressor is mixed with fuel and burned. Stable combustion can only be achieved if an approximately stoichiometric mixture ratio is present. This means that the fuel - air mixture must contain sufficient oxygen that complete combustion takes place. If a stoichiometric mixture is present we speak of an air surplus λ of one. As with model piston engines we have a rich mixture when λ is less than one, and a lean mixture when λ is greater than one. If the mixture is too lean there is a risk that combustion will simply cease - the flame goes out.

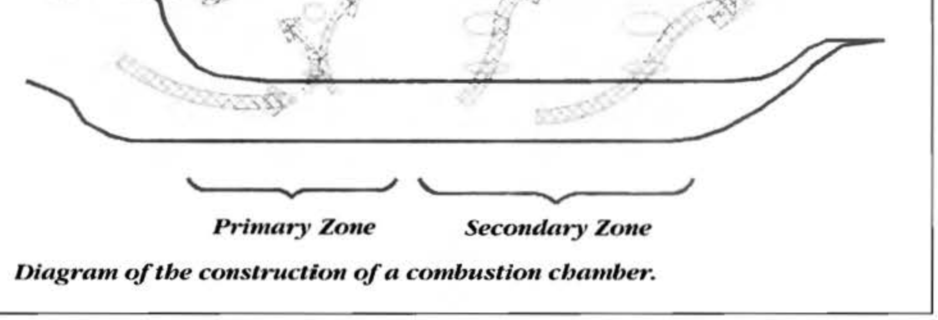


Diagram of the construction of a combustion chamber.

In the model jet engine this situation can occur if the throttle is closed suddenly. The compressor is still supplying a large quantity of air which then burns with little fuel present. The flame in the combustion chamber is then simply blown out.

The opposite problem - too rich a mixture - occurs when there is a lack of air in the combustion area. When the engine is running this fault manifests itself as a yellow flame visible through the turbine blades. The yellow flame consists of glowing carbon particles which cannot be oxidised to carbon dioxide because the necessary oxygen is absent. The usual result is a layer of soot deposited on the combustion chamber walls.

When burning kerosene or diesel stoichiometric combustion occurs with an air - fuel ratio of 14.7 to one. Stoichiometric mixtures burn at very high temperatures - even in model engines this may be up to 2,000° C, depending on the final compressor temperature. If we are to reduce this high value to the desired combustion gas temperature (around 650° C at idle and up to 850° C at full throttle) we have to introduce supplementary cool air into the hot gases after they have left the combustion zone.

To achieve this we have to divide the combustion chamber into two areas: primary and secondary. The major part of the fuel combustion process occurs in the primary zone, and the air supply has to be adjusted to ensure that an approximately stoichiometric mixture is present at that point. In the secondary zone the hot combustion gases are mixed with the supplementary air supply, and the result should be a temperature which the turbine stage can withstand. In overall terms the air surplus λ in the model jet engine lies within the range four to five.

Temperatures of up to 2,000° C can occur in the primary combustion zone of full-size jet engines, and this presents immense problems. Glowing carbon particles radiate heat, raising the temperature of the combustion chamber walls to 900° C in spite of the enveloping flow of fresh air ducted from the compressor. In this environment only extreme high-temperature resistant materials can survive. Nickel-based alloys are the usual solution, such as certain sorts of Nimonic or Inconel.

In contrast, combustion chamber cooling is not a problem in the model jet engine. The low pressure ratio means that air is only heated slightly in the compressor, so the overall temperature level is lower and the cooling effect of the air supplied by the compressor is considerable. As a result ordinary 316 sheet stainless steel is an adequate material. The combustion chamber is cooled internally by means of fine cooling air holes about 1-1.5 mm in diameter. The air which flows into the combustion chamber through these small holes only penetrates to a depth of a few millimetres, and this tends to cause the formation of a cooling film which lines the combustion chamber walls.

On the other hand it is desirable that injected air should penetrate further into the secondary zone of the combustion chamber. Within certain limits the gas mixing can be influenced by varying the hole geometry. If a given area of opening is required for the combustion chamber, that opening can be divided up into many small holes or a few large ones, and the choice has its effect on the temperature profile at the outlet of the combustion chamber. For example, if we opt for a large number of small holes, then we obtain a low temperature at the edges of the flow, and a hot central core.

The aim of every model jet engine designer - and this applies to all gas turbines too - is perfectly even temperature distribution. Lower temperatures are desirable at the base of the turbine blades, as the stresses in this area are so high. Thus a secondary aim is to restrict the heat flow to the centre of the turbine disc, in the direction of the shaft and bearings.

The question of fuel

In principle the jet engine is not confined to a particular type of fuel. The main requirement is that the maximum quantity of energy is released during combustion. In practice most jet engines are designed to run on one of the many mineral oil products which are commercially available.

Methanol is widely used for other types of model engine, but it and other forms of alcohol are of limited use as jet fuel because of their low energy density, although one of the author's engines has run successfully on methylated spirits, or ethanol. Two calorific values are quoted for fuels - an upper and a lower value. The upper value can only be exploited if the water vapour produced by combustion is condensed. In consequence only the lower calorific value of fuels is of relevance to model jet engines.

The most promising route to instant success is to use gaseous fuels such as propane or butane. No fuel pump is required as the pressurised gas flows into the model jet engine naturally. Mixing the gas with air is also relatively straightforward; usually all that is required is a few injection openings distributed around the combustion chamber. The flow of pressurised gas draws sufficient air in with it to produce a combustible mixture.

SPECIFICATION OF POSSIBLE MODEL JET ENGINE FUELS

	Diesel	**Petrol**	**JP1/Jet A**	**JP4**	**Propane**	**Methanol**
Density [kg/1]	0.85	0.76	0.804	0.76	0.5(1)	0.79
H_{0u} [MJ/kg]	42.8	42.5	43.3	>42.6	46.3	19.5
Boiling Range (°C)	190-334	80-130	160-260	60-240	-42	65
Fuel tank Capacity (ml) (5 Minutes, 30 N Thrust)(2)	880	990	920	990	1,380	2,080
Flammability/Fire Hazard	Low	High	Low	High	Very High	High
Price (E/1)	0.8	1.05	1.2	?	0.7	0.6

(1) Liquid Under Pressure

(2) Sufficient for 5 minutes of powered flight at a thrust of 30 Newtons. (Specific Consumption = 0.3 kg/N/h)

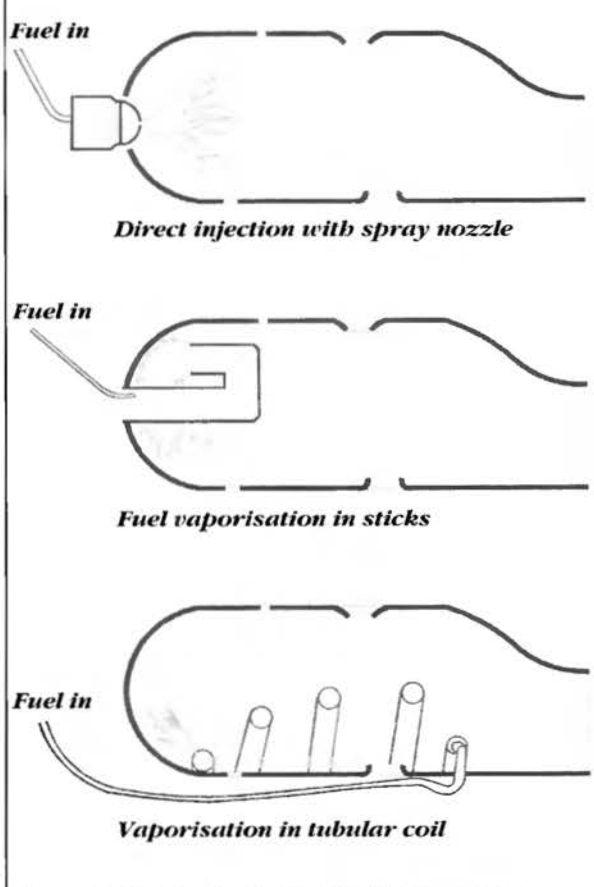
Propane gas is flammable when mixed with air in any concentration in the range 2.1 to 9.5 per cent by volume. This broad ignition range offers clear advantages in the combustion chamber, but it also presents major drawbacks in terms of handling the fuel. Propane gas is a serious fire hazard and readily mixes with air to form an explosive mixture. As a result it is essential to be very careful when working with these materials. Liquid gas is particularly dangerous to handle. You should not attempt to use liquid gas unless you possess appropriate instrumentation and hose equipment. An especially dangerous practice is to supply liquid gas to an experimental jet engine by inverting the gas bottle. If a hose becomes disconnected the result will be an uncontrollable gas escape.

The boiling point of liquid propane gas is -42° C at normal ambient pressure. Escaping liquid gas immediately cools to this temperature and in so doing draws a high level of thermal energy from its environment. If that environment is your skin you will very quickly suffer cold burns.

Liquid fuels such as petrol, diesel and kerosene are generally easier to handle. All these materials are mineral oil distillates, differing primarily in their boiling point. The density and energy content of fuels represent average values and are liable to vary from batch to batch. Special fuels for jet engines include the JP1 to JP8 varieties of kerosene (jet petrol), although in fact only JP1 or Jet A used in civilian aviation and JP4 military jet fuel are of real interest to us.

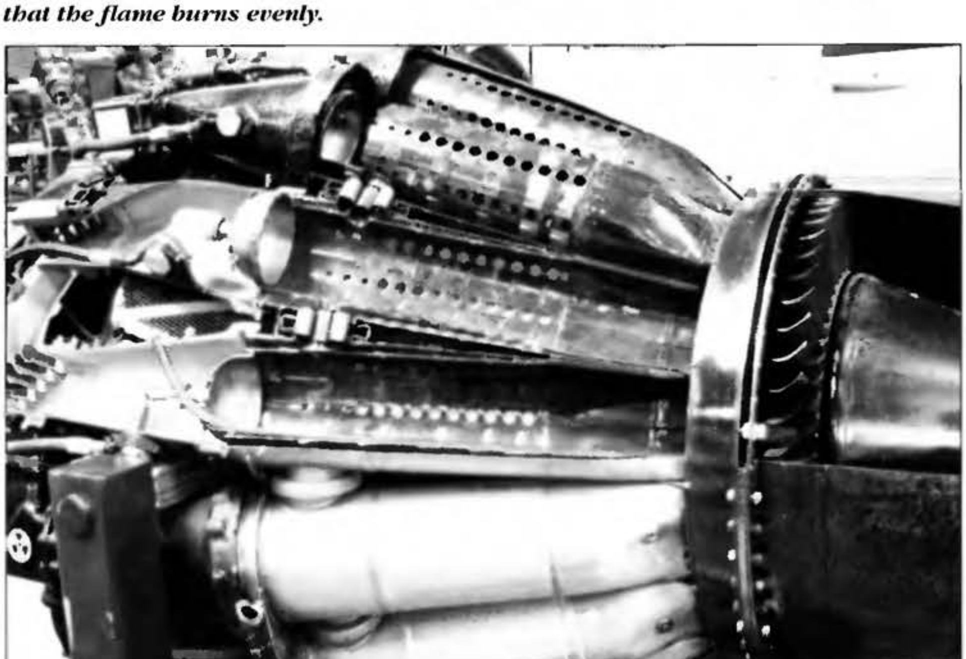
Petrol and type JP4 kerosene contain the highest concentration of volatile hydro-carbons. They have a low boiling point and therefore represent a very serious fire hazard. JP4 kerosene is primarily used in the military sphere. This material's low boiling point and low flash point (the temperature at which sufficient liquid evaporates to form a mixture which can still just be ignited by sparks) mean that they can be ignited in a combustion chamber under extreme circumstances. JP4 vaporises well, which means that it can be expected to mix well with air and produce a stable flame. Unfortunately it is difficult to procure JP4 in small quantities, which means that this fuel will probably never be widely used by modellers.

Pure petrol has similar properties to JP4 but the boiling range is more narrowly defined, which results in a less stable flame in the combustion chamber. For this reason it makes sense to use a mixture of petrol and other less volatile fuels such as JP1 or diesel. For example, the engines



Means of fuel injection in model jet engines.

The Allison J33-A-35 features a total of 14 individual combustion chambers with one atomiser jet each. The inter-connections at the primary zone area ensure that the flame burns evenly.



The combustion chamber of the Turbomeca Marbore. The fuel is injected through the tubular shaft.

made by Kurt Schreckling run on a mixture of 15% petrol and 85% diesel. The petrol should be of the unleaded type. The octane rating, which is so important for car engines, is of no interest to the model jet engine. Anti-pinking fuels such as Super or Super-Plus possess a greater proportion of highly toxic aromatics such as benzene and toluene, and they generally do not have a higher calorific value.

For model jet engines diesel, petroleum and JP1 are a very good choice, and these fuels are generally easy to obtain. Kerosene is best purchased at small airfields which are equipped to refuel helicopters. Note that airfield refuelling equipment is invariably fitted with a huge nozzle, so take a container with a large opening. All the fuels mentioned above have a relatively high flash point, which means that it is not possible to ignite spilt fuel with a match. Even so, please don't underestimate their ability to get a fire going. Balsa wood soaked in fuel burns rather well.

Overall we have found that JP1 kerosene is the best fuel for model jet engines. Its wide boiling range provides good vaporisation and a stable flame, and in these respects it is far superior to diesel and petroleum. The model jet engine presented in the following section is designed to run on petroleum and kerosene, but fuel combustion is better with JP1. One further positive point is that JP1 has a more pleasant smell than diesel oil when burned. In fact the fragrance of the exhaust gas suggests that you must be in the vicinity of an airport.

Vaporiser combustion chamber with tubular coil – Schreckling type.

Mixture formation

As with model piston engines good combustion can only be achieved if the fuel is thoroughly mixed with the combustion air. In a model jet engine this process has to be completed in a very short time to ensure that as much as possible of the fuel supplied is burned, and does not simply leave the combustion chamber unused.

With the use of liquid fuels there are two possible methods of forming the mixture: atomisation and vaporisation. Most full-size aircraft engines employ fuel atomisation, whereby complex injection pumps force the fuel into special injector jets under high pressure. The quality of combustion is very largely determined by the droplet size of the atomised kerosene: the smaller the individual droplets the faster they vaporise and burn. In practice atomisation only works effectively if the injection pressure is high, as the throughput of an atomiser jet rises with the square root of the injector pressure.

A realistic requirement for a model jet engine would be a fuel metering range of one to five and an atomiser pressure of around 2 bar, and this would call for an injector pump capable of producing at least $2 \times 5^2 = 50$ bar at full throttle. Standard swirl jets could be borrowed from a domestic oil-fired central heating system, but this calls for a high level of understanding of complex pump technology. Industrial aircraft engines usually use what are known as double jets with one opening for the idle range and additional injector cross-sectional area for full throttle.

Nevertheless, direct fuel injection appears to be feasible for small engines.

In small professionally-made gas turbines a simple but very effective solution has been adopted: fuel is injected into the combustion chamber through the hollow rotor shaft. The fuel is pumped through the compressor under low pressure, then into the engine's revolving shaft. At the appropriate point it passes in a finely atomised form into the combustion chamber through small openings, whereby the spinning shaft works as a centrifugal pump. The advantage of this technology is its simplicity. The atomiser cone is exactly circular, which promotes even temperature distribution. Even at low rotational speeds the process results in fine atomisation of the fuel.

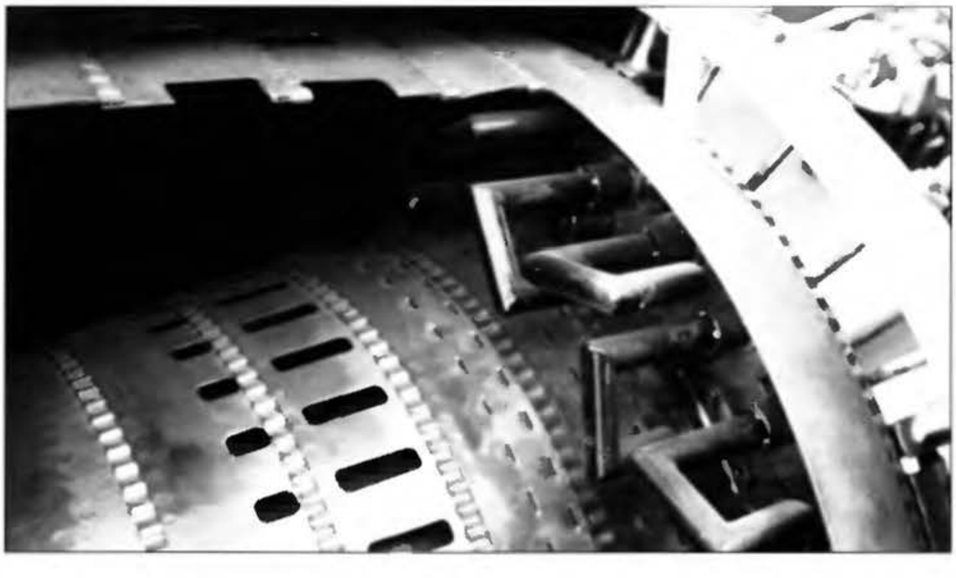
The crucial drawback of shaft injection is the complex air path through the engine. The combustion chamber must be immediately adjacent to the shaft, and this arrangement closes off the air supply to the inside of the combustion chamber. It also makes it impossible to use a shaft tunnel to strengthen the engine.

The Turbomeca Marbore exploits this injection technology, and in this case air flows into the internal space of the engine through hollow guide blades. This is an interesting solution, but rather complex for our purposes. In the model sphere fuel vaporisation systems are generally used. In principle these systems are simple heat exchangers which feed part of the heat of combustion to the fuel. However, these systems are not as efficient as the term "vaporisor" might lead us to believe. As a rule part of the fuel remains in liquid form and only turns into gas in the primary zone of the combustion chamber.

Kurt Schreckling's engines exploit this technology. The fuel enters the combustion chamber through a coil consisting of one to one and a half metres of stainless steel tubing. The hot gases of combustion wash around the coil of tubing, vaporising part of the fuel which flows into the primary zone under high pressure. In developing this technology Schreckling confronted many and various problems, but his experimental work certainly produced a workable system.

Because of the high temperatures to which the coil of tubing is subjected, it is not possible to solder injector jets to the tubing, which means that the entire injection process must take place by means of accurately cut holes alone. The length and arrangement of the vaporiser are crucial, and must be "just so". If the coil is too short, or located in the cold area, too much fuel leaves the vaporiser in liquid form, with poor combustion and a wake of fire streaming behind the engine the net

Fuel injection by means of hooked tubes.



Front part of the combustion chamber with six hooked tubes.

result. If the vaporiser is too long the temperature tends to rise uncomfortably high, with the following result: when the throttle is closed the fuel heats up to a point above its thermal stability (for JP1 and JP2 approx. 260° C). In the worst case solid carbon particles tend to form, which in the course of time block the injector openings.

A further problem is that the column of liquid in the vaporiser tube tends to oscillate, in which case the power of the engine rises and falls at intervals of a few seconds. The engine is very difficult to control if this happens, since there is sufficient fuel in the vaporiser for 2-3 seconds of running at full throttle even if the fuel pump is switched off. If the vaporiser system has a tendency to oscillate then the engine must not be considered as a power plant for a model aircraft. The cause of the oscillation is sudden vaporisation of the fuel. When this happens, only a little fuel reaches the combustion chamber since the fuel gas requires a lot of volume. Combustion only resumes properly when the coil of tubing has cooled slightly, so that liquid fuel leaves the vaporiser again. The coil of tubing then heats up again in turn, and the cycle continues.

The usual remedy for this problem is to run the engine on a fuel mixture with a higher boiling range. Kurt Schreckling's FD engines run best on diesel with an addition of 15% petrol. The petrol has a low boiling point, and this ensures that part of the fuel vaporises reliably even when vaporiser temperatures are relatively low.

The walking stick method owes its name to the shape of the vaporiser tubes, which are curved round like the handle of an umbrella or walking stick. These hooked tubes duct air and fuel directly into the primary zone of the combustion chamber. The fuel is actually injected through thin tubes each of which opens into one hooked tube. The advantage of this technique is that the fuel mixes with the air to some extent even before it reaches the combustion zone. The remainder of the liquid fuel is squirted onto the front face of the combustion chamber.

The great advantage of this technique is that vaporisation takes place under combustion chamber pressure. In the case of the model jet engine presented in this book the actual injector pressure is only about 0.5 bar higher than the combustion chamber pressure. In consequence the fuel supply system is correspondingly straightforward. To avoid supplying too much kerosene a throttle has to be built in, which itself raises the injector pressure to about 2 bar. The vaporisation itself has no effect on the injection process, so oscillations in the column of liquid fuel in the system do not occur. The technique of pre-vaporisation is primarily utilised in small gas turbines and jet engines. It was developed in England by Armstrong-Siddeley and used successfully in the Viper series of engines. This type of engine used two sets of twelve vaporiser tubes, but we can manage with far fewer for a model engine. Only six tubes are required to obtain satisfactory temperature distribution.

The fuel injector tubes must be constructed with particular care, as their quality is crucial to the temperature distribution within the engine. As with atomiser jets, the quantity of injected fuel is proportional to the square root of the injector pressure.

As a result the fuel pump must provide a very wide range of pressures if the engine is to be fully controllable. At idle the injector pressure is so low that even the hydrostatic pressure difference in the ring of distributors in the combustion chamber manifests itself, as slightly more fuel flows through the bottom vaporiser tubes than through the upper ones.

This results in slightly stronger combustion in the lower part of the combustion chamber when the model jet engine is idling. At full throttle the hydrostatic pressure difference is no more than 6 cm of fuel column. This is negligible, and combustion is very even.

The significance of re-circulation zones

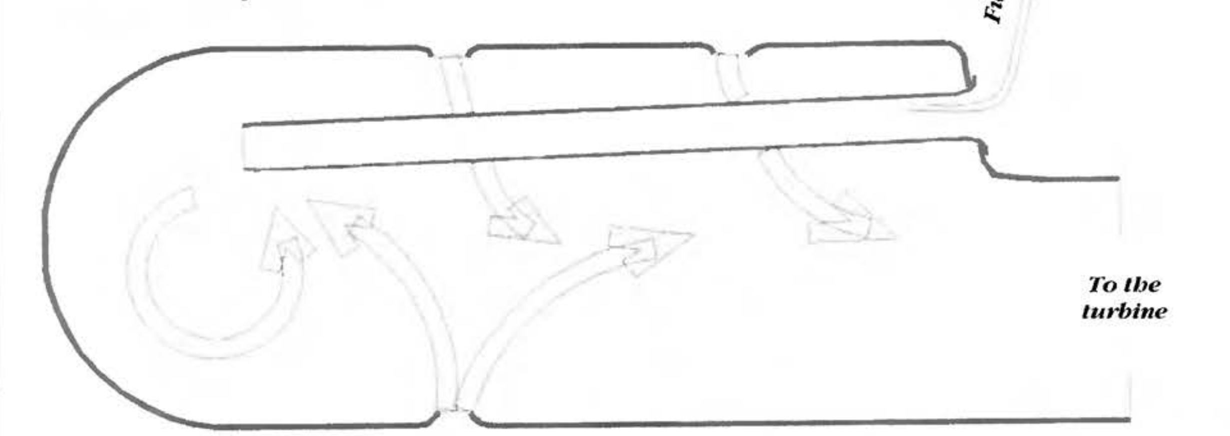
An important factor in the development of an efficient combustion chamber is the design of the primary zone. Even if the fuel and air are thoroughly mixed the flow speed in the combustion zone must be kept very low. If the flow speed is higher than the expansion speed of the flame front, the combustion simply goes out, but even if the gas speed is sufficiently low the results with a small combustion chamber are inevitably unsatisfactory. The fuel burns so slowly that the combustion chamber needs to be very long.

For this reason it is important to design the combustion chamber in such a way that hot gas - if possible still burning - passes through the primary zone again. Unless this reverse flow (re-circulation) takes place, it is impossible to vaporise and ignite that part of the fuel which is still liquid. If re-circulation can be achieved a stable core of hot gas forms in the primary zone. If a back flow area is present, the flame in the primary zone is virtually anchored in that position. This appears to be the only way of constructing a small combustion chamber which works efficiently.

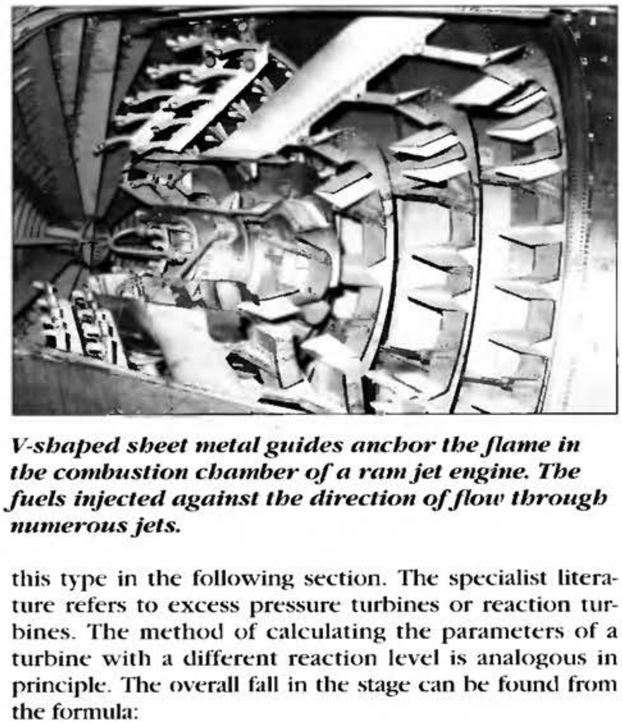
Re-circulation of the hot combustion gases is an essential feature of the model jet engine described in the next section. The vaporiser is not capable of vaporising all the fuel in the hooked tubes, and the liquid residue is flushed onto the front face of the combustion chamber. This fuel would not vaporise and burn without the heat of the re-circulating combustion gases. In fact the fuel undergoes a cracking process at the front cover of the combustion chamber. In the course of time this results in the formation of a layer of coke-like material which peels off periodically. The model engine then spits out glowing particles of soot like an old-fashioned open fire.

There are many possible methods of achieving re-circulation. The usual course is to select a hole geometry which promotes gas flow towards the front face of the

Diagram of the reverse flow in the primary zone of a combustion chamber with sticks from rear.



combustion chamber. It is also possible to inject the fuel in the opposite direction to the main flow. This tends to suck hot gas out of the rear part of the combustion chamber and feed it back to the combustion area. Baffles are also widely used, especially in the afterburners of aircraft engines, together with rings of V-shaped cross-section which produce a re-circulation area. However, where these methods are used in model jet engines the result can be harmful cracking of the combustion chamber. I have to admit that practical experimentation is the model builder's most useful aid when it comes to designing a combustion chamber. Since the turbine nozzle guide vane system allows us to observe the flame in the combustion chamber when the engine is running, it is at least possible to draw useful inferences regarding possible deficiencies simply by watching the engine.



V-shaped sheet metal guides anchor the flame in the combustion chamber of a ram jet engine. The fuels injected against the direction of flow through numerous jets.

Turbine stage and exhaust cone

How the turbine stage works

The turbine stage, also known simply as the turbine, extracts from the hot combustion gas the work required to drive the compressor. Its method of working is therefore the exact opposite of the compressor. The turbine reduces pressure and converts it into kinetic energy. The gases are deflected in the turbine blades and thereby subject the blades to a peripheral force which manifests itself as torque.

The turbine stage itself consists of a nozzle guide vane system and a rotor. The overall effect of the stage is to process the heat fall. The proportion of the work carried out by the rotor blades in the stage as a whole is expressed, as is the case with the compressor, by the reaction level r.

$$r = \frac{\Delta h_{Blades}}{\Delta h_{Stage}}$$

Δh_{Blades}, Δh_{Stage} are the fall in enthalpy in the rotor and in the overall stage respectively, in J/kg.

In practice gas turbine stages are almost always designed with a reaction level of r = 0.5. This means that the heat fall Δh_{Stage} is divided equally between the nozzle and the rotor. For this reason we will only discuss this type in the following section. The specialist literature refers to excess pressure turbines or reaction turbines. The method of calculating the parameters of a turbine with a different reaction level is analogous in principle. The overall fall in the stage can be found from the formula:

$$\Delta h_{Stage} = c_p \times T \times (1 - \pi^{-0.286})$$

when the hot gas is expanded with a friction-free flow, a speed of

$$c = \sqrt{(2 \times \Delta h)}$$

is achieved. However, in practice losses occur which reduce the maximum possible speed by about 5%. This means an actual energy loss of about 10%, since kinetic energy rises in proportion to the square of the speed. In general terms these values are much better than the efficiency of the compressor stage. It is also true that the gas flow in the turbine's acceleration ducts is more stable, which means that much greater gas deflections can be achieved overall, giving substantial levels of energy conversion. That is why a single turbine stage is ample for a model jet engine. A two-stage turbine would provide no improvement in the engine's running characteristics.

The combustion gas flows first into the turbine's nozzle guide vane system, where the blade ducts work like small jets, accelerating the gases in the direction of rotation of the rotor. At the same time the gas expands. As pressure and temperature fall, speed rises rapidly, reaching values of around 450 m/s (1,620 km/hr) even in model engines.

At this point the gases strike the turbine blades. Since the turbine wheel is already spinning at very high speed, we must differentiate very clearly between absolute and relative speeds. If we could travel on the revolving rotor we would be subjected to a gas flow not from the direction of the nozzle guide vanes, but to a greater or lesser extent from the front. It is therefore a mistake to imagine that the turbine blades should be set at right-angles to the diffuser blades. The idea that the gas would strike the broad side of the blades at right-angles is correct - but only when the turbine is at rest. Once it is in motion the situation is different.

The torque produced by the turbine is the result of a peripheral force which acts upon the turbine blades.
This force can be explained as follows: the gases are accelerated again in the rotor blades, and are forced out at high speed in the direction opposite to rotation. Thereby each flow duct virtually forms a small jet producing a thrust which acts upon the turbine blades. The total peripheral force is the sum of the thrust forces working in the direction of rotation.

In the final analysis of turbine power we are only interested in those speed components which are in the peripheral direction, since work can only be performed in the direction of rotation. The peripheral force is calculated using the same rules which apply to the engine's thrust:

$$F_u = \dot{m}.\Delta w_u; \Delta w_u = w_2 - w_1$$

F_u = Peripheral force (N)
ΔW_u= Speed difference in the peripheral direction between the inflowing and outflowing gas (m/s)
w_1, w_2 = relative speed at the rotor inlet (1) and the rotor outlet (2) (m/s)

Finally the power of the turbine is calculated as follows:

$$P = F_u \times u = \dot{m} \times \Delta w_u \times u$$

P = Theoretical turbine power (Watts)
u = Average peripheral speed (m/s)

The gas which leaves the turbine has virtually no residual swirl. When the gas flows through the stage it

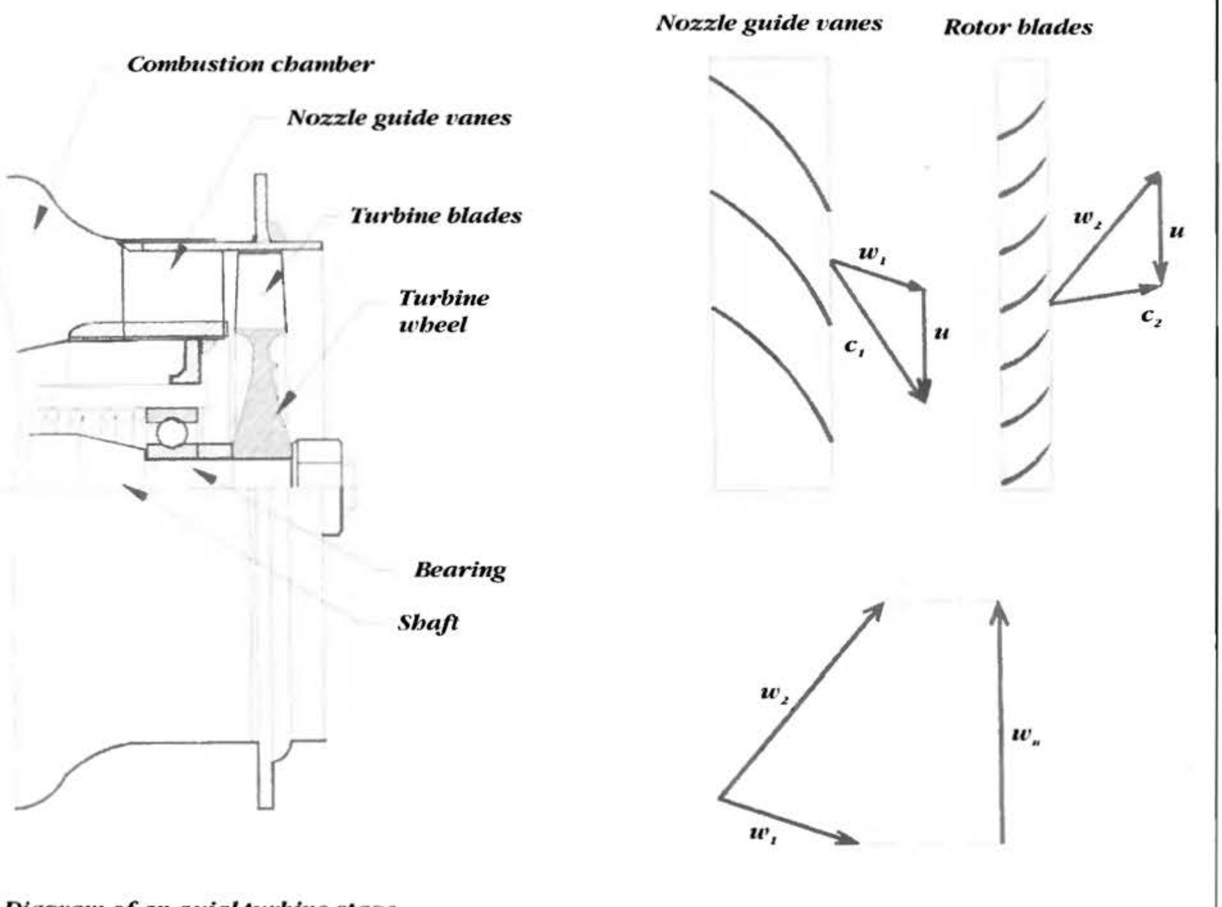


Diagram of an axial turbine stage.

Not much effort is required to produce a small turbine wheel with a good level efficiency.

expands, and the total surplus pressure built up by the compressor is reduced. In consequence the volume of the gas rises, and this effect must be taken into account when the turbine stage is designed. The same reduction in enthalpy has to take place in the nozzle guide vane and the rotor blades. This means that the speed of the gas is the same in both areas. The continuity equation now tells us that the free cross-sectional area for gas flow in the nozzle guide vanes must be smaller than in the rotor, where the gas has already been expanded fully, and therefore takes up much more space.

In multi-stage gas turbines this effect is taken into account by increasing the rotor diameter from stage to stage. However, even with a single-stage turbine this must be allowed for if it exceeds a certain pressure ratio. The essential enlargement in cross-section varies according to the engine's pressure ratio. At low pressures, as for example in Kurt Schreckling's FD series, it is feasible to ignore compressibility altogether.

At higher pressure ratios a constant cross-section turbine would result in a rise in the reaction level and a slight fall in efficiency. For this reason it is best to make the free cross-sectional area of the turbine in a model jet engine about 15 to 25% larger than the nozzle guide vane cross-section, the actual figure depending on the pressure ratio achieved. In practice this means increasing the height of the blade or increasing the blade angle.

Axial turbine or radial turbine?

In theory both types of turbine are possible contenders. In full-size aircraft engines the axial turbine has become the standard choice almost without exception, since it achieves significantly better efficiency levels at that scale. At model scale the situation is very different, and radial turbines are certainly a sensible proposition. Radial turbines of a size suitable for model engines are used in turbochargers, and they have been developed over many years to the stage where they represent sophisticated high-tech products. They are manufactured in special heat-resistant alloy (such as Inconel 713C) using a precision casting process, and are capable of withstanding extremely severe stresses. As already mentioned, one advantage of using such a turbine is that the unit is exactly matched to the corresponding compressor wheel in terms of throughput. To use the turbine in a model jet engine all we lack is a nozzle guide vane system.

However, for quite different reasons the use of a radial turbine appears to be a poor choice for the amateur. One reason is the mass of the rotor. Even at model sizes

Radial turbine of a turbocharger (Garrett). The diameter of the wheel is only 52 mm.

A snail housing is used as the turbine entry system of a radial turbine. No nozzle guide vanes are required with this type of entry system.

the rotor might weigh anything up to 0.4 kg. That means a high moment of inertia and a correspondingly poor ability to accelerate.

The turbine wheel is attached to the shaft using a special welding process: friction welding. This technology keeps to a low level the heat transfer from the hot wheel to the shaft and the bearings. Attempting to attach the wheel to a different shaft does not seem sensible, and is unlikely to succeed in technical terms. On no account is it permissible to drill through the wheel. The severe tangential stresses which would act upon the bored area would result in the wheel failing catastrophically at quite a moderate rotational speed.

So there lies the rub: the main problem besetting the use of a radial turbine in a model jet engine is of a mechanical natSoure, and not thermo-dynamic at all. The design of the rotor shaft means that the combustion chamber must be very small or external, as demonstrated by the PAL system. Moreover the thick shaft necessitates the use of large bearings which are generally less able to withstand high rotational speeds.

Design and vector diagrams of an axial turbine

In principle the starting point for calculating the turbine is the compressor, as this dictates the engine's throughput and rotational speed. The turbine should be designed to harmonise well with the existing compressor. Of course, there is no reason why we should not start with a given turbine and build a suitable compressor. However, since we wish to make use of a ready-made compressor wheel from a turbocharger, everything in terms of pressure, rotational speed and throughput is already determined, so the method described here appears to be the most sensible.

Although much of the data is already fixed there is still some scope for variation in the design of the turbine. For example, within certain limits it is possible to vary the diameter of the turbine wheel and the blade tip angle, although there are certain points which have to be borne in mind. The gas which leaves the turbine should flow out of the engine as straight as possible (minimum swirl motion). We also have to take into account the wheel's strength and efficiency when considering its design. To achieve low gap losses it is desirable to keep the turbine blades long, as this achieves a favourable relationship between gap length and blade length. On the other hand the strength of the turbine wheel increases if the blades are shorter and lighter. The little matter of the designer's experience also plays a not inconsiderable role in the final design. A turbine with the same diameter as the compressor has proved to be a good solution, with a blade tip angle α in the range 30 to 35°. At the low end of the range the gas deflection in the peripheral direction is more pronounced. The net result is that a larger proportion of the overall fall in enthalpy is converted into shaft work to drive the compressor. This in turn means that less remains for thrust production. With such a configuration the exhaust gas temperature will be low, and the model jet engine will run very reliably but give less thrust. If the blade tip angle is steeper the situation is different: the gas deflection in the peripheral direction is reduced, and in order to drive the compressor wheel and keep the engine running, a higher level of enthalpy must be present overall. This means that the exhaust gas temperature will inevitably be higher. If our aim is to produce a model jet engine which runs reliably, it is clearly better to select a turbine wheel blade tip angle at the lower end of the range, at least initially. Later on you can always adjust the angle of the blades or fit a new wheel to discover if the modification is worthwhile.

Typical calculation: turbine design for a model jet engine

The following example presents the steps in calculating the design of a turbine stage based on the engine described in these building instructions. In the case of the Micro-Turbine we aim for a combustion chamber discharge gas temperature of 923 K (650° C). This value must not be confused with the exhaust gas temperature. As the hot gases expand, the temperature in the turbine falls by a good 100 K. These temperatures are well within the range of standard nickel-chromium steels, and a satisfactory useful life can be expected. We assume a nominal rotational speed of 100,000 rpm and a corresponding pressure ratio of 1.9. Measurements and calculations concerning the compressor show that an air mass of 0.18 kg/s flows through the engine in this state.

A further factor to be considered is the loss of gas pressure in the combustion chamber. A realistic value for pressure loss in a model turbine is around 4% at full throttle. The pressure ratio before the turbine stage is therefore around 1.9 x 0.96 = 1.824. Remember also that the specific heat of the air rises at high temperature. With the gas temperature T3 one can assume a Cp of 1,100 J/kg/K. The heat fall can then be calculated from the following formula:

$$\Delta h = c_p \times T_3 \times (1 - \pi^{-0.286})$$

In our example the heat fall amounts to 160,350 J/kg, which is significantly greater than the heat fall required to drive the compressor. The hot gas still contains a very large amount of energy which is exploited to produce a high efflux velocity and thus plenty of thrust. In the model jet engine it is practicable to allow all the enthalpy to expand in the turbine stage. This means that the turbine wheel processes a higher fall than would be required to drive the compressor alone. With this consideration in mind, we can arrange the geometry of the turbine wheel to exploit this advantage. The rotor blades are arranged at such an angle that the exhaust gas has a large component in the direction of the thrust axis. This allows us to use short blades, which are advantageous in terms of mechanical strength. In this way a large proportion of the thrust is already present in the turbine. This means that a proportion of the heat fall which can be exploited for thrust production is already present as efflux velocity at the turbine wheel. Finally only a relatively small residual fall takes place in the actual thrust nozzle.

We start from the heat fall and gas temperatures already found. If we aim at a reaction level of 0.5, half the fall, i.e. =0.5x160,350= 80,175 J/kg, is processed in the diffuser wheel, and half in the rotor wheel. When the gases are accelerated in the blades a speed c is reached in each wheel. Only 95% of the velocity can be converted due to wall friction and flow losses.

$$c = 0.95 \times \sqrt{2 \times 80.175\,\mathrm{J} / \mathrm{kg}} = 380\mathrm{m} / \mathrm{s}$$

Now comes the calculation of the free cross-sectional area of the turbine stage, which is defined by the continuity equation. However, before we do this we have to calculate the density of the gas at the outlet of the nozzle guide vane system and at the end of the turbine wheel. At the end of the turbine nozzle guide vanes the enthalpy fall has been reduced by half. The pressure ratio is then approximately:

$$\sqrt{1.824} = 1.35$$

As the gases expand the temperature also falls slightly. Here again the turbine works like a compressor in reverse. The fall in temperature can be calculated as follows:

$$\Delta T = \eta_{\mathrm{Turbine}} \times \frac{\Delta h}{c_p}$$

If we assume turbine efficiency to be 75% the temperature difference is:

$$\Delta T = 0.75 \times 80.175 / 1{,}100 = 55^0\mathrm{K}$$

As a result the temperature between the diffuser blades

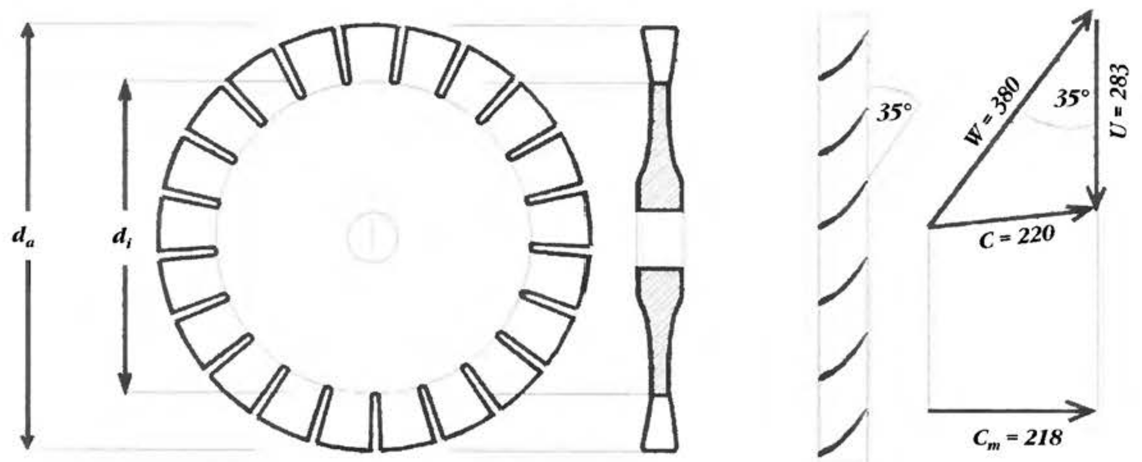


Diagram of the turbine wheel as used in the calculations.

and the rotor blades is 923 - 55 = 868 K (595° C). The gas density at this point is as follows:

$$\rho = \frac{1.35 \times 101.325\text{Pa}}{868\text{K} \times 287\text{J / kg / K}} = 0.55\text{kg / m}^3$$

At the turbine outlet the temperature falls by a further 55 K to the exhaust temperature of 813 K (540° C), at which point gas pressure corresponds to atmospheric pressure. The final density of the exhaust gas is:

$$\rho = 101{,}325 / 813 / 287 = 0.434\text{kg / m}^3$$

From this information we can calculate the free blade cross-sectional area of the turbine as follows, using the continuity equation. As at the start of the calculation, the engine's throughput is 0.18 kg/s:

$$A_{ngv} = \frac{\dot{m}}{c \times \rho} = \frac{0.18\text{kg / s}}{380\text{m / s} \times 0.55\text{kg / m}^3} = 0.00086\text{m}^2$$

$$A_{blades} = \frac{\dot{m}}{c \times \rho} = \frac{0.18\text{kg / s}}{380\text{m / s} \times 0.434\text{kg / m}^3} = 0.00109\text{m}^2$$

These results show that small overall cross-sections are correct, at 8.6 sq cm and 10.9 sq cm. In fact, this is due to the characteristics of the compressor wheel. The model jet engine will be fitted with a turbine wheel featuring very small blades, and that is why the wheels are able effectively to withstand the centrifugal load acting upon the blades. This is the basic reason why the engine can be run at high rotational speeds without requiring the use of special high temperature alloys.

These calculations also show that the cross-sectional area of the wheel must be larger than that of the nozzle guide vane system. In the interests of simplicity, and to allow us to keep the nozzle guide vane and rotor blades the same diameter, the blade tip angle of the nozzle guide vane wheel is set at 30° and that of the rotor at 35°. In fact, the shallower the blade angle, the smaller the free flow cross-sectional area. This is the key fact which allows us to use blades of similar height. We have now already determined the geometry of the turbine based on the calculated data and the angles and diameters we have established. In general terms the free blade cross-sectional area can be calculated as follows:

$$A = \sin(\alpha) \times \pi \times \tau \times (da^2 - di^2) / 4$$

τ is what is termed the blade taper factor which takes into account the effective reduction in cross-sectional area due to the thickness of the blade. We can reckon on a figure for τ of 0.95. If we select a turbine diameter of 66 mm to match that of the compressor (as in our example), then the internal diameter is found from the following equation:

$$di = \sqrt{da^2 - \frac{4 \times A}{\sin(\alpha) \times \pi \times \tau}} = \sqrt{0.066^2\text{m}^2 - \frac{4 \times 0.00086\text{m}^2}{\sin 30° \times 3.14 \times 0.95}}$$

$$= \sqrt{0.066^2\text{m}^2 - \frac{4 \times 0.00086\text{m}^2}{\sin 30° \times 3.14 \times 0.95}} = 0.0453\text{m}$$

Thus we find that the blade height should be (66 - 45.3)/2 = 10.35 mm. If we assume a blade tip angle of 35° and a density of 0.434 Kg/m³ we can calculate for the rotor wheel an internal diameter of di = 43 mm and a blade height of 11.5 mm.

Finally we can plot the overall vector diagram using the data determined thus far. The speed reached in the blade ducts is 380 m/s. The average peripheral speed can be calculated from the average stage diameter:

$$d_m = (d_u + d_i) / 2 = 54$$

and the rotational speed.

Another interesting point to note is the outflow speed of the gases from the turbine wheel.

$$u = d_m \times \pi \times n / 60 = 0.054\text{m} \times 3.14 \times 100.000 / 60 = 283\text{m / s}$$

We have deliberately kept this value high, so that the maximum amount of thrust is developed. The outflow speed can be found from the equation. Without any supplementary exhaust cone the engine's thrust is already at least:

$$F = c_m \times \dot{m} = 218m/s \times 0.18kg/s = 39N$$

With a good thrust nozzle this value rises by a further 20-25%, and at a speed of 105,000 rpm a final thrust of 50 Newtons is achieved.

The design of the turbine would not be complete without some mention of the optimum number of blades. Here again there can be no definite answer.

The important point is that the number of blades of the nozzle guide vane system and the rotor should not have a common divisor, otherwise the engine may tend to suffer oscillations because of in-phase gas flow through the blade ducts. A good system has proved to be eleven blades in the nozzle guide vane system, and 19, 21 or 23 blades in the rotor.

Centrifugal loads on the rotor wheel

The turbine wheel is undoubtedly the most highly stressed component in a model jet engine, as it has to withstand high temperatures as well as centrifugal forces of exotically high values. The weakest point of the wheel is usually the blade roots since they are subject to high temperature and must also withstand the total centrifugal force acting upon the turbine blades. Inevitably the resultant stresses rise with the square of the rotational speed.

For these reasons it is essential to ensure that the maximum permissible rotational speed for the engine is never exceeded. However, the temperature of the gas inside the engine plays a very important role here, for at high temperatures the steels we are using lose much of their strength. This applies in extra measure to the modeller, who generally does not have access to super-quality heat-resistant alloys.

The stresses on the wheel material in the turbine blade region are influenced by the peripheral speed, the blade mass, the material cross-section and the radius of the wheel.

To simplify matters slightly, we will consider the mass of a blade as a unit operating at its centre of gravity. The centrifugal force on the blade is then:

$$F = \frac{m \times u_m^2}{r_m}$$

F = Centrifugal force in Newtons
u_m = Average peripheral speed in m/s
r_m = $d_m/2$ = average radius in m
m = blade mass in kg

If we assume all the data found in the preceding sample calculation, with an actual blade mass of around 0.6 grammes, the average radius is 0.027 m, the average peripheral speed 283 m/s, then the calculated centrifugal load is 1,780 Newtons. This means that the effective mass of the blade is 181 kg.

The tensile stress at the base of each blade varies according to the cross-sectional area of the material at that point. Naturally, this depends to a considerable extent on the actual construction of the turbine wheel. The cross-sectional area will vary depending on the blade geometry and the thickness of the disc. However, it is easy to maintain a cross-sectional area of twelve square millimetres, which results in a tensile stress of around 150 N/mm^2. If the temperature of the material is 650° C we can still get by with nickel-chrome steels such as stainless steel, V4A, INOX or similar grades. If rotational speeds are substantially higher, then only special high-temperature materials should be considered.

The centre of the turbine wheel is also subject to very severe stresses, although the load varies according to the design of the wheel. A plain turbine disc (without a mounting hole) is at least twice as strong as a wheel of the same size with a central bore. This applies even if the hole is microscopically small. The reason for this is tangential tension which occurs along the hole.The practical results of a bored turbine are as follows: as the turbine runs up to full speed the hole expands and suddenly there is play where it meets the shaft. In an extreme case the turbine wheel mounting hole may grow by several tenths of a millimetre. The damage generally goes unnoticed until you stop the engine, or when serious vibration sets in when the engine is run up to speed. Calculating the tensile forces at the centre of the wheel is a very complex procedure since the formula has to take into account the precise wheel form and the influence of the blades.

However, if we assume a disc of constant thickness and a small hole relative to the turbine diameter, we can approximate the maximum stress in the centre of the wheel as follows:

σ = $0.825 \times u_m^2 \times \rho$
σ = Maximum tangential tension in N/m^2
u_m = Average peripheral speed in m/s
ρ = Material density (generally around 8000 kg/m^3)

If we consider the turbine discussed here we can calculate a tensile stress of:
$\sigma = 0.825 \times 283^2 \times 8000 = 528MN/m^2 = 528N/mm^2$
This means that the load in the centre of the wheel is more than three times higher than that acting upon the

Even this short exhaust cone produces an increase in thrust of 15-20%.

blade bases. Although relatively low temperatures prevail in the centre - around 250° C - the material is not usually capable of withstanding these forces. This means that the turbine wheel must be thicker in the centre than at the blade position. This applies even if heat-resistant materials are used. The profile of the wheel can be designed to achieve an even load distribution through the material.

Various styles of exhaust cone.

The exhaust cone

The thrust of our jet engine is simply the product of throughput and efflux speed.

Therefore the space immediately aft of the turbine is very important in terms of the actual thrust produced. It is normal practice to arrange an exhaust cone immediately adjacent to the turbine wheel, whose purpose is to reduce any remaining enthalpy and accelerate the exhaust stream further. In a model jet engine this classic arrangement does present certain problems. In general terms overall efficiency is relatively low, so only a small amount of enthalpy remains which can be added to the engine's thrust. It therefore makes sense to reduce all the enthalpy in the turbine stage and design the blades in such a way that the outflowing gas leaves the turbine at high speed.

The nozzle of this drone engine can be modified by adjusting the inner cone.

In this case the main task of the exhaust cone is to direct the gas into the open air whilst incurring the smallest possible losses. The model jet engine presented here is therefore fitted with a nozzle whose cross-sectional area is virtually constant. Fitting the exhaust cone increases the engine's thrust by about 20%. Clearly the main reason for this increase in thrust is the avoidance of vortices aft of the turbine wheel, which incur high losses. The cone also promotes the formation of a boundary layer which produces an effective reduction in cross-sectional area, leading to a further acceleration of the exhaust gases.

A genuine exhaust cone, known as a convergent cone, presents unacceptable problems at model scale, mainly because the gas leaving the turbine is still extremely turbulent and usually still exhibits a slight residual swirl motion. No matter how efficient the turbine, we cannot eliminate this swirl.

The swirl is unavoidable when you accelerate the engine or close the throttle, and the exhaust flow would have to be straightened before it could be accelerated further in the cone. The straightening process requires a smoothing passage for the gas. In industrially produced small jet engines fitted with a convergent cone this calming component is very large in volume, and for our model jet engine we can certainly manage without the extra complication.

The shaft of a model jet engine

The final essential component of the engine is the shaft, whose task is to transfer the energy in the turbine wheel to the compressor. The actual torque concerned is very low, but the special characteristic of the system is its extreme rotational speed, which forces us to adopt a very special design of shaft. Initially it appeared that hollow tubular shafts would offer great advantages, because they are light in weight and have a high natural resonant frequency. In fact, solid shafts have proved to be thoroughly practical, and this section therefore assumes the use of a solid shaft.

The assembly comprising shaft, compressor wheel and turbine wheel is a system capable of vibration. If its natural resonant frequency is close to the frequency of rotation, then the system will start to oscillate, and if actual resonance occurs, the vibration will be so severe that the shaft bends. In the course of development of this jet engine I have several times encountered sudden and severe vibration when the engine was run up to high speed. Once the engine had been stopped it was possible to see the eccentricity in the shaft with the naked eye, just by looking at the compressor.

The only solution to this problem is to design the rotor system in such a way that its natural resonant frequency is as high as possible. The weakest point in the system is usually the compressor. The mass of these wheels is relatively high, and their centre of gravity is a long way from the bearings. If high rotational speeds are to be achieved it is advantageous to use a short shaft, and to locate the bearings close to the rotating wheels. In practical terms the solution is simply to make the shafts for our model jet engines from solid steel.

Calculating the critical rotational speed

Calculating the critical rotational speed of a model jet engine is extremely complicated, but this is very useful information if you wish to experiment with shafts and rotors. The following section includes a method of calculating the approximate critical speed based on the MicroTurbine. In essence it is based on the formulae stated by Bohl (author - see bibliography). The actual calculation is a two-stage process. The first step is to calculate the critical rotational frequency of the compressor, the turbine and the shaft individually and independently of each other. The second step involves combining the three individual values to determine the critical speed of the entire rotor.

First we tackle the compressor wheel. We will consider the engine's shaft to be a zero-mass holder for the rotor. The crucial influence on the oscillation frequency is the distance between the wheel's CG and its bearing. The wheel's CG can be found by balancing it on a matchstick.

$$\omega = \sqrt{\frac{3 \times E \times I}{m \times (l + c) \times c^2}}$$

ω is the bending critical angular velocity. To find the rotational speed we multiply by $30/\pi = 9.55$ to give rpm.

I = Area moment of the shaft
$d^4 * \pi/64$

d = Shaft diameter, in our case $I = 1.886 * 10^{-9} m^4$

E = modulus of elasticity of the shaft material. With almost all steels it is:
$210 * 10^{-9} m^4$

l = Bearing spacing, in our case 96 mm = 0.096 m

c = Distance from the wheel CG to the first bearing, in our case 16 mm = 0.016 m

m = Wheel mass, in our case 0.062 g

The value for $\omega_{Compressor}$ is thus 28.852 l/s, which corresponds to a critical rotational speed of 246,864 rpm.

Now we repeat the procedure for the turbine wheel. Its mass may well vary, but in our case it is around 50 g. Cast wheels are slightly heavier at 70 g, or 0.07 kg. The distance to the turbine bearing is only 0.012 m. As a result we find a much higher critical angular velocity of $\omega_{Turbine}$ = 28.057 l/s. Finally we have to calculate the critical speed of the shaft on its own. The formula for the solid shaft is:

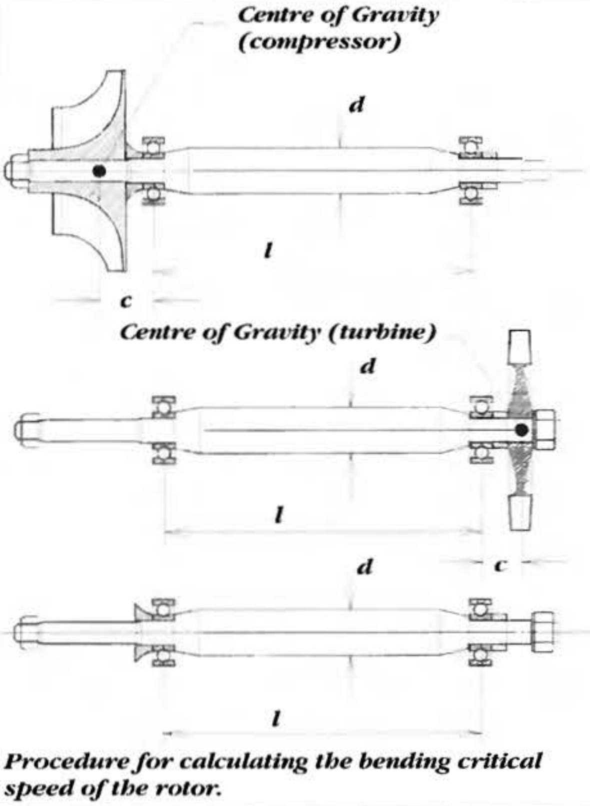
$$\omega = \sqrt{\frac{3 \times E \times I}{m \times (l + c) \times c^2}}$$

l = Bearing spacing
d = Material thickness
ρ = material density, in our case 7800 kg/m³

Based on the data used in these formulae we arrive at a critical angular velocity of the shaft of ω_{Welle} = 21.597 l/s. In the second stage of the calculation, as already mentioned, we calculate the critical speed of the rotor as a whole.

$$\frac{1}{\omega^2} = \frac{1}{\omega_{Compressor}^2} + \frac{1}{\omega_{Turbine}^2} + \frac{1}{\omega_{Shaft}}^2$$

This procedure clearly shows that the bending critical speed ω is 14,270 l/s, corresponding to a bending critical speed of the whole rotor of 136,270 rpm, which is significantly above the maximum design speed of 105,000 rpm. A safety margin of at least 20% between nominal speed and critical speed is certainly advisable in order to shield the engine from severe vibration. If an even heavier compressor wheel is used you may well encounter problems in pushing the critical speed to a sufficiently high value, and if you are in any doubt you should use a thicker shaft and bearings. On no account is it permissible to attempt to turn down the wheel on the lathe in an attempt to save weight!



Procedure for calculating the bending critical speed of the rotor.

Chapter 2

A Home-made Model Jet Engine

Introduction

Building your own jet engine is not as complex an undertaking as you might expect. After all, the design presented here, based on a single-stage compressor and turbine, utilises the simplest possible layout.

Even so, any reader considering building his own turbine should not underestimate the potential problems, as there are several pitfalls awaiting the unwary. For example, these power plants have one insidious characteristic: if the engine should fail to run, it provides no clue of the cause; at least, not to the inexperienced constructor.

What this means is that you must have some technical understanding of how turbines work right at the outset. If you want the engine to be capable of flying a model, it must be capable of running at very high rotational speeds, and this in turn demands a high level of preci-sion in the manufacture of the rotor system. The bearing seatings must be accurately machined, and the shaft must run true to very tight tolerances. Dynamic balancing also calls for considerable patience. You will certainly need to work carefully and accurately, and will need all the tools of the typical fully equipped amateur workshop - but that is all you need.

If the engine is to run well it is crucial that a small number of important parts should be made really accurately and fitted precisely. This caveat primarily concerns the rotor system, the angle of the blades and the combustion chamber. In other respects model jet engines will shrug off a few inaccuracies.

I have heard of home-made turbines which run well, even though the turbine wheel has poorly formed vanes with no specific profile, even though the compressor has an excessively generous clearance, and even though one diffuser guide vane was simply broken off during machining.

The version presented here - the Micro-Turbine - is based on a turbocharger compressor wheel with a diameter of 66 mm. The engine's mass lies within the range 1100 to 1200 g, depending on construction, and it represents a viable power plant for model aircraft of medium

The small version: the Micro-Turbine.

After numerous modifications the Mini-Turbine produced a thrust of 40 Newtons.

size. Overall diameter of the engine is 110 mm, length 235 mm. The engine requires Jet A1 kerosene as fuel, and it has to be injected into the engine at a pressure of around 3 bar at full throttle. The bearings are lubricated by means of the kerosene fuel, which is mixed with 3% two-stroke oil for this purpose, thereby eliminating the need for a separate oil tank. The design is intentionally optimised to keep exhaust gas temperatures relatively low, as this produces an engine which is fairly straightforward to operate.

This emphasis in the engine's overall design means that we can just "get by" without using special high-temperature steels, provided that thrust is restricted to 40 Newtons. However, high-alloy nickel-chrome steels such as stainless steel are still the only choice as the turbine material. If high-temperature materials are used you can safely increase power slightly. Fitted with a turbine wheel made of Inconel 713, Nimonic 90 or other heat-resistant alloys the engine produces more than 50 Newtons of thrust on the test bench without problem at a rotational speed of 105,000 rpm. These wheels are produced using a precision casting process, usually from Inconel 713. Most of these wheels share a common diameter of 66 mm, are designed for this size of turbine engine, and can be used without any problems.

Since its introduction the general arrangement presented here has shown itself to be very effective. The combination of a turbocharger compressor, "stick" combustion chamber and axial working turbine has proved to offer many advantages. These turbines are powerful engines, easy to start, and require little in the way of auxiliary equipment. Evidence of the efficacy of this layout is the fact that, since the drawings were first published, several manufacturers have adopted the same basic principle and produced similar designs. The size of the compressor and turbine used in this design provide a level of thrust sufficient for most model jet aircraft of average size. You can expect 50 Newtons of thrust – with a little luck perhaps even 60 Newtons, and this is adequate for model aircraft with a take-off mass of up to 10 kg. In our experience most model jets are considerably lighter than this, and are overpowered even with 50 Newtons of thrust. If the model is very light and very sleek, airspeeds can be uncomfortably high; the pilot must be prepared to concentrate hard on the flying, and be prudent and circumspect in handling the model in the air.

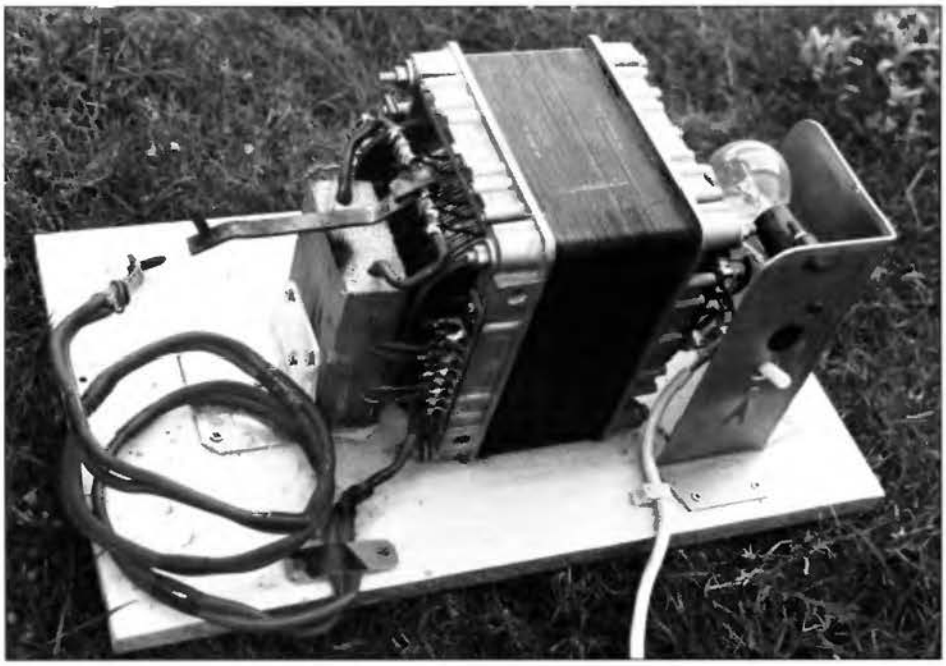
Certainly the design presented here is capable of even higher levels of thrust. Practical experience shows that more power is available simply by increasing the turbine's rotational speed, but please allow me to warn you off this idea right now. The rotational speed of the model jet engine as presented here should be limited to a maximum of 105,000 rpm, as already stated; this speed corresponds to a pressure ratio of 2.0. The thrust actually achieved by the engine varies according to the implementation of the individual machine. If the quality of the combustion chamber, the turbine guide vane system and the turbine wheel vary, so will the engine's power output. However, if you run the engine at a speed higher than recommended, you are eating into the reserves of strength which are deliberately built into the design. At the same time the useful life of the engine in general, and of the bearings in particular, is reduced considerably by excessive speeds, not to mention the additional problem of a pronounced rise in noise levels.

What tools will I need?

My aim in preparing the drawings was to provide the amateur constructor with the means to build the engine as described, and this really is possible. Where welding is required, I have kept material thicknesses generous, as this makes the process easier. The only parts which have to be purchased are the bearings, the compressor wheel and a few small items. The turbine wheel can certainly be home-made; however, since many professionally produced turbine wheels are now available commercially, the easy course is to resort to one of these. Cast turbine wheels are safe at higher rotational speeds, and this makes your engine potentially more powerful. The gain in efficiency over a home-made wheel is quite moderate, but you do spare yourself the extremely time-consuming task of making your own wheel.

In recent years rapid progress in manufacturing technology has made modern machine tools accessible to the amateur constructor, and certainly some components of the turbine can be produced significantly better and lighter using CNC

Sheet metal up to one millimetre thick can be joined easily using a spot-welder of this type, made by converting a transformer.



FAILURE TIME/TENSILE STRESS OF POPULAR MATERIALS FOR TURBINE WHEELS IN N/mm2

No.	Designation	Trade Name	Strength	600°C	700°C	800°C	900°C
2.4816	NiCr 15 Fe	Inconel 600	$\sigma_{B/1.000}$		80	40	21
2.4634	NiCo 20 Cr 15 MoA1Ti	Nimonic 105	$\sigma_{B/1.000}$	853	490	245	93
2.4632	NiCr 20 Co 18 Ti	Nimonic 90	$\sigma_{B/1.000}$		373	117	39
2.4964	CoCr 20 W 15 Ni	L605, HN 25	$\sigma_{B/1.000}$		216	118	59
1.4981	X 8 CrNiMoNb 16 16	Böhler T255	$\sigma_{B/1.000}$	290	140	55	
1.4841	X 15 CrNiSi 25 20	Ferrotherm 4148	$\sigma_{B/10.000}$	130	44	20	
1.4300	X 12 CrNi 18 8	Stainless steel	$\sigma_{B/100.000}$	100	40		

$\sigma_{B/...}$ = Failure after . . . hours

milling machines and TIG welding equipment. To cater for this possibility I have included a second, more professional version of certain components in the present edition.

Building a jet engine requires no more than a workshop equipped with the usual tools for metal working. One absolute essential is a robust lathe with a length between centres of 200 mm and a centre height of at least 120 mm. The facility to cut left-hand threads is very useful, as this saves having to buy special left-hand dies. Other requirements include an accurate pillar drill, a cut-off tool and a small grinder, and you will need facilities for silver-soldering as well as some form of electric welding apparatus. A Metal Inert Gas (MIG/MAG) welding machine or even a TIG welder are valuable tools, but not indispensable. Other essential equipment includes measuring tools such as a vernier caliper, screw micrometer and dial gauge. For basic shaping of sheet metal a nibbler or similar device is very helpful.

Many parts of a jet engine are fabricated from thin sheet metal; this material is used for the engine casing, the combustion chamber and the thrust nozzle. Sheet metal is also used for clips and straps, the thrust pipe and other parts required to install the turbine in the model. Unfortunately it is difficult to produce sound electric-welded joints in sheet metal if the material is less than one millimetre thick. This applies in particular to stainless steel and other thin heat-resistant metal sheet. In such cases spot-welding offers many advantages, and it is little trouble to make your own device for this task. Indeed, it is worthwhile procuring or making a spot welder for home-building a model jet engine, if you do not already have access to a TIG welder.

The simple design described here has proved to be very effective; all that is required is a transformer with a capacity of at least 300 Watts. Such items can be found as isolating transformers; alternatively you may be able to cannibalise an old welding machine. The essential factor is that the primary 240 Volt winding should be intact, as any secondary winding is removed in any case. If you work carefully you can cut away the wires neatly, which avoids the need to dismantle the metal core.

The next step is to obtain some thick wire with the largest possible cross-sectional area; jump-start cable for cars is a good source. Wind a few turns of the wire onto the core with the aim of producing a no-load voltage of about 3-4 Volts. The actual welding electrodes consist of brass points, although copper points are even better. Wire up a foot-switch which actuates the primary side of the transformer. I recommend that you connect a 60 Watt filament bulb across this switch as a bridge; when the switch contacts are open, the bulb acts as a dropping resistor. When the welder is not on load, the bulb glows dimly. When the electrodes make contact, the bulb immediately lights up brightly, and the welding process can begin.

Please remember that mains voltages are lethal and the construction of the spot welder should be checked for safety by an electrically competent person **before** the welder is connected to the 240 volt mains electricity supply.

To produce a welded joint, press the electrodes onto both sides of the metal and operate the foot switch for a moment to switch on the primary side of the transformer. It is important that the electrodes are exactly opposed to each other at the moment of welding. Please remember to wear protective goggles for welding. It is a good idea to install one electrode in a fixed position on the welding device, with the second electrode hand-held. You can use a handle made of wood or heat-proof plastic for the hand-held one.

This simple machine provides an effective means of joining thin stainless steel sheet reliably and with little effort. You will find that you are able to spot-weld sheet metal reliably after only a short period of practice. For very thin sheet material you will have to reduce the current slightly; this applies to combustion chambers and thrust pipes, for example. The simplest method is to clamp a second length of jump-start cable between transformer and electrode to act as a series resistance.

Selecting materials

Apart from the parts which come into contact with hot gases the engine is assembled from standard materials which you should find straightforward to obtain. Only the metal for the turbine, the turbine nozzle guide vane system, the combustion chamber and the thrust nozzle have to be able to withstand high temperatures.

The steel industry has developed hundreds of alloys which are many times superior to normal steel in terms of heat resistance. Most of these materials possess material numbers which begin with 1.4 or 2.4. It is very difficult for the amateur to obtain extreme heat-resistant steels in small quantities, and working these alloys is not simple, although in my experience cutting alloys based on nickel and cobalt is quite possible using amateur tools provided that you are aware of a few "wrinkles" (special techniques). It is very important that you take your time over sawing and drilling. If you work too quickly both the tool and the workpiece heat up. The turning tool or saw blade soon loses its strength, but the workpiece usually survives the ordeal unscathed. This just means that you must always work patiently and use copious quantities of cutting fluid.

In the engine itself the material is subjected to high temperatures and tensile stress, and if certain loads are exceeded the material slowly begins to change shape. Elastic deformation, which disappears again when the engine stops, is acceptable, but if the material goes beyond this point a permanent distortion sets in which gradually worsens with time. The magnitude of this effect varies according to the strength of the material. This in turn varies very greatly according to temperature. Stainless steel and other commonly used nickel-chrome steels exhibit a clear decline in terms of strength over time at a temperature of 650° C. That is why it is essential to ensure low exhaust gas temperatures when these materials, with their limited heat-resistance, are used. Tables of material strength include the value $\sigma B/1000$ which is important to constructors of engines. This value states the load and temperature at which the material will fail after 1000 hours.

However, the actual fracture is preceded by a linear expansion of the material by a few per cent. What this means in practice is that overloading a model jet engine will not usually cause the blade bases to fail. It is usually the case that excessive speed stops the engine in an utterly unspectacular fashion: the turbine blades twist and eventually foul the casing. A further important item of information is the scaling resistance of the material, which should be at least 800° C. This applies in particular to the turbine nozzle guide vane system where the highest temperatures are encountered. Scaling results in a constant wearing away of material which can eventually lead to fracture.

As a rule standard nickel-chromium steels are relatively easy to obtain. Thin sheet material can even be bought from builders' merchants. A good source of the thicker material which is required for the turbine wheel is a scrap merchant, as the stainless sheet material is usually collected separately because of its higher value. Externally these materials can be recognised by their rust-free condition. When you are on the hunt for these materials, a magnet is an important ally. If you are lucky you may find a piece with the material number printed on it, and you can then check its suitability for your engine by consulting a materials list. The standard alloy constituents of these steels are 18% chromium and 8% nickel, but if they also include molybdenum, manganese, niobium or titanium, so much the better. Another likely source is any company which manufactures equipment for the chemical industry. These companies use high-alloy steels for making acid- and heat-resistant valves, pumps and instruments. Certain stainless steels are resistant to inter-crystalline corrosion and as such are used in shipbuilding, and these have also proved suitable for engine construction. A much used steel in this area is Nitronic 50 (1.3964). I have made several turbine wheels from this material which to date have withstood the stresses without complaint.

The compressor wheel

The compressor wheel required for our model jet engine is manufactured for use in KKK turbochargers, and can be purchased as a spare part. It is supplied very accurately dynamically balanced, and is therefore absolutely ready to use.

These wheels are available exclusively via authorised service points, and not from the turbocharger manufacturing company itself; supply sources are listed in the appendix. No work of any kind needs to be carried out on the compressor wheel. The wheel (5326 123 2037) has a diameter of 66 mm, a 42 mm Ø inlet and a blade height of 5 mm. In addition to the wheel specified in this design, two further models from the same range of compressors are also available and usable for our purpose. All three wheels are produced from the same basic

A low exhaust gas temperature is very important if the engine is to operate reliably.

casting, and differ only in the contour machined into it. This results in differences in potential throughput, albeit only at fairly high rotational speeds. The two other types have an inlet diameter of 46 mm and offer slightly superior performance at very high speeds, but are a little more expensive to buy. In any case, the differences are negligible when the turbine is used normally, i.e. up to the engine's maximum design thrust. The alternative wheels (5326 123 2038 and 5326 123 2022) can therefore be used as straight alternatives. If you do use one, note that you will need to increase the vane height of the compressor diffuser vane system to 6 mm. If you opt for the latter wheel you only need to adjust the shape of the compressor cover to match it; all the other engine components can be used unchanged.

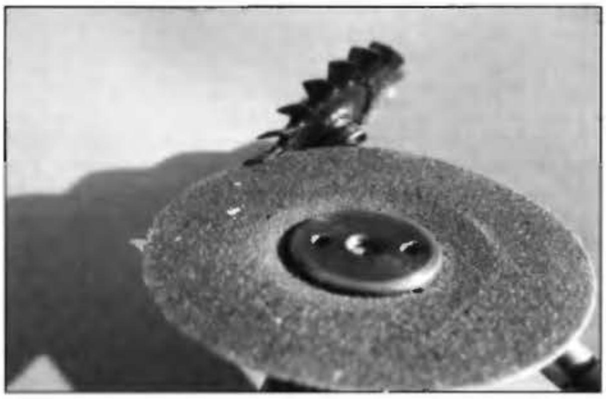
Constructing the engine

Making the shaft

Heat-treated steel should be used to make the shaft. A proven method is to make the shaft components from large machine screws with a strength rating of 12.9. This type of screw - typically M16 x 180 or M20 x 180 - is available from specialist dealers. If you have to use other materials the steel must be really tough. Hydraulic cylinder pushrods have also proved to be a source of excellent material. These are generally alloy steels such as 42 CrMo 4. The pushrods are often case hardened (nitrided), which means that the thin hardened layer must be removed before turning, using a grinder. The shaft material must be very tough, but not brittle; the shaft simply must not break. The modulus of elasticity of various types of steel varies very little, and as a result the bending critical speed for all shafts is about the same. Stainless steel is not a suitable material for turbine shafts. As a conductor of heat, standard commercial stainless steel is around four times worse than low alloy steel, and therefore the heat from the hot turbine wheel is not dissipated quickly enough. Neither are titanium and its alloys good shaft materials. The threaded shanks of titanium shafts tend to degenerate with the fluctuating mechanical and thermal loads, and safety considerations therefore dictate that this material should not be used. If the joint between the turbine wheel and the shaft comes loose, the result could be that the entire threaded spigot is torn off. In any case, titanium has a low modulus of elasticity, and therefore offers no advantage in terms of bending critical speed with this shaft design.

The first step is to rough-turn the shaft on the lathe.

Grinding the rotor blades.



The combustion chamber of the Micro-Turbine. View from rear.

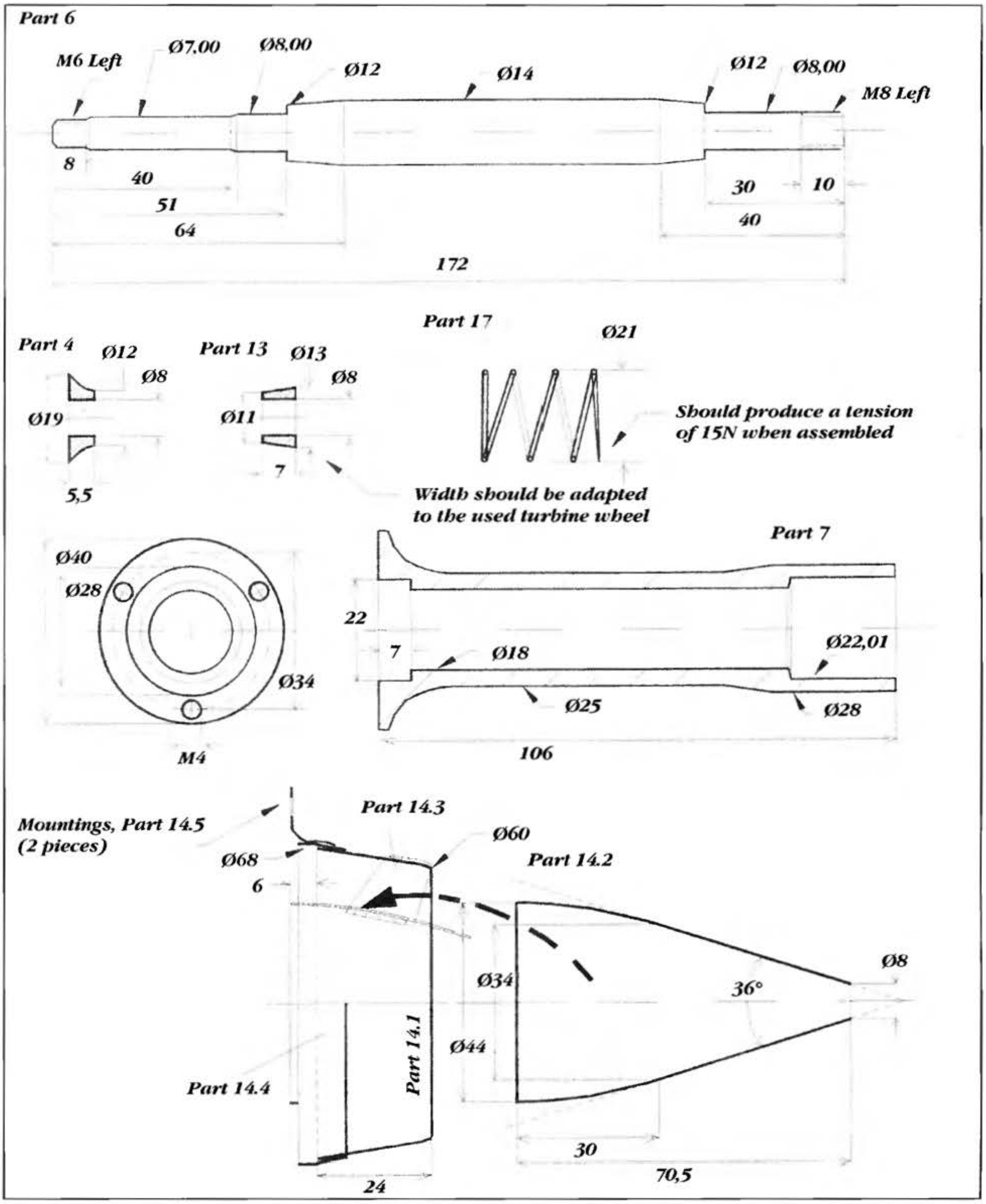
For best results use turning tools with a tungsten carbide cutting tip. All fits should be left clearly oversize. As a lead-in to the sections which are later to be threaded you should turn the shaft down to a diameter of 6 mm for a few millimetres (turbine end) and 4.8 mm (compressor end), to ensure that the threads start straight.

Centre up the shaft blank and bore a centre hole at both ends. Now is the time to machine the cylindrical sections to final size, turning between centres. If you have a grinding attachment on your lathe, that's what you should use. The bearing seatings and the shoulders for the compressor and turbine must be machined to an accuracy of one hundredth of a millimetre. Check the concentricity of the shaft at the centre and the shoulders using a dial gauge. The maximum permissible deviation should be less than two hundredths of a millimetre.

Cut a left-hand thread in both ends of the shaft. Please do not consider any other form of attachment at this point - nothing else will do. Please don't attempt to save the £20 for a suitable tap and die.

The spacer discs should be considered part of the shaft. Two are required: one at the compressor, the other at the turbine wheel. Great precision is required when forming the inner sleeves; they must have no backlash on the shaft, and the inner bore must be finished using a reamer. The two end surfaces must be exactly parallel to each other. I recommend that you check this accurately using a screw micrometer. Any inaccuracy will result in a shaft which does not run true, and many imbalance problems can be traced back to this area.

The cooling channels and lubrication tube at the rear side of the diffuser system.



The shaft tunnel and bearings

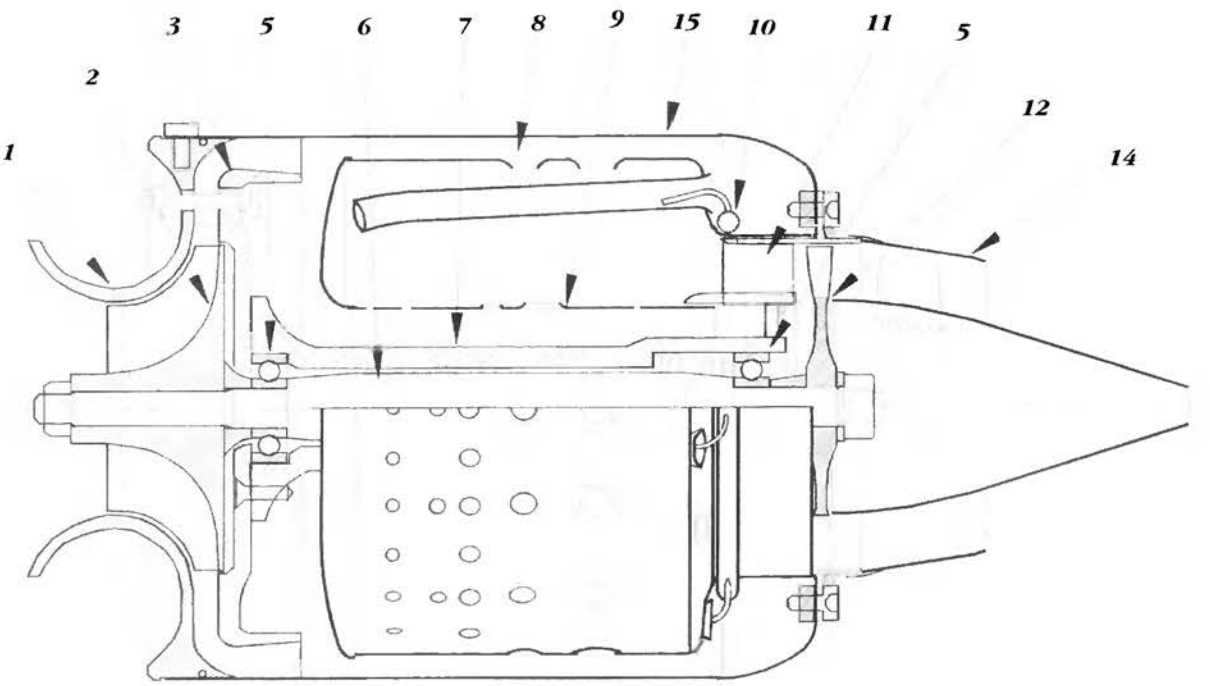
The shaft tunnel (7) is made of aluminium. The ball-race at the compressor end should be a good press-fit in the bearing seating, and the bearing should end exactly flush with the flange. In contrast, the turbine end bearing housing must be oversize in order to allow for the differential expansion of shaft and tunnel. Since the bearing's operating temperature is high, the play should be one hundredth of a millimetre. If the rear bearing is slightly tight when cold, this is no cause for anxiety. The thermal expansion of aluminium is greater than that of steel, so the correct clearance will develop when the parts reach running temperature.

A component part of the shaft tunnel is the thrust spring for the bearing at the turbine end. This spring provides the essential pre-load in the bearing. The correct force for this spring has proved to be 15 Newtons, and this value should not be exceeded by a significant

NO.	NO. OFF	DESCRIPTION	MATERIAL/TYPE	DIMENSIONS/NOTES
1	1	Compressor cover	Aluminium	Turned
2	1	Compressor wheel	Al-Si alloy	Ready made (KKK 5326 123 2037)
3	1	Compressor diffuser system	Aluminium	Compound component
3.1	18	Guide vane	Aluminium	1mm thick sheet
4	1	Spacer disc	Steel	Precision turned
5	2	Ballrace	ISO 608	"C3" ballrace without shields; hybrid ceramic bearings better
6	1	Engine shaft	Screw steel 12.9.	Turned from large machine screw
7	1	Shaft tunnel	Aluminium	Turned
8	1	Combustion chamber jacket	Stainless steel	Spot-welded
8.1	1	Combustion chamber sleeve	Stainless steel	Sheet, 0.3-0.5 mm thick
8.2	1	Rear section	Stainless steel	Sheet, 0.5mm thick
8.3	1	End piece	Stainless steel	Sheet, 0.5mm thick
8.4	6	Stick	Stainless steel, Inconel 601	¼" tube; alternatively 6 mm
9	1	Combustion chamber inner section	Stainless steel	Welded
9.1	1	Inner tube	Stainless steel	Sheet, 0.3-0.5mm thick
9.2	1	Front section	Stainless steel,	Sheet, 0.5mm thick, pressed
10	1	Injector ring	Brass	Soldered
10.1	1	Injector ring	Brass	4 Ø x 0.5 mm
10.2	6	Injector needle	Syringe needle	Size 2, 0.8 Ø x 40 mm (pharmacist)
10.3	1	Guide	M4 socket-head cap screw	Drilled out
11	1	Turbine nozzle guide vane	Stainless steel, Inconel 601	Compound component
11.1	1	Inner ring	Stainless steel	Turned
11.2	11	Tunnel guide	Stainless steel	Turned
11.3	11	Blade	Stainless steel, Inconel 601	Sheet, 0.7-1 mm
11.4	1	Turbine jacket	Stainless steel	Sheet, 1.5 mm
11.5	1	Flange	Stainless steel	Sheet 1.5mm
12	1	Turbine wheel	As heat-resistant as possible	As instructions, or ready made
13	1	Spacer disc	Stainless steel	Precision-turned
14	1	Thrust nozzle	Stainless steel	Spot-welded
14.1	1	Outer cone	Stainless steel	Sheet, 0.3 - 0.5 mm
14.2	1	Inner cone	Stainless steel	Sheet, 0.3 - 0.5 mm
14.3	3	Lug	Stainless steel	Sheet, 0.5 mm
14.4	1	Spacer	Stainless steel	Sheet, 0.3 mm
14.5	2	Mounting ring	Stainless steel	Sheet, 0.5 mm
15	1	Casing	Stainless steel	Spot-welded, soldered
15.1	1	Housing jacket	Stainless steel	Sheet, 0.3 mm
15.2	1	Rear section	Stainless steel	Sheet, 0.5 mm, pressed
15.3	3	Hole reinforcement	Stainless steel	Sheet, 0.5 mm
15.4	1	Guide	Steel	Tube, 5 Ø x 12 mm
16	1	Lubrication tube	Brass	3 Ø x 0.3 mm
17	1	Pre-load spring	Steel	Thrust pressure: 15 Newtons
18	2	Pressure take-off nipple	Brass	From 6 mm Ø rod
19	1	T-piece	Brass, steel	Injector needle soldered in
20	1	Auxiliary gas injector	Brass, steel	Injector needle soldered in

Various other small parts such as screws, nuts and clips not listed individually.

amount. The pre-load spring itself can consist of a series of spring washers. The spring tension can be adjusted by means of a sleeve between the spring and the bearing if necessary. For initial test running it is not necessary to pre-load the bearings. The bearing configuration used in this design assumes the use of standard ballraces. If flanged races are used the spring force must be considerably higher. In any case you can expect good results with perfectly standard bearings. If you keep to moderate rotational speeds - say, up to 100,000 rpm - you can expect a useful life of more than 20 flights. The ball cages should be made of steel or plastic, and the bear-



Cross-section of the Micro-Turbine.

ings should certainly be inspected regularly. Bearings with rolled brass cages are not suitable. Hybrid bearings with silicon nitrite balls offer a virtually unlimited life, and suitable types can be obtained in small quantities.

The final part of the shaft tunnel is the lubrication system. The oil pipe (16) is made from thin brass tubing, bent to the shape shown. The oil pipe is clamped in place in one of the three air ducts when you screw the shaft tunnel to the compressor diffuser vane system. The shaft tunnel should be held in place using high-strength screws, preferably socket-head types, and thread-lock fluid. The other end of the tube exits the engine through a hole in the compressor cover. The lubrication tube can then be connected to a T-piece in the fuel supply line using a short length of flexible tubing.

The turbine nozzle guide vane system

The nozzle guide vane system for the turbine (11) is one of the most complex parts of the engine. It has two primary functions: feeding the gases to the turbine wheel and providing a location for the shaft tunnel. The mounting flange to the housing (11.5) also serves as a burst shield (containment). The first step is to make the inner ring (11.1). It can either be turned from a suitable piece of tube or bent to shape from sheet metal. Mark the eleven blade slots as shown in the drawing and saw them out using a piercing saw. You may need to shorten the saw blade (hard metal grade) to prevent it fouling. If you have any choice, select a good heat-resistant material for the nozzle guide vane blades, but otherwise use stainless steel. Cut out the blades (11.3) leaving them well oversize, bend them to approximate shape, then place them in the inner ring. If you look at the guide vane system from the front, the vanes should overlap each other as far as possible; it should not be possible to see right through the vanes except towards their tips. The angle of the vanes can certainly be allowed to decline by one to two degrees towards the outside. Finally weld the blades in place from the inside using an electric welder. Fit the shaft tunnel seating (11.2) and attach it, again using the electric welder. The nozzle guide vane blades can now be turned down to size as shown in the drawing. This is easiest if you have a grinding attachment on your lathe. The last step is to grind the blades to a rounded profile at the inlet and a point at the outlet.

The next step is to machine the flange and weld the turbine jacket (11.4) in place. In this state the inside of the component should be machined on the lathe to guarantee an exactly circular cross-section. Insert the inner section, mark the position of the slots for the edge of the nozzle guide vane blades and saw them about 3 mm deep in the turbine shroud. The gap between the blades and the turbine jacket (one tenth mm) disappears when the engine is at running temperature. Each nozzle guide vane is fixed to the turbine shroud with a single spot-weld. At this stage the vane system should be mounted in the lathe again; when you are confident that it runs dead true, you can safely machine out the central seating for the shaft tunnel to its final diameter.

The turbine wheel

In technical terms the turbine wheel (12) is not as difficult to make as you might expect. The actual wheel is made of 6 mm thick sheet metal. Cut out a suitable blank and bore the central hole for the shaft. Heat-resistant steel should be bored out in stages using a low rotational speed and cutting fluid. Use a reamer to open up the hole to the exact size.

The blank can now be turned down to size on the lathe, again using a low rotational speed. Tungsten carbide tipped cutting tools have proved a good choice for this task. Leave the wheel diameter about 1 mm oversize. The next step is to saw the 19 blades down to a diameter of 46 mm. An ordinary hacksaw fitted with an HSS blade has proved suitable for this job. Saw slowly but use plenty of pressure; you will find that a generous supply of cutting oil makes the work easier. If you are using extreme heat-resistant material such as Inconel 625 or Nimonic 90 you should feel pleased with yourself if you manage a 5 cm linear cut per saw blade.

Heat the turbine blades to red heat using a gas torch, then twist them in the clockwise direction through 30 to 35° using a pair of pliers or a home-made claw tool. The final blade angle is established when the turbine blades are ground to shape. This is done using a disc cutter clamped in a drill press. The first step is to continue the saw cuts down to the final dimension of 44 mm: hold the turbine wheel at an angle of about 35° to the disc cutter and grind through to the final dimension.

Now the profiling of the individual blades can begin. Grind material away using a coarse epoxy abrasive wheel, cutting mainly on the side facing the combustion chamber and aiming at the approximate profile shown in the drawing. Minor variations in this respect are not critical, but each blade must be slightly cambered. The mean line of the profile should follow a radius of about 15 mm. To ensure sufficient strength at the blade base the profile thickness of the blades should increase constantly towards the centre of the wheel. The blade tips should be no more than 0.7 mm thick. The blades taper towards the rear edge and are rounded off at the front.

Finally check the tip angle of each turbine blade: it should be 34°. Any blades deviating from this value can be adjusted using a pair of pliers. Clamp the wheel on a mandrel to check that it runs true, then carefully turn it down to final size. The final stage of finishing the turbine blades consists of sanding them carefully using the abrasive wheel mentioned earlier.

Polishing the blades to improve the surface finish does not provide any measurable increase in power. If you have used special heat-resistant material it is important to anneal the turbine wheel to free it from internal stresses. The annealing temperature and time for the material in question should be found by referring to the appropriate material lists.

A cast turbine wheel is an equally good choice for this engine. The blade angle and profile of these wheels are usually designed with high thrust as top priority. The best results are obtained by producing a turbine nozzle guide vane system which lines up as well as possible with the turbine wheel blades. If you use a cast wheel, the nozzle guide vanes can be flattened slightly towards the outer diameter. The wheel attachment takes the form of an 8 mm Ø bored hole. The cast blank should be bored out in stages at low speed, starting with a small pilot-hole. This task should always be carried out on the lathe. The wheel can be held in the lathe chuck by clamping it from the inside, against the ring of vanes. Alternatively you can fit a slotted aluminium ring over the wheel to protect it, then clamp it from the outside. It is important that the turbine wheel should run as true as possible. The best method of cutting the main bore is to use an 8 mm Ø tungsten carbide masonry drill, modified as follows: sharpen the tip of the drill, at the same time grinding down the diameter slightly in order to achieve a 7.8 mm Ø hole. A reamer can then be used to finish off the bore to final diameter. The final stage is to turn down the turbine wheel to its final diameter. Tungsten carbide tipped turning tools (wear goggles!) are best for this. If you have a grinder, use it to reduce the wheel to final size. The clearance of the cast turbine wheel must be very close; certainly not more than 0.2 mm on each side.

Wheels produced using the investment casting method are extraordinarily strong, and therefore offer great reserves of strength, but please don't let this fact tempt you into running the engine at higher speed than is permissible. The turbine wheel manufacturer's instructions and recommendations must be observed.

Balancing

To balance the turbine wheel it is necessary to mount it on the turbine shaft. The fit must be accurate, i.e. the wheel should require slight force to install it on the shaft. Fit two new ballraces (22 mm diameter ISO 608) when assembling the shaft. The ballraces are supplied grease-filled, and the grease should first be rinsed out with kerosene or petrol. In this state the bearings are very free-running. Hybrid ceramic bearings are ideal for this application. Naturally it is essential to keep everything spotlessly clean, as even a tiny quantity of dust will falsify the results of the balancing process. We recommend that you keep one set of bearings especially for this purpose, and protect them very carefully from dust. Install the shaft, bearings and turbine wheel in a metal tube with an internal diameter of 22 mm.

The next step is to lay the tube, complete with shaft, on a flat surface, and cautiously and continuously roll it a quarter turn to and fro. This action will cause the shaft to align itself with the heavier side at the bottom. Mark this point on the turbine wheel using a felt-tip pen. Material now has to be removed from the heavier side by carefully thinning the blade profile using a grinder. Apply tape over the turbine bearing to protect it when using the grinder. Do not remove any extra material from the inside of the wheel, and never be tempted to drill or scrape the wheel, or work it in any uneven pattern, in an attempt to balance it. If you are using a cast wheel, as far as possible grind material from the cast-in balance ring only. On no account do anything which might weaken or disturb the ring of blades.

With a little practice you quickly obtain a "feel" for the amount of material which needs to be ground away, and you will soon have a smooth-running shaft. The method described here is quite accurate enough, and when the assembly shows no imbalance with perfectly clean bearings, the shaft is sufficiently well balanced, and is ready for use.

The compressor system

The compressor cover (1) is made first: the part is turned from solid as shown in the drawing. The critical area here is the part which covers the compressor wheel, as it needs to exhibit a constant gap 0.3 mm wide to the blades of the rotor wheel. Turn the blank to an internal diameter of 42.6 mm and clamp the inlet side in the chuck so that you can machine the correct profile. If you are using a compressor wheel other than the one presented here, obviously the diameter of the cover will have to be adjusted to suit. At this point you can start turning the required profile. Offer up the compressor

The shaft is balanced on a perfectly flat surface.

Insert the shaft and the compressor wheel, centre up the cover and mark the position of the retaining bolts. Remove the threads from the bolts where they pass through the blade ducts, and screw them into the diffuser vane bearer. The three remaining diffuser blades can now be installed: cut each one in two and fair them into the bolts with a fillet of epoxy resin.

The alternative is to machine the diffuser vanes from the solid. This is only feasible if you have access to a high-precision CNC automatic milling machine. Here again, the vanes start with an angle of 21 degrees. The radial and axial vanes are arranged in two rings. An M2 thread can be cut in the 15 radial vanes to accept the cover mounting screws, and the compressor cover then has to be modified to suit. The initial diameter of the axial vanes is 98 mm, and the vane height is a constant 6 mm.

wheel repeatedly to check where more material has to be removed. When you are satisfied, the rest of the part can be machined to the shape shown in the drawing. Don't drill the mounting holes until further components have been completed.

The diffuser vane holder (3) can now be made up as shown on the plan. Note that air ducts for cooling the bearings must be machined in at the point where the shaft tunnel meets the holder. Each duct is 5 mm wide and is located between a pair of adjacent mounting screws. The ducts should be one millimetre deep - this is quite adequate.

A small proportion of compressed air from the compressor enters these ducts, and at the same time some of the fuel-oil mixture is blown in with it. The air flows through both bearings and leaves the shaft tunnel at the rear.

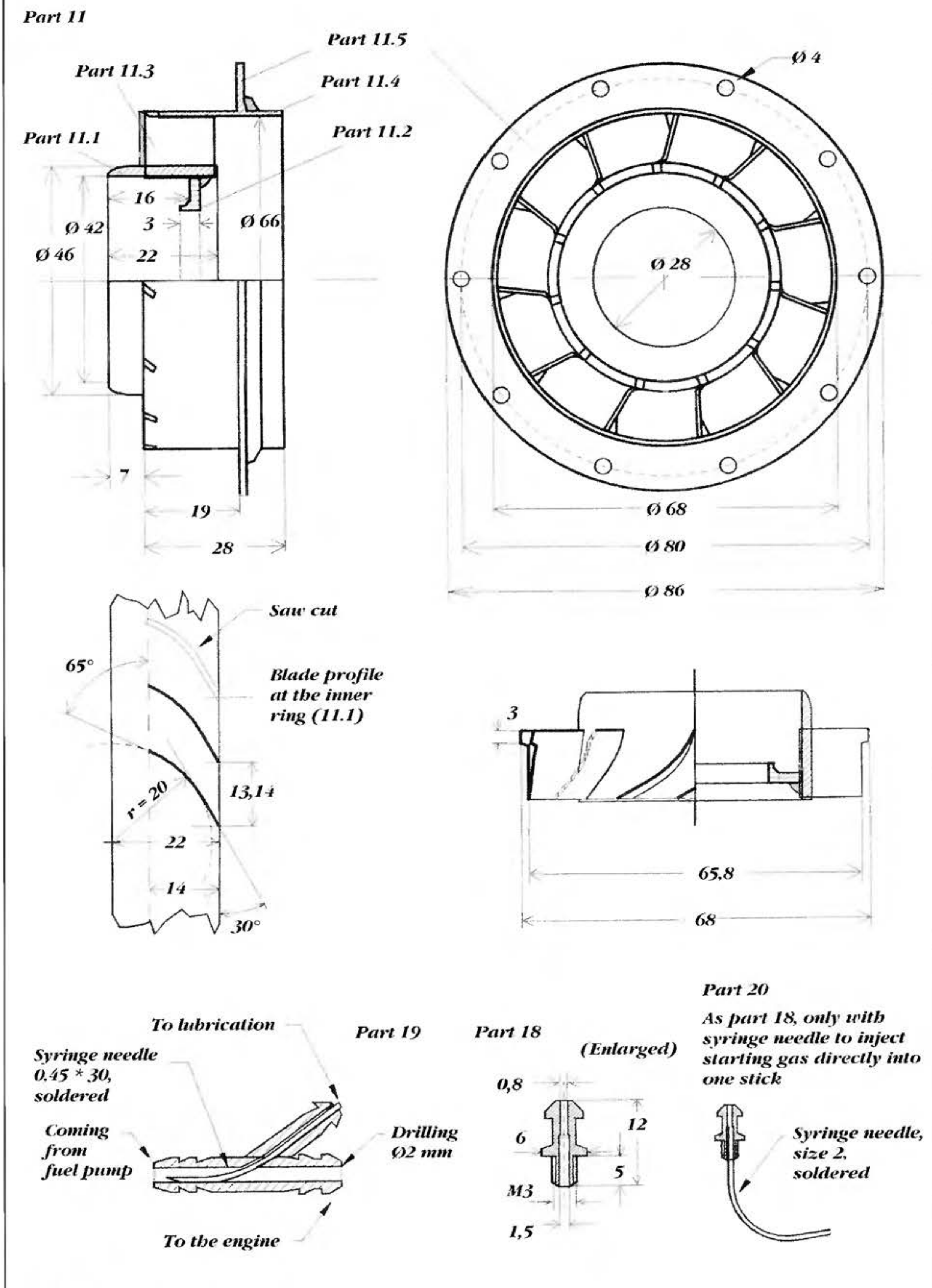
The three retaining bolts for the compressor cover are located on a diameter of 84 mm. Drill and tap (M4) these holes first. Mark the slots for the diffuser blades on the surface and saw them out using an electric piercing saw. The standard saw blades produce a slot 1 mm wide. Three of the slots should run exactly through the centre of the threaded holes. Cut out the diffuser blades (3.1) from 1 mm thick sheet metal, leaving them slightly oversize. To improve the strength of the glued joints drill countersunk holes along the joint lines before gluing 15 of the 18 blades in place using epoxy resin. For the time being don't glue the blades in the slots which coincide with the retaining bolts.

When the resin has cured the diffuser blades have to be trimmed to match the profile of the compressor cover. Screw the diffuser vane bearer to the shaft tunnel and clamp the whole assembly in the lathe so that you can cut back the blades using a file or a sharp turning tool. The region immediately behind the compressor wheel is important, and a blade height of exactly 5 mm must be maintained at this point. Any gap on the axial side between blades and casing which occurs after the point where the gases are deflected is not of crucial importance.

The combustion chamber

This is made of thin stainless sheet steel. The ideal material for this component is 0.3 mm thick sheet, and this should be used if available; otherwise you can use the more widely available 0.5 mm thick sheet. Carefully weld all the individual pieces of metal together. The front part (9.2) is pressed to shape on the lathe over a former made of hardwood or aluminium, which should duplicate the approximate shape of the front section. The minimum requirement is that the part should be cleanly cambered. The curvature of the combustion chamber cover produces a smooth, rounded geometry in the primary zone, and this helps to eliminate dead areas in the airflow, and unburned fuel is re-turbulated more quickly. The outer jacket (8) and combustion chamber inner section (9) should fit together with little play. It is important that there should be no gaps through which supplementary air could penetrate. The combustion chamber as a whole should not be too tight a fit in the nozzle guide vane system. Normally the combustion chamber components form a really rigid assembly when fitted together. Nevertheless, you can weld the parts together later if you prefer. Three sheet metal lugs can now be spot-welded to the combustion chamber jacket in order to provide additional centring for the combustion chamber in the casing.

It is up to you whether you bore the holes first then weld the parts together or vice versa. In either case all the holes which are larger than 4 mm diameter should be opened up slightly using a die and punch. This results in a nozzle-shaped hole and at the same time removes the sharp edge. For a given size of hole this allows the jets of cooling air to penetrate to a greater



Turbine nozzle guide vane system.

The inner ring of the turbine NGV system.

depth. The recessed holes should be pilot-drilled using a bit one millimetre smaller than final size, then opening up to the stated diameter. All the other holes in the sheet metal just need to be drilled with a normal amount of care.

The vaporiser tubes (8.4) consist of 6.35 mm O.D./5.55 mm I.D. stainless steel tubing (i.e. ¼" tube). Each stick is made from a 70 mm length of tube, which is first belled out at one end to 8 mm Ø. This is best done by clamping the tube in the lathe chuck and pressing a fixed centre punch into the end at moderate speed. Angle the end of the tubes slightly as shown in the construction drawing. The tubes are fixed in place as shown in the drawing: brazing is quite adequate.

The last part to make is the injector ring (10). The injector tubes are made from size 2 syringe needles. These are fitted into the injector ring tip-first, and silver-soldered in place. You can check that the injectors work evenly with a test burn using propane gas. Use a length of the same tubing as the fuel feed pipe (10.3). Braze the guide (10.4) in one end. Finally the fuel line connecting piece runs through the casing and out of the engine. A suitable hose nipple is then fitted to the end, sealed with teflon tape. The injector ring is tied in place using Inox wire (from builders' merchants). You will need to drill holes in the rear section of the combustion chamber to take the wire. The injector needles should be bent in such a way that the fuel flows on to the wall of the vaporiser tubes.

The shaft is made from a high strength socket-head car screw, M16 x 180.

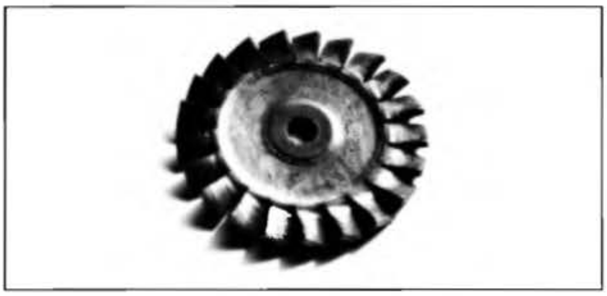
Blades and stabilisers welded together.

The housing

The best material for the jacket is thin stainless steel sheet, which should be soldered or spot-welded. Ordinary steel sheet is also adequate for the jacket, but the result is not so elegant. Only the tail end (15.2) needs to be made of stainless steel sheet, and this part can be spun out of one piece on the lathe. The outcome is a very good-looking, smoothly rounded casing which is extremely rigid. The easiest method of forming the part is to make an aluminium former for it; it does not need to conform to a particular shape or radius. The tail end should be as tight a fit as possible in the jacket, as this ensures that the spot-welded or soldered joints are easy to produce. It is helpful to anneal the metal during the spinning process. The obvious alternative is to make the component from three parts, each of truncated conical shape.

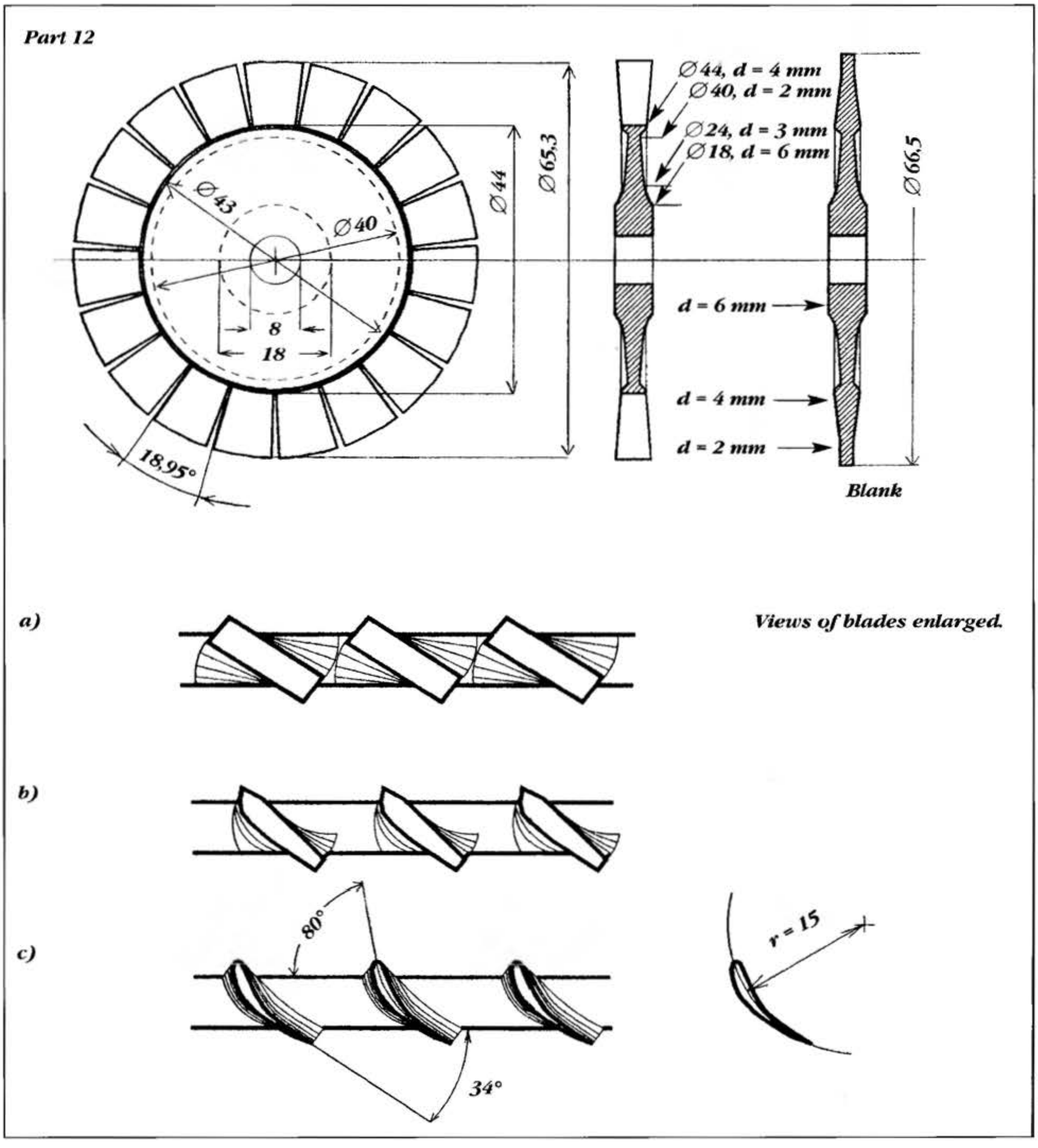
Initially it is advisable to make the casing two millimetres longer than stated, to give you scope for correcting any inaccuracies. The casing jacket (15.1) should not be too tight a fit on the compressor cover (1). Cut a suitable hole in the rear part of the casing to accept the fuel feed line, and install a pressure take-off nipple (18) in the tail end. Unused nipples do not need to be sealed when the engine is running, as their cross-sectional area is small. The supply line for auxiliary gas should also be

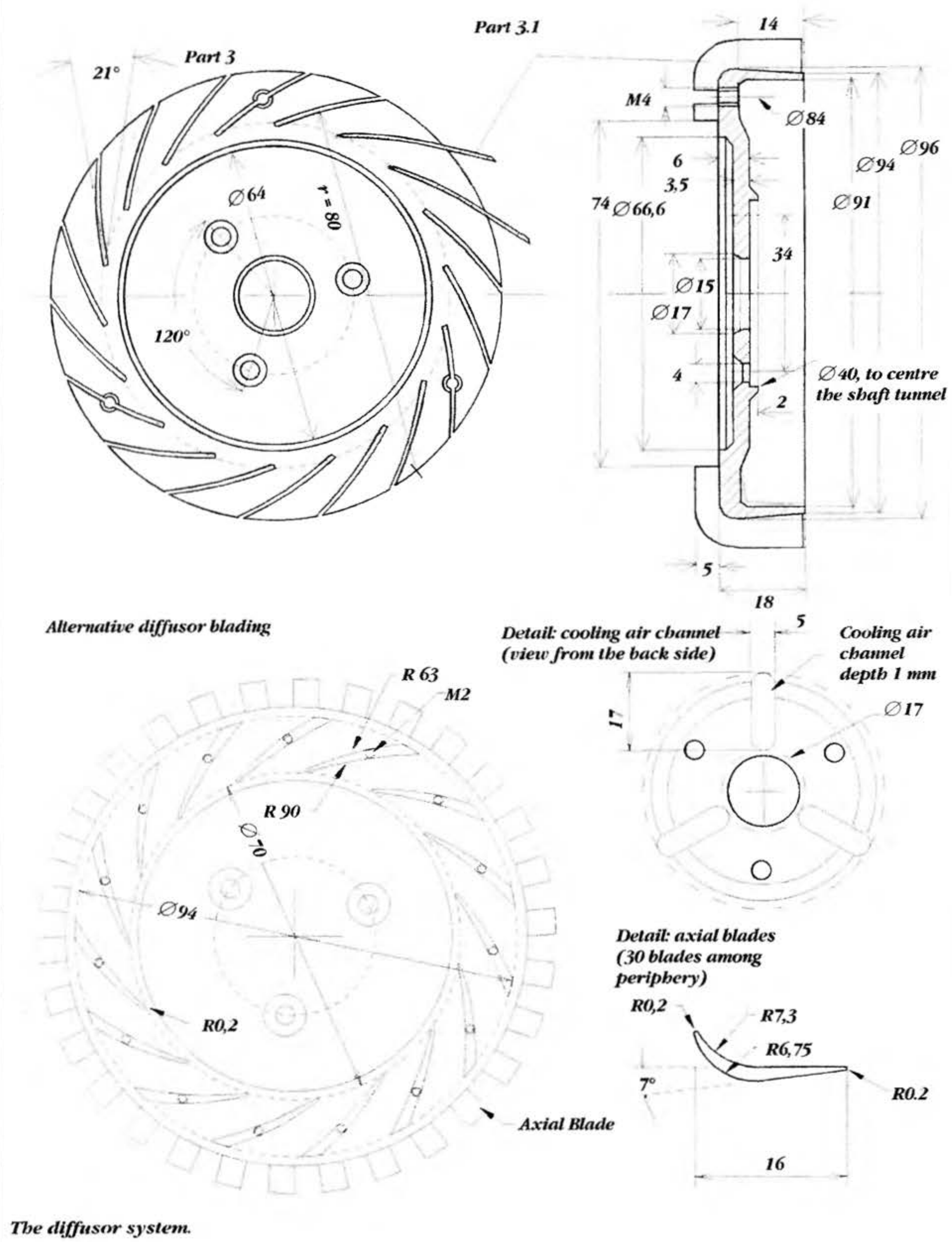
The rear of the engine with the shaft removed. The shaft tunnel locator is clearly visible.



A half finished turbine wheel. The version with 21 blades also worked well, but failed owing to my carelessness.

The rotor of the Micro-Turbine.





The diffusor system.

fitted at this stage. When you assemble the engine the needle should project exactly into one of the six sticks. If you have made the casing of ordinary steel, you should finish it with heat-resistant paint once assembled, and cure the paint according to the manufacturer's instructions.

The diffuser flange at an early stage.

The completed compressor diffuser system.

Assembling the components

The individual components are assembled as shown in the construction drawings. The shaft tunnel, compressor diffuser system, rotor and cover form one subassembly. The compressor cover is attached using three self-locking nuts which should be tightened no more than hand-tight. It is important that the compressor rotor should be exactly central when you have tightened these nuts. The shaft can be withdrawn from the rear together with the turbine wheel and bearing, leaving the compressor wheel, spacer disc and front bearing in the compressor.

The nozzle guide vane system and the engine housing are also permanent fixtures. When assembling the engine you should seal the flange with several layers of aluminium foil folded together. Tighten the ten screws carefully, working alternately from side to opposite side, like the valve cover bolts on a car engine. Insert the combustion chamber in the housing and secure the fuel pipe by screwing a hose nipple in place. This method of retention is very simple but quite adequate, since the combustion chamber itself is located by the nozzle guide vane system. When assembling the parts it is important to ensure that the auxiliary gas feed tube projects correctly into one of the vaporiser tubes.

You can now fit the compressor in the housing complete with the shaft tunnel. Twist a length of teflon tape to form a cord, and lay the cord in the channel machined in the compressor cover. However, a good alternative is to use a small rubber band. When placed in oil the rubber swells slightly and provides a reliable seal. Wrap a layer of insulating tape over the outside. Insulating tape is quite sufficient for initial experiments at low pressure.

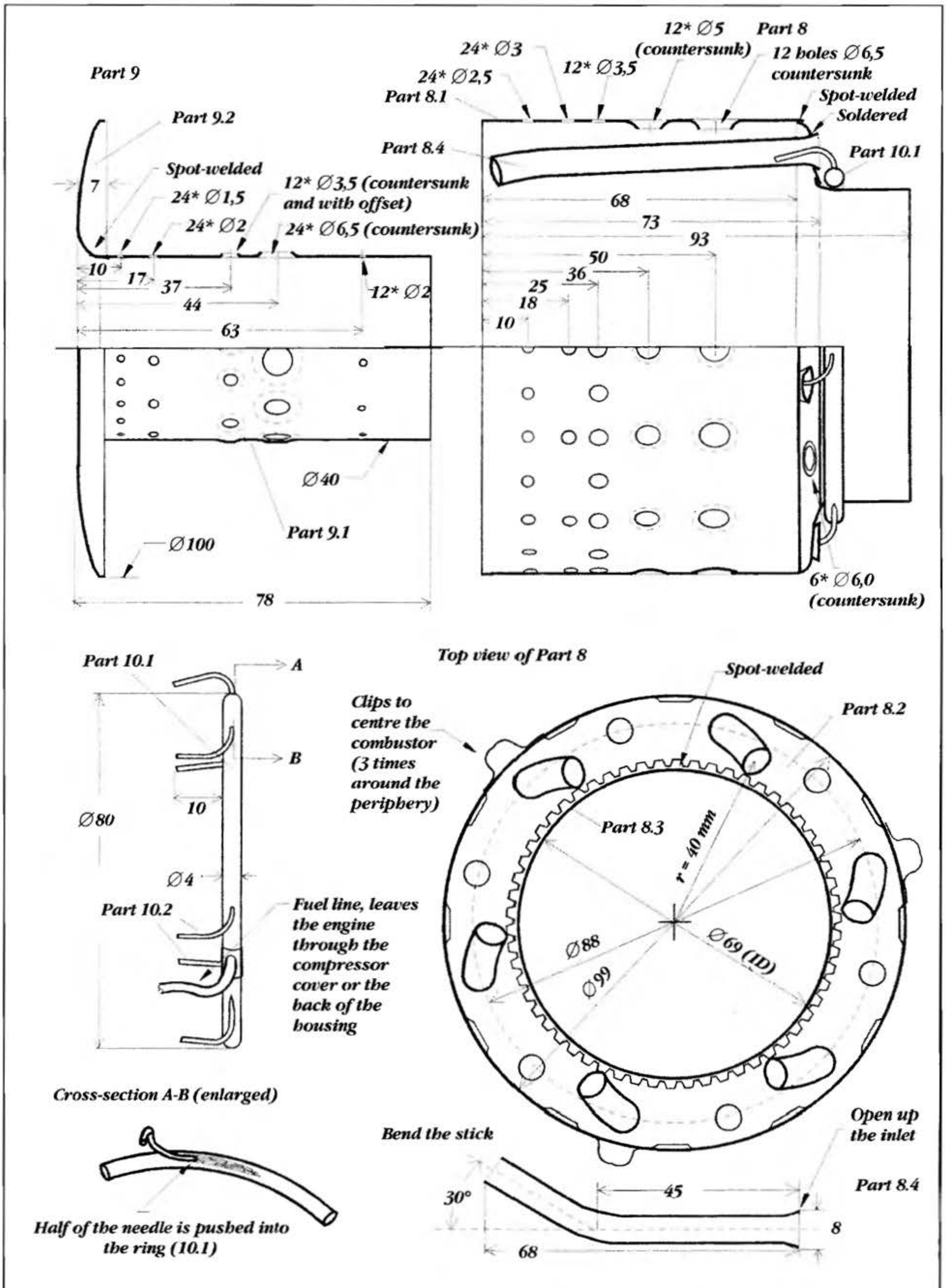
The next step is to fit the shaft/turbine wheel assembly into the engine from the rear. Use a feeler gauge to check that the running clearance is an even 0.25 mm. Screw the compressor on the shaft, but leave it only hand-tight for the moment. You will find that you quickly get used to the left-hand thread. The last stage is to install the thrust nozzle. Two or three screws in the flange of the nozzle guide vane system are sufficient to hold the nozzle in place. The screws or studs should be fitted in such a way that plenty of thread projects at the rear.

Combustion chamber components and fuel manifold.

When you dismantle the engine, the first stage is to remove the shaft towards the rear. The engine is now ready for its first run, without its thrust nozzle and bearing loading spring.

Running the engine for the first time

Initial test runs of your new model jet engine should be made using propane gas. Propane is ideal for testing since it burns well in the combustion chamber and is easy to meter. If possible use a 5 kg propane bottle in conjunction with the matching solder gun attachment. Smaller bottles and gas cartridges will give you problems starting your turbine; the system must be capable of supplying full gas pressure. Fittings for camping apparatus are just not up to the job. Run the gas to the kerosene feed connection. To start the engine you will also need a starter fan or compressed air. In fact you can set the rotor spinning just by blowing into it, but this does take a little practice. The more powerful the airflow, the more likely it is that your first attempt at starting will be successful. Vacuum cleaner fans have proved excellent starters. Other equipment you will need includes a U-tube filled with water to measure compressor pressure. This should be connected to an unused pressure nipple in the housing. One centimetre of water column corresponds to one millibar, i.e. 0.001 bar. Obviously an oil



Combustion chamber.

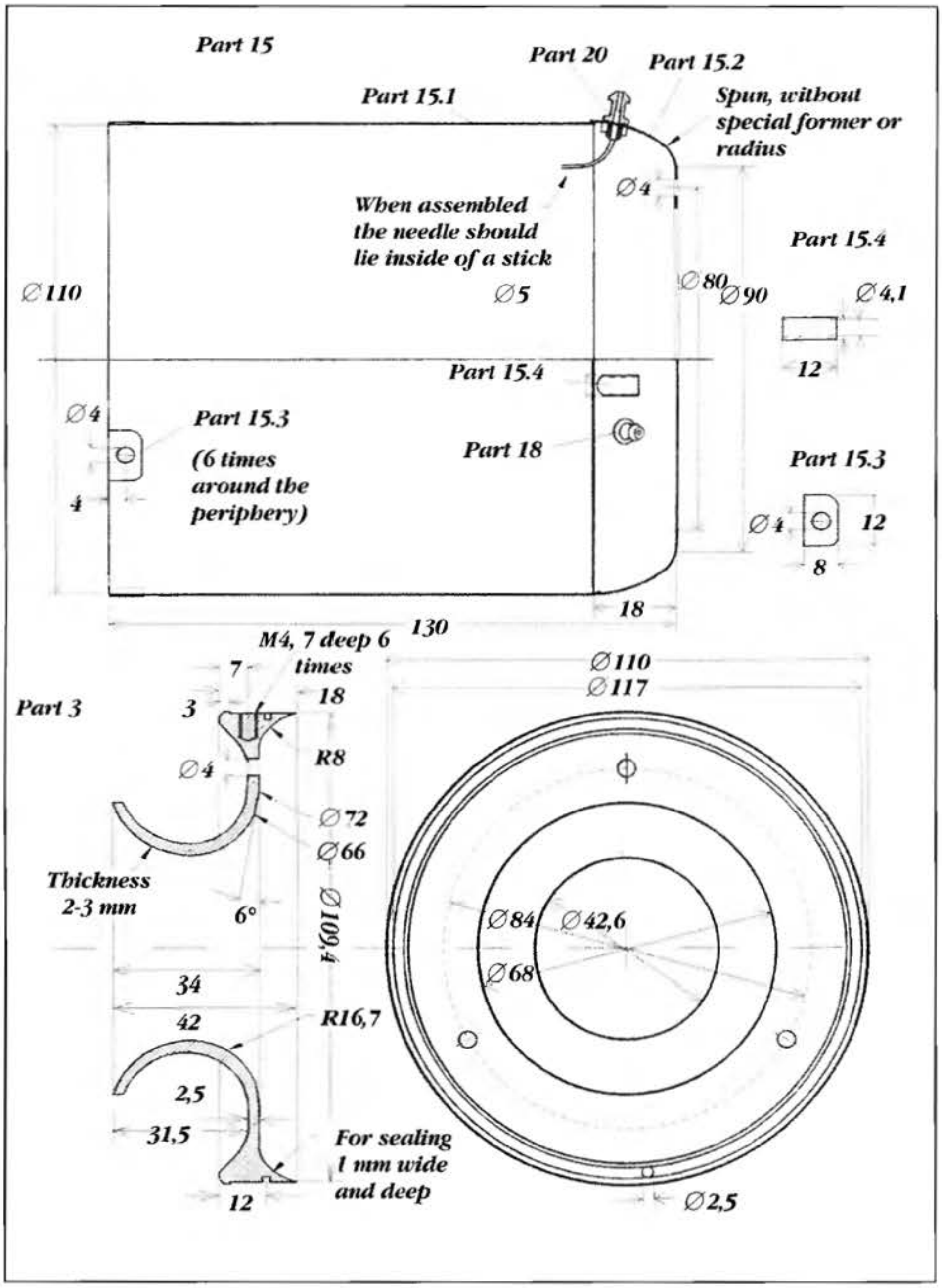
supply must be provided to the bearings. Pour about 20 ml of bicycle oil or sewing machine oil into a small pressure tank with a dip pipe. This in turn is connected to the engine's housing pressure via a second connection, so that oil is automatically pumped into the lubrication system. A plastic bottle with a screw cap makes a good oil tank. This temporary oil system will be dispensed when the engine is run on kerosene.

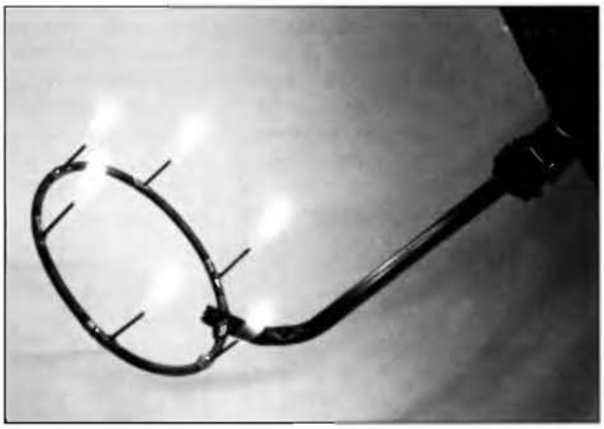
Mount the engine on a base in the open air using two mounting straps made of thin sheet steel. You don't need a thrust gauge at this stage. Connect everything to the engine: oil, pressure gauge and finally the propane. Ask your assistant to stand behind the engine so that he can observe the turbine wheel. During the starting procedure it should not glow brighter than cherry-red.

The actual starting procedure is simple: use the starter's airflow to set the rotor spinning, then take the fan away, open the throttle slightly and light the gas mixture at the exhaust with a match. The flame should run back into the combustion chamber with a characteristic "plop" sound, at which point you should immediately open the throttle a little further and switch the fan on again. You will clearly see and hear rotational speed and pressure rise. If everything is in order and the housing pressure produces at least a 30 cm column of water, you can safely switch off the fan. The engine should now run with a quiet whistle, the tips of the turbine wheel blades glowing dull red. If vibration occurs or one of the wheels is audibly fouling the casing, cut off the gas supply immediately in order to avoid damage. You now have to establish the cause of the problem and eliminate it. If the shaft runs freely and without vibration but the engine still does not work, there are a number of points to check. The blade profile in the nozzle guide vane system and on the turbine wheel must be reasonably accurate, and this should be checked. Another possible problem area is the combustion chamber. If it is obvious that the temperature distribution is very uneven just by looking at the engine, or if flames are visible, then you should check over the combustion chamber in general, paying particular attention to the injector ring. Don't attempt to run the engine on kerosene until the engine runs satisfactorily on propane gas.

Bench running stand for kerosene operation

You will need a stable test stand to run up the engine to maximum rotational speed. This should be designed for running the engine on kerosene, i.e. it must be fitted with a suitable fuel metering system. Please read the chapter on safety before you carry out any test runs with kerosene. In particular, ensure that nobody is standing in the rotational plane of the rotating parts before the





The injector ring being tested on propane gas.

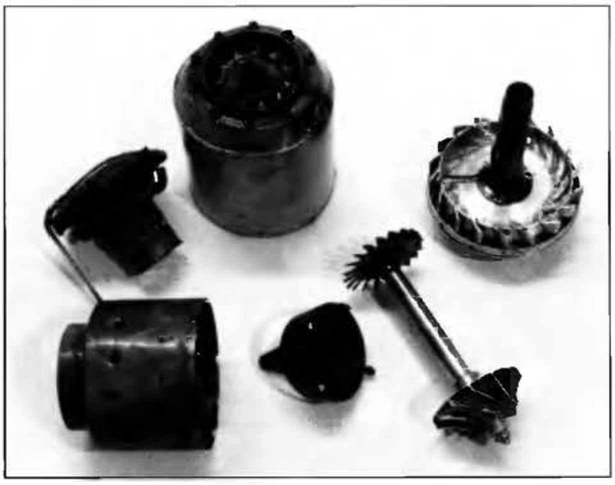
engine is first run up to speed. The safe places to stand are in front of and behind the engine.

Pumps, tanks and other equipment

The test stand should be fitted with a fuel tank of generous size, i.e. a capacity of about one litre of liquid. It must also be resistant to petrol, diesel fuel and kerosene. A plastic lawn mower tank works very well for our purposes. Fit a fuel filter between the tank and the pump. Car petrol filters and the larger types of model engine filter are equally suitable. The fuel pump should be of the geared variety. Various examples are available commercially, but unfortunately not all pumps are resistant to kerosene. As a general rule we recommend brass-geared pumps, and the Kavan version in particular has proved to be a good choice. This is only available with a 12-Volt motor, but even with seven cells it provides plenty of injector pressure. To control the pump we use an electric flight speed controller or an adjustable regulated voltage power supply.

There must be a fuel valve between the fuel pump and the engine, and the valve must provide reliable and fine control. Air valves designed for aquarium use are very good, and you will be able to obtain suitable hose material from the same supplier. A cheap and simple solution to the fuel hose problem is PVC tubing, which resists jet fuel well. This type of hose incorporates what is

A converted vacuum cleaner makes an excellent starter fan.



The engine can easily be dismantled into a small number of components.

known as a plasticiser, but in the course of time the kerosene washes it out of the material. As a result the hose hardens after a few months, but this only seems to make the material stronger, if anything.

Kitchen scales mounted on the test stand are the easy way to measure the engine's thrust, and you will need a pressure gauge. The pressure gauge is connected to the vacant pressure nipple on the engine housing. It needs a measurement range of up to 1.5 bar, and since its accuracy has implications for the safe running of the engine, we recommend that you check that it gives a realistic reading. The model jet engine itself should be mounted on a carriage fitted with worn-out ballraces as wheels. The other hose connections to the engine will make hardly any difference to thrust readings. As soon as the engine is producing substantial levels of thrust the carriage should be secured to the test stand with a chain,

This starter was made from the remains of a car vacuum cleaner. it is not very powerful, and has to be placed directly against the engine in order to start it.

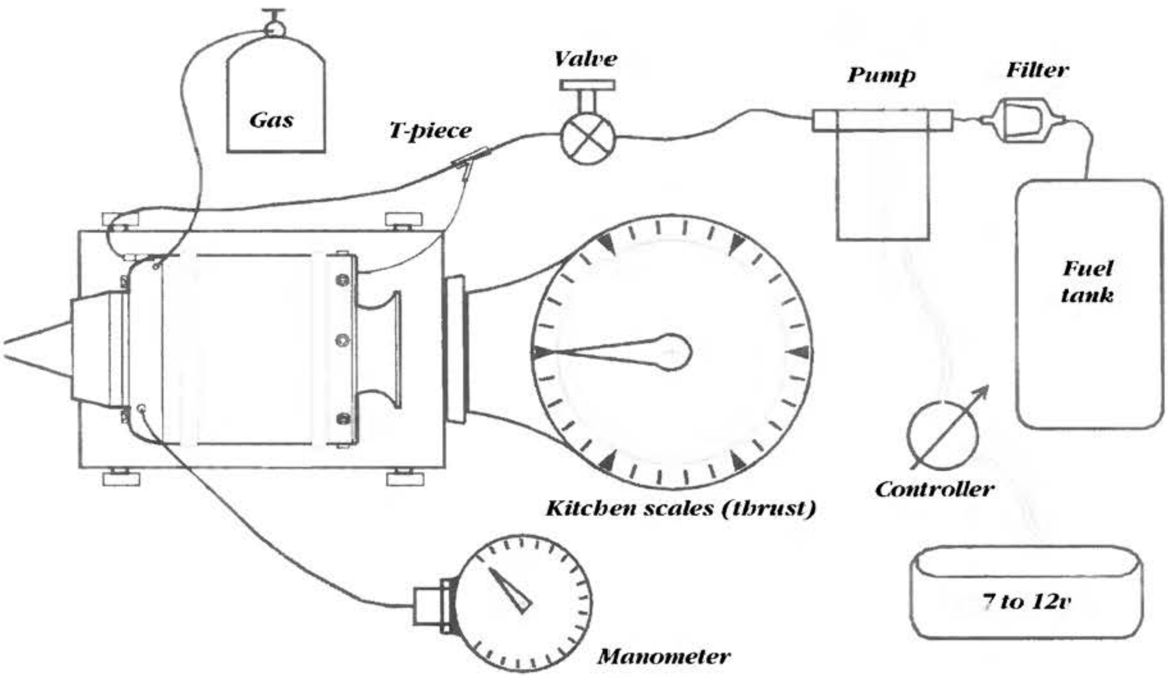


Diagram of the engine connections on the test stand.

as we don't particularly want to see the engine cartwheeling across the meadow.

Running the engine on kerosene

When a jet engine is running on kerosene you should be aware that its rotational speed is solely dependent on the metering of the fuel. There is simply no such thing as a jet engine's maximum rotational speed. What this means is that it is quite easy to exceed the maximum permissible speed by being careless. If the power rises to this extent the usual result from the engine is that the turbine blades distort and foul the casing. It is vital that you monitor the housing pressure by keeping one eye on the pressure gauge, or, if you have one, the rev counter. Later on, when the engine is installed in a model aircraft, the power of the injector pump has to be restricted to exclude the possibility of the engine "running away".

The next step is to fill the fuel tank with Jet A1 kerosene. To lubricate the bearings add 30 ml of two-stroke oil to each litre of kerosene. If you cannot obtain kerosene, diesel fuel can also be used. The lubrication feed is completed using a T-piece connected with transparent tubing, so that you can see directly whether the system is working properly. A good material is the PVC hose used to actuate retractable undercarriages. Once everything is wired up as shown in the diagram, you can start the turbine. The first step is to connect the propane to the appropriate nipple on the casing. Switch on the starter fan and ignite the engine as previously. As soon as the flame is alight in the combustion chamber, start the fuel pump and carefully open the metering valve. The turbine's speed will now rise rapidly. At the same time the pressure gauge starts to deflect, and the carriage runs against the thrust gauge. The fan and the starting gas are now no longer needed. Open the fuel valve to the point where the housing pressure rises to at least 0.1 bar. This pressure corresponds to a rotational speed of slightly more than 35,000 rpm. The idle speed of the engine should be set to this value.

The engine can now be slowly run up to speed. As with the initial test runs it is important at this stage to observe the turbine wheel using a mirror. Normally the

The test stand after a test run. Friendly relations with the owner of the field are essential.

The Micro-Turbine running almost at full throttle on the test stand.

model jet engine is just as simple as starting a good model piston engine.

General instructions for different compressors

The desire for power and then more power is omni-present amongst modellers. If you want to increase the engine's thrust there are two possible approaches:

Making the existing engine more powerful, or simply building a larger version. In my opinion the latter route probably offers the better prospect. At least in theory we could squeeze a little more power out of the engine presented here - by raising the gas temperature and the rotational speed - but this would undoubtedly require more complex technology which would take the engine well out of the scope of the amateur workshop.

The following section gives details of the essential dimensions and cross-sectional areas relating to model jet engines. This information should enable the modeller with prior experience of jet engines to build a model jet engine based on any turbocharger rotor. This approach exploits the fact that most compressor wheels of this type usually exhibit similar geometry, and therefore their characteristic values are also similar. Of course, the formulae stated here cannot be expected to coincide exactly with the throughputs and pressures produced by different wheels. For this reason I cannot guarantee that the gas turbine you make will necessarily work. That is why I added the caveat "with prior experience" when I mentioned the possibility of building a larger engine, so that the constructor has a fighting chance of correcting any mismatches. If you are lucky enough to have access to a performance graph relating to the turbocharger compressor in question you should naturally base your calculations on this valuable information.

Turbocharger wheels of suitable size are used in lorry engine turbochargers, and individual components may be obtained from engine repairers or lorry scrapyards, and can even be purchased as replacement parts for turbochargers. Wheels with retro-curved blades are always preferable. The crucial dimensions are the blade height h at the wheel outlet and the wheel diameter d2. The higher these figures, the higher the throughput and the higher the thrust.

We strongly recommend that the modeller should base his design on all the dimensions shown in the drawings, including those declared to be critical. For example, if you use a 90 mm diameter wheel you would use a scale factor of 90/66 = 1.364. The diameter of the holes in the combustion chamber should be increased

exhaust temperature falls as rotational speed rises, and eventually no glow will be visible. Engine speed can now be increased successively over the course of several runs, remembering to check the engine briefly every time you start it, and to listen for unusual noises. If your turbine is made of stainless steel, the maximum housing pressure should not exceed 0.7 bar. With other special heat-resistant materials you should call a halt at a maximum of 1 bar to preserve the bearings, as this figure corresponds to around 105,000 rpm at standard temperature and pressure.

Once you have completed a few test runs, starting the engine becomes purely a matter of routine. The important point is to acquire a feeling for when the fan is needed, and when the turbine is able to run up to speed under its own power. With a little practice starting a

Even at a compressor pressure of 0.85 bar the thrust gauge is almost at its maximum.

FORMULAE FOR CALCULATING SIMILAR MODEL ENGINES

Table of critical diameters and angles

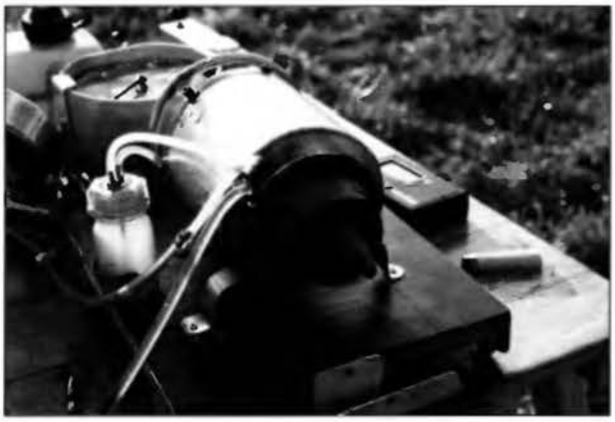
Compressor type:	
Retro-curved rotor blades	**Radially tipped rotor blades**
Given: d_2,h	Given: d_2,h
$d_3 = 1.12 \times d_2$	$d_3 = 1.1 \times d_2$
$d_4 = 1.67 \times d_2$	$d_4 = 1.7 \times d_2$
$\alpha = 21°$	$\alpha = 18°$
No. of blades = 18	No. of blades = 18
Combustion chamber, scaling factors	
For holes	**For holes**
$f = \sqrt{(3030 \times d_2 \times h)}$	$f = \sqrt{(2600 \times d_2 \times h)}$
No. of hooked tubes $[18{,}200 \times d_2 \times h]$	No. of hooked tubes = $[16000 \times d_2 \times h]$
Turbine NGV system	
$\mathbf{d_a = d_2}$	$\mathbf{d_a = d_2}$
$d_i = \sqrt{(d_2^2 - 6.8 \times d_2 \times h)}$	$d_i = \sqrt{(d_2^2 - 5.3 \times d_2 \times h)}$
$\alpha_{ngv} = 30°$	$\alpha_{ngv} = 30°$
No. of blades 11 or 13	No. of blades 11, 13 or 17
Turbine Wheel	
$d_a = d_2 - 2 \times Gap - 0{,}99 \times d$	$d_a = d_2 - 2 \times Gap = 0{,}99 \times d_2$
$d_i = \sqrt{(d_2^2 - 7.2 \times d_2 \times h)}$	$d_i = \sqrt{(d_2^2 - 5.8 \times d_2 \times h)}$
$\alpha_{Wheel} = 34°$	$\alpha_{Wheel} = 35°$
No. of blades 19 or 21	No. of blades 21 or 23

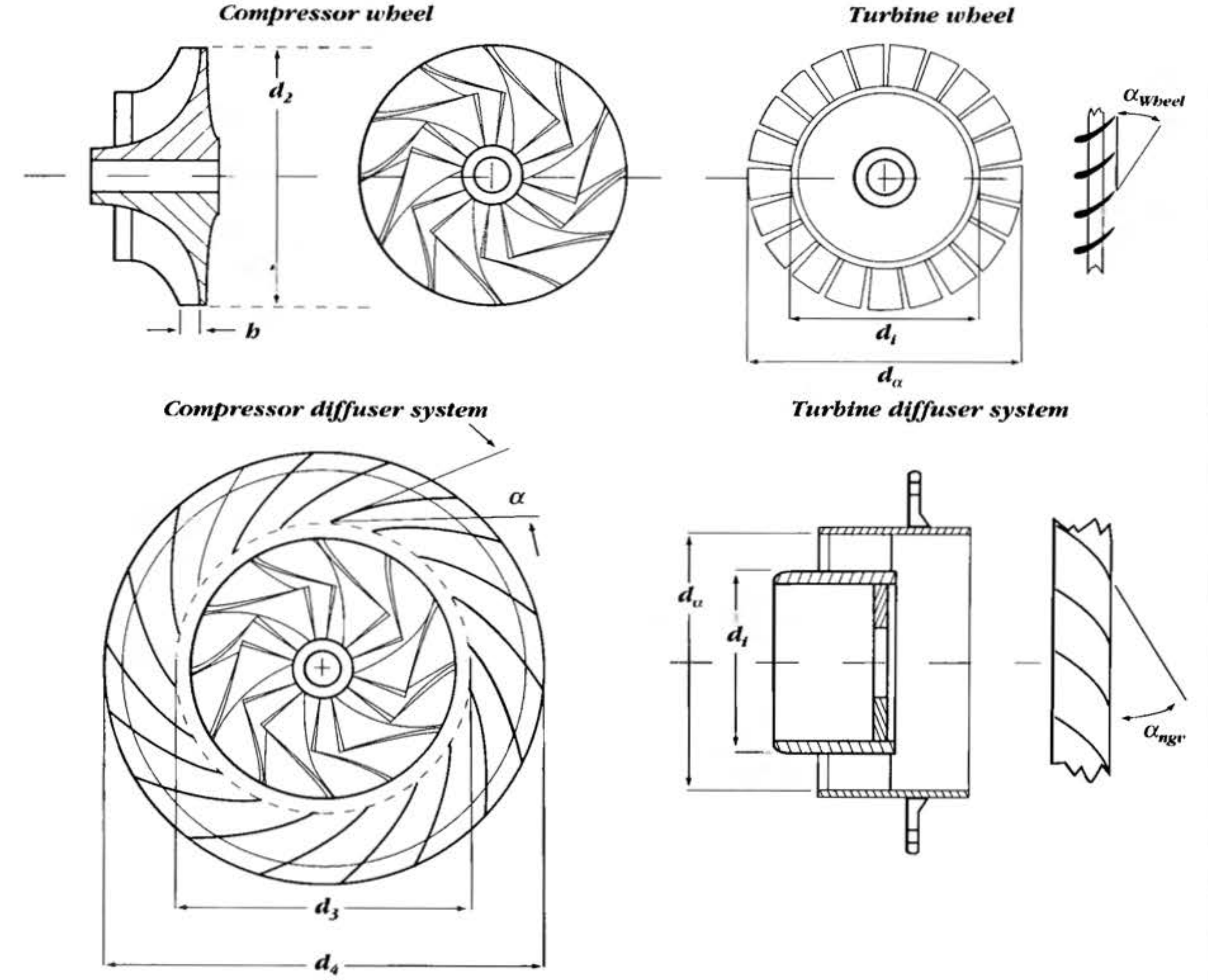
by the factor stated in the formula, although the number of holes can be left unchanged. Only the number of "walking sticks" and air jets needs to be calculated separately, using the stated formula. The geometry of the hooked pipes and the air jets can be left unchanged. You can expect a rise in thrust of at least $1.364^2 = 1.86$ times provided that the compressor wheel is of similar geometry. Since the efficiency of larger wheels is significantly higher you might expect a thrust of more than 60 Newtons. If you can achieve a reduction in exhaust gas temperature you can even use a convergent exhaust cone.

All data should be stated in the same units, i.e. metric units. The formulae listed here are based on an engine with a nominal peripheral speed of 300 m/s.

The maximum rotational speed will be lower, again by the scale factor we have calculated. In our example, if a special heat-resistant steel is used for the turbine, it will be 104,000/1.364 = 77,000 rpm, and correspondingly less if the turbine material is of lower quality. If you run the engine at a higher speed it is essential to re-calculate the shaft's bending critical speed. Many compressor wheels feature reinforcements on their rear face. As a result they are high in mass and their centre of gravity is in an unfavourable position. To achieve a sufficiently high bending critical speed it would then be necessary to use a correspondingly thick shaft and bearings. Under no circumstances is it permissible to make modifications to the wheel itself, as this would have a serious effect on its ability to withstand high rotational speeds.

The Micro-Turbine at moderate rotational speed. You can see that there is nothing to see. The exhaust gas temperature is 550°C – so low that the turbine wheel is not glowing and no flames are visible.





Geometrical data related to formulae taken from general instructions.

Optimising the performance of model jet engines

In this section we will consider all the techniques we can try in order to make a small gas turbine even more powerful. All this information is based on the assumption that the system already works, and you have already gained some experience in handling the jet engine.

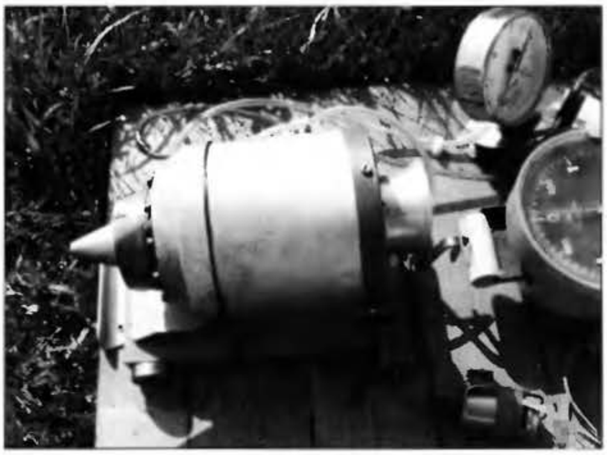
There are two basic methods of increasing a jet engine's thrust – at least in principle: increasing the maximum rotational speed and raising overall efficiency, so that more enthalpy is available to produce thrust. Increasing engine speed presents problems. For a brief period any model jet engine will certainly cope with higher speeds, but the inevitable result is a considerable shortening of its useful life. Usually it is the bearings and the turbine wheel which are affected in this way. Therefore it makes sense to limit ourselves to improvements in efficiency.

The best indicator of the overall efficiency of the rotor system, including that of the compressor and the turbine and mechanical losses, is the exhaust gas temperature.

Any improvements in the engine can be monitored simply by measuring the exhaust temperature. If you manage to reduce the gas temperature to below 600° C, you can exploit this to produce thrust by narrowing the exhaust cone. This raises the temperature again slightly, but the engine's efflux speed rises, and the result is more thrust.

In our experience you can expect the greatest improvement in the running characteristics of a model jet engine by optimising the combustion chamber. The Hot Spots, which manifest themselves as small areas of the housing glowing ominously, should be systematically eradicated. For the same reason you should use a thermometer to attempt to pin-point areas which are particularly cold, i.e. where the gas is doing almost nothing to push the turbine round, and make efforts to eliminate them. The best method here is to adjust the curvature of the hooked pipes using a pair of pliers, and then re-test the system. A test run with propane gas is usually adequate for this purpose.

How the hooked tubes should be curved, and in which direction, depends on the circumstances in your particular engine, and the only way to find out is to experiment. If you use a combustion chamber with a tubular vaporiser coil, as shown in Kurt Schreckling's drawings, you can use his method of combating hot



The engine with a short exhaust cone. The slightly larger cross-sectional area means that the efflux speed at full throttle was only about 230 m/s.

The Mini-Turbine after optimising the exhaust cone. It proved possible to increases the engine's thrust by about 10% whist maintaining an approximately constant exhaust gas temperature.

spots, i.e. adjusting the air inlets in the combustion chamber and narrowing the injector openings with wire. You can congratulate yourself on building a good combustion chamber if the maximum variation in the average exhaust gas temperature is less than 100°K. You cannot improve the quality of a combustion chamber by drilling additional holes at random points. Quite the contrary: combustion chambers with too large an opening area usually refuse to work at all.

Another method of improving efficiency is to work as accurately as you possibly can when constructing the engine. This applies in particular to those areas of the engine where gas flows at high speed. The compressor diffuser system is especially critical in this respect. The transition from the compressor to the fixed diffuser vane bearer should be as smooth and even as possible. The diffuser blades should taper to a point front and rear and should all begin at the stated angle. Polishing the compressor does not help matters. On the one hand the surface soon loses its shine due to sucked-in oil residues and dust, and on the other a healthy degree of roughness helps to prevent the airflow becoming detached.

In the turbine area a further significant improvement in efficiency can be gained by reducing the running gap of the turbine. However, if the gap width is less than 0.25 mm you have really done all you can. In fact the turbine wheel itself offers greater potential, and the turbine expert can aim at an improvement in airflow deflection by making the base of the turbine blades thicker. However, making such a wheel is not for the faint-hearted.

Checking the match between the turbine and the compressor is a sensible aim, but it is difficult to do accurately and in any case is only possible within certain limits using amateur equipment. The aim is to discover whether the rotor wheels are operating close to their optimum efficiency. This generally requires the use of sophisticated test stands to record the characteristic curves of the compressor and turbine. However, gross errors in matching the wheels in a model jet engine can be picked up easily once you have gained a little experience. A small sheet metal flag can be used to check the direction of the gas flowing out behind the turbine wheel. A minor swirl angle of up to 15° in the direction opposite to turbine rotation is normal. A greater reverse swirl usually indicates too great a reaction level. Narrowing the cross-section of the turbine nozzle guide vane system whilst enlarging the rotor cross-section should then remedy the situation. Both effects can be achieved by modifying the blade height or the blade angle. If there is a residual swirl in the direction of rotation the opposite remedy is appropriate. Minor experimental corrections can be carried out by bending the blades with pliers. Usually just a few degrees makes all the difference. If you wish to obtain an overall idea of the flow conditions inside your engine it may be helpful to plot the vector diagram of each stage.

If you complete the optimisation procedures outlined above and thereby succeed in reducing the exhaust gas temperature significantly, you can exploit the engine's extra potential by fitting a slightly narrower exhaust cone. This increases the outflow speed and thrust, although you have to take into account the inevitable residual swirl of the gases and the turbulence behind the turbine wheel.

If at all possible, it is best not to reduce the outside diameter of the exhaust cone to avoid the gases accelerating in the direction of the swirl, as the result would be an effective narrowing of the cross-sectional area due to the non-axial throughflow of the cone, and a resultant rise in gas temperature. A more sensible option is to narrow the nozzle by enlarging the inner cone. Once again you will have to resort to experimentation, and in any case you should not allow the maximum exhaust gas temperature to rise above 650° C at full throttle.

Chapter 3

The Engine in Practice

Safety: the First Commandment

In principle model jet engines are safe power plants which can be considered as general-purpose model engines. A piston engine has an integral hazard in the shape of a whirling propeller, but all the rotating parts of a jet engine are safely hidden inside the housing. This eliminates one very typical modelling injury at the outset. Nevertheless, the engine's revolving parts do represent a hazard, and a number of basic rules must be borne in mind when you are building and operating this type of power plant. Every engine fitted with an airscrew is supplied with a dire warning about standing in the rotational plane of the revolving parts, and every propeller comes packed with a similar note of caution. It is simply very dangerous to stand in that position under any circumstances, and the same applies to the model jet engine. Any particle sucked into the engine, or – worse still – a fractured turbine blade always flies off to one side of the engine. You should therefore never bend over the running engine or allow spectators to stand in the hazardous zone – especially if the engine is an experimental unit. If this is not possible, then the model jet engine must not be run at high rotational speed. The safest places are in front of the engine and behind it.

Another important point is that model jet engines must be firmly mounted when they are being run. Keep the immediate environment in front of the intake opening free of dirt, tools and other small items at all times, as these engines develop considerable suction power and happily suck in all possible rubbish, with blade damage the usual result.

Jet engines should only be run in the open air. It is true that kerosene is very difficult to ignite with a flame, but on the other hand fuel-soaked balsa wood burns wonderfully well. It is essential to keep a fire extinguisher or at least a fire blanket to hand at all times. Carbon dioxide extinguishers have proved a good choice in practice since they usually cause no damage to the model. If there is a fire risk in hot, dry Summer conditions – don't fly your jet model.

The most dangerous characteristic common to all jet engines is their tendency to "run away", or run out of control up to an excessive speed. In principle these engines have no natural maximum rotational speed. If the throttle is opened without restraint any gas turbine will accelerate until some component or other cannot withstand the stress and fails. In model jet engines the weakest component is generally the turbine wheel. If the engine is already running close to its maximum speed it does not even matter in what form the fuel reaches the turbine. Even liquid kerosene sucked into the compressor will be burned.

You, the modeller, must be aware of this fact, and operate the power controller with a corresponding degree of caution at all times. The fuel supply system should be designed in such a way that it is impossible to feed a significant excess of fuel to the engine. When installed in a model the engine must be limited reliably to its maximum safe rotational speed. The voltage of the fuel pump battery should be no higher than is necessary.

One problem in this regard is the process used to start jet engines. Any fuel which is not immediately ignited tends to collect in the housing, and when the engine first runs up to speed the excess fuel burns, and the engine "runs away". For this reason a flooded jet engine must be tipped "on its nose" before any further attempt at starting, so that residual fuel can run out. Care is also called for when you switch types of fuel. Geared pumps operate at much higher pressures with viscous diesel oil than they do with petrol or kerosene.

The following points should also be taken into account if you are running your own, home-built engine: the rotor wheels must be fixed securely on the shaft; there must be no danger at all of them coming loose. The only way of ensuring this with a right-hand rotation engine is to use left-hand threads. Self-locking nuts and/or locknuts are just not up to the job! As soon as the rotor system starts vibrating the solid connection between compressor and drive shaft will tend to loosen. If the compressor wheel comes adrift, the immediate reduction in load causes the turbine and shaft to accelerate, and in a fraction of a second they are spinning at a dangerously high speed.

The turbine wheel itself should always be made from a perfect, unblemished sample of sheet steel, which should have the highest possible resistance to high temperatures. This should guarantee that you are using fault-free material. If you are using a cast wheel, you can only enjoy this sense of security if the casting material has been approved specifically for gas turbines, and if the wheel itself has been checked. If you are not sure, under no circumstances should you use the component. Cavities, bubbles and casting faults can result in the whole wheel bursting, which could easily be the cause of a fatal accident. Nickel-based alloys in sheet form and high-alloy nickel-chrome steels are outstandingly tough materials, and before the material actually fails it expands considerably. This means that over-revving the turbine causes the whole wheel to expand, at which point the blades foul the housing and jam the rotor. As a result rotor wheels made of these tough steels have, within certain limits, a built-in safety margin. In my experience to date any blade fractures that have occurred have been a result of mechanical problems, and are completely unspectacular in nature. Individual broken blades have no chance of breaking through the turbine casing, although this only applies if you ensure that the turbine's rotational plane coincides exactly with the mounting flange which acts as containment. This is your responsibility when you are building the engine.

Measuring the engine's performance data

If you wish to optimise the performance of a gas turbine it is essential that you gather its basic thermodynamic data. You cannot hope to carry out sensible modifications until you have an accurate idea of what is actually happening in the model jet engine. Thus the systematic recording of all operational data acts both as an aid to you and as a means of monitoring progress. The main problem for the amateur when trying to keep track of this ever-changing data is the limited equipment in his workshop. Even so, if you are as accurate as you can be when measuring pressure, temperature and thrust you can make reasonable deductions regarding the actual gas flow inside your engine. Some of the thermodynamic data, such as pressure ratio and exhaust temperature, can be measured directly; others - such as efflux speed and mass throughput - can only be calculated.

Rotational speed, pressure and thrust

These are the fundamental data for a model jet engine, and they can all be measured directly. A set of scales for measuring thrust and a pressure gauge to check housing pressure should be available on the engine test stand at all times, and they should be monitored constantly in order to nip in the bud any tendency for the engine to over-rev. For pressure measurements please note that the pressure take-off nipple should be located in such a position that it opens into an area of the housing where the gas flow speed is low. Measuring pressure in the compressor area can give deceptive results since the gas speed and pressure are not uniformly distributed immediately aft of the compressor diffuser system. For low pressure monitoring you can certainly use a water-filled U-tube, but you will otherwise require a pressure gauge with a measurement range of around 1.5 bar. Gauges designed for use in heating systems have proved to be a good choice. The reading is generally stated in metres of water column, whereby ten metres of water column correspond to one bar. The unit of thrust is the Newton, and one Newton corresponds to the weight force of a bar of chocolate (100 g chocolate and 2 g packing). If you use kitchen scales as a thrust meter and would like to obtain a true result, take the displayed figure in kilogrammes and multiply by a factor of 9.81.

Measuring the engine's rotational speed is a little more difficult. Basically a simple optical rev-counter designed for piston engine propellers can be used, with the front balance mark on the compressor rotor wheel serving as the sensor marker. For the rev-counter to work well this marker must be lit by a concentrated beam of light, and shrouded from any disturbing stray light. You will have to multiply the reading by the number of blades, bearing in mind that some rev-counters include modes for two- or three-bladed propellers. In bright sunlight it is very difficult to take measurements without expensive special equipment, in which case you have to be satisfied with measuring engine pressure. It is also possible to record the rotational frequency acoustically with the help of video or audio recording equipment. The whistle of the engine is the result of oscillation at the frequency of the rotor's rotation. Using an oscilloscope or a reference tone from your home computer it is possible to determine the engine's rotational speed with great accuracy.

Measurements for the advanced operator

If you require more information about your engine you have to disentangle the web of data by measuring other values and calculating derived parameters. Accurate measurement of a model jet engine's exhaust gas temperature is much more complicated than anything discussed so far. When we were building the first jet engines this value was estimated simply from the colour of the glowing turbine blades. However, this method is imprecise and, of course, limited to wheels which are actually glowing. A low-cost hand-held thermometer can be used to measure temperatures up to 1000° C and more, but you should be aware of a number of snares lurking for the unwary. Secondary air quickly penetrates the exhaust gas stream and cools it down, and in daylight the result can be falsified by flames which are impossible to see in bright conditions. The best method is to take measurements at various points immediately aft of the thrust nozzle and then calculate the arithmetic average value.

It would be extremely interesting to be able to mea-

For complex measurements, in this case combustion chamber pressure loss, up to seven connections are made to the engine.

sure temperatures inside the engine itself, and indeed this information would be necessary if you wanted to establish the efficiency of individual stages. However, the heat radiated by the glowing combustion chamber walls would lead to substantial errors in the measurement readings. Investigations on much larger engines than ours give inaccurate results even when radiation-shielded thermometers are used.

With industrial gas turbines calibrated venturi nozzles are used to measure engine throughput. In the model arena such complexity is not appropriate: the continuity equation which states that:

$$\dot{m} = A \times \rho \times C$$

applies at the outlet of the exhaust cone, and the gas density can be calculated from the measured exhaust temperature. We also know that the engine's thrust is found from

$$F = \dot{m} \times C$$

Kurt Schreckling states that a simple formula can be derived from these equations to give engine throughput:

$$\dot{m} = \sqrt{(A \times F \times \rho)}$$

The cross-sectional area of the exhaust cone to be used should be reduced by 10% to allow for the influence of the boundary layer and the residual swirling motion of the gas. The average outflow speed can now be found from the values for throughput and thrust. At this point the continuity equation allows us to calculate the flow speed for any cross-sectional area. These formulae are particularly useful in so far as they allow us to check the compressor's supply value.

It can also be productive and worthwhile to establish the engine's fuel consumption. All you need to do is set up a calibrated cylinder as a fuel tank, then you can use a stopwatch to measure consumption very accurately under different operating conditions.

To find the actual consumption figure for model flying we just have to multiply the fuel volume by the corresponding fluid density. This gives a good idea of the size of fuel tank you will need in your model.

Another interesting value is specific fuel consumption, which tells us how many kilogrammes of fuel are consumed per hour and per Newton of thrust. This value will vary widely according to the engine's rotational

SUMMARY OF ESSENTIAL MEASURED VALUES AND THE FORMULAE FOR CALCULATING THEM

Parameter	Formulae	Unit
Peripheral speed:	$u = n \times d_2 \times \pi / 60$	m/s
Pressure ratio:	$\pi = (P_u + P_0) / P_0$	
Gas density	$\rho = P / T / R$	kg/m3
Throughput:	$\dot{m} = F / c = \sqrt{(A \times F \times \rho)}$	kg/s
Outflow speed:	$c = F / \dot{m} = \sqrt{(F / A / \rho}$	m/s
Specific fuel consumption:	$b_s = \dot{m}_b \times 3600/F$	kg/N.h
Jet power:	$P_{st} = c^2 \times \dot{m} / 2$	Watt
Burning efficiency:	$\eta_b = (P_{st} + \dot{m} \times c_p \times (T_4 - T_0)) / (\dot{m}_b \times h_{0u})$	
Pressure level (compressor):	$\psi = 2 \times C_p \times T_0 \times (\pi^{0.286} - 1) / u^2$	
Specific thrust:	F/Engine mass	N/kg

Measured parameters and constants

n = Rotational speed	rpm
$P_ü$ = Excess housing pressure	Pascal (N/m²) 1 Pa= 0.01 mbar
P_0 = Atmospheric pressure	Pascal (N/m²) 1 Pa = 0.01 mbar
A = Nozzle cross-sectional area	m² (See description)
F = Engine thrust	N
$\dot{m}$ = Fuel Consumption	kg/s
T_4 = Exhaust gas temperature	Kelvin
T_0 = Inlet Temperature	Kelvin
R = Gas constant for air	287 J/kg/K
C_p = Specific heat of air	1000 J/kg/K
h_{0u} = Specific heat of fuel	43.3 MJ/kg (for Jet A1 kerosene)

speed, as specific consumption is much lower at higher pressure ratios and efflux speeds. Nevertheless it remains true that a model jet engine at full throttle requires two or three times as much kerosene per Newton of thrust as other engines of comparable size.

It is even possible to relate the quantity of heat which is fed to the air in the combustion chamber to the calorific value of the fuel used. This calculation gives us the efficiency of the fuel burning process in the combustion chamber, whereby the converted calorific power corresponds to the sum of the power from exhaust heat and jet power. The burning efficiency of the Micro-Turbine rises with increasing rotational speed and reaches just over 90% at full throttle, taking into account measuring inaccuracies. Thus about 10% of the fuel leaves the engine unused. Industrial miniature gas turbines achieve a burning efficiency of more than 99.5%, so there is certainly scope for improvement.

Using jet engines in model aircraft

Fundamental special features

In comparison with propeller engines and powerful impellers (ducted fans) the thrust produced by the model jet engine seems to be on the low side. At take-off the model jet certainly appears to be inferior to a propeller aircraft. However, static thrust is entirely inappropriate as a means of comparing the effectiveness of these different types of engine. Comparing a turbine-driven aircraft in this way would be like measuring the performance of a car which could only run in top gear. The take-off performance may be no better than moderate, but at high airspeeds the jet engine cannot be beaten. The performance characteristics of a propeller-equipped model are exactly the opposite. Static thrust is very high, but it falls off quickly with increasing airspeed.

One possible method of comparing different types of engine is flight performance under given conditions. The precise airspeed at which the jet aircraft exhibits superiority depends on the circumstances prevailing at the time, and as a result it will probably never be possible to give an answer which is valid in general terms to the question of which engine is better. The answer depends on what the individual modeller expects from his model. For example, it is not true that a jet aircraft must be flown fast at all times. If you can keep the wing loading of your model down to a sufficiently low level, jet flying can even be recommended for the relative beginner to model flying. Speaking personally, I made my first ever powered flights with a turbine aircraft. It was not until several months later that I first flew a "normal" piston-engined model, thanks to a friendly colleague.

How jet engines behave in flight

The thrust of a model jet engine increases slowly as the model's airspeed rises. In order to produce any form of forward power the engine must suck air into itself and give it an impulse in the opposite direction to the model's flight. Since air enters the model at its current airspeed when the model is flying, the engine only produces useful thrust if the outflow speed exceeds the airspeed. Dynamic thrust can be calculated as follows:

$F = \dot{m} \times (c - v)$

c = Exhaust speed in m/s
v = Airspeed in m/s
$\dot{m}$ = Air throughput in kg/s
F = Thrust in N

Now we only need to understand how the engine itself behaves in flight – especially in terms of throughput and outflow speed. The kinetic energy of the air flowing in can be exploited if the inlet opening of the engine is designed carefully (i.e. the correct size). In this regard it makes no difference whether the engine is mounted inside the fuselage or on top of the aircraft, right in the airflow. Don't imagine that what modellers call dynamic

Moturex 1 in action. In spite of its conservative layout the model was not always good-natured in the air. (Photo: Kurt Schreckling).

Three jet-powered models with a total of four jet engines. (Photo: Kurt Schreckling).

throughput increase slightly, they cannot compensate for the loss of thrust. Even so, the speed of the gas flow is around 100 m/s (360 km/hr) which is extremely high in model terms, so in theory about 70% of the static thrust is still available to the model. In this respect jet engines with characteristically high outflow speeds, such as the Dutch Pegasus engine or the French JPX T240, have the advantage.

In full-size jet aircraft there is a well-known phenomenon of increasing thrust at high speeds, but this cannot be duplicated in our models. We can also expect diminishing thrust which only rises gradually above the initial value when airspeeds exceed 300 m/s. The airspeeds achieved in the modelling world are much too low to have any significant effect on the engine. At a realistic model speed of 50 m/s the dynamic pressure of the air amounts to only about 0.015 bar. You could only expect to see a detectable difference if you placed the model in a dive with the engine throttled back. Gas temperature then falls off markedly, although in practice this is not evident in any other way.

The powerful Pegasus engine mounted on a Heinkel Salamander. The engine's thrust substantially exceeds the weight of the model, endowing the model with a very convincing flight performance. (Photo: Pulse-Jet-Team Helmond).

pressure represents a build-up of air in front of the engine. What actually happens is that there is a low pressure area immediately in front of the compressor wheel under normal circumstances, and this is eliminated when the model is flying, as the air now flows into the engine naturally. The net result is an increase in gas density and engine throughput.

What exactly happens next depends on the engine control system. Some control systems enforce a constant maximum rotational speed or a particular maximum pressure when at full throttle. If we base our considerations on the simplest case - a constant fuel supply - we achieve the maximum effect. Rotational speed and pressure ratio rise slightly as airspeed increases, until the engine reaches a state of equilibrium between compressor power and turbine power. This equilibrium occurs at a slightly lower exhaust gas temperature.

In overall terms the engine's dynamic thrust falls with increasing airspeed.

Calculations show that, although out-flow speed and

Air intake design

You can expect to improve the model's flight performance slightly by optimising the design of the intake opening. For best results careful profiling is necessary in this area, but at least you must ensure that the jet engine is fed sufficient air. If not it will overheat, like a hair dryer with a hand held over the inlet side. For everyday model flying all you need to worry about is making the opening large enough. The air mass which the engine requires is very small compared with a ducted fan system, so small cross-sectional areas are usually quite adequate. For scale jet models the scale intake area is generally sufficient. If it's big enough for the full-size, it's likely to be big enough for us.

When the engine is operated statically the suction process always involves a loss in pressure. After all, the pressure inside the aircraft's fuselage must be lower, otherwise air would not flow in at all from outside. In the worst case, i.e. when the airflow is totally turbulated by the internal fittings in the fuselage, and the kinetic energy of the air cannot be exploited, we can estimate the effect as follows:

$\Delta p = \rho/(2 \times c^2)$
ρ = Air density (approx. 1.225 kg/m³)
c = Air inlet speed in m/s
Δp = Pressure difference in Pascal (100 Pa = 1 mbar)

This effect is termed inlet pressure loss, and the engine must compensate for it. The compressor has to work slightly harder, which in the end results in a higher exhaust gas temperature. Of course, the exact temperature variations depend on the engine in use. With a pressure loss of 1,000 Pa (0.01 bar) the exhaust gas temperature of the Micro-Turbine is approximately 12° K higher at full throttle when the inflow speed is 40 m/s. This value is reasonable for a model jet. Now we can calculate the minimum cross-sectional area of the inlet opening from the data we already know. The following continuity equation applies:

$$\dot{m} = c \times \rho \times A \Longrightarrow A = \dot{m} / c / \rho = 0.15 / 40 / 1.225$$

$$= 0.00306\text{m}^2 = 30.6\text{cm}^2$$

$\dot{m}$ = Engine throughput at full throttle in kg/s

c = Maximum inlet speed (here 40 m/s)

ρ = Air density (under normal conditions 1.225 kg/m3)

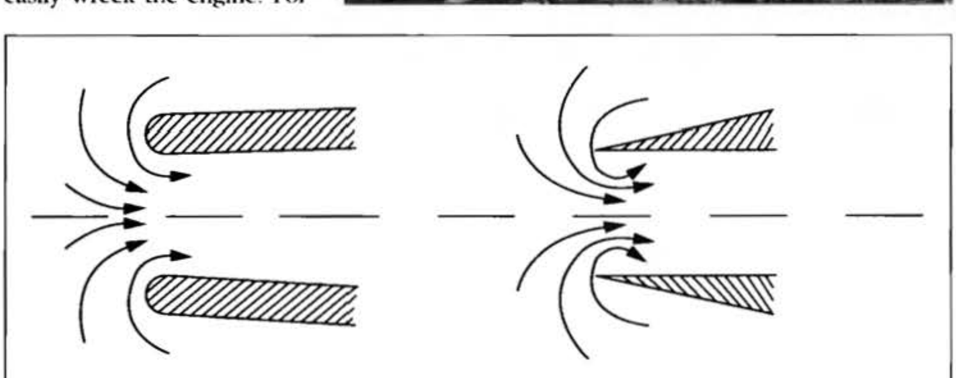
This cross-sectional area corresponds to an opening of 62.5 mm diameter, but take care - the calculated figure assumes a zero-loss airflow. This size of intake will therefore only work if the edges of the inlet are carefully rounded. In contrast, if we are considering a scale jet with a scale-sized air intake designed for high airspeeds, then we have to take into account the turbulence which occurs during static running. The easy way to do this is to correct the cross-sectional area by a value which we will call the contraction factor. If in doubt you should certainly double the calculated area, or measure the pressure loss using a U-tube.

If the jet engine is to exploit the airflow to the full the airflow due to the model's motion must be slowed down in a diffuser. This establishes a dynamic pressure in the model's fuselage which varies with the square of the model's airspeed. At the same time the energy of the flow is diminished. What this all boils down to is that the internal fittings in the model aircraft's fuselage will have little effect on the engine's power provided that they do not reduce the cross-sectional area too much.

In consequence installing an air duct running directly to the engine is of little value. In any particular case you can measure the pressure loss easily. Much more important is that you lock and secure all movable parts, screws and nuts, so that there is no chance of them coming loose. Even a single screw sucked into the intake at full throttle could easily wreck the engine. For the same reason it is obviously essential to clear away all traces of soil and dirt from the model after an out-landing in a field.

When designing an intake diffuser it is important that it should open out at an angle of no more than 10°, otherwise the airflow will break away. You should aim at slowing the airflow down to about 25 m/s, since at that speed more than 60% of the energy has already been converted [into pressure].

With a semi-scale or scale model you are bound to the full-size machine's intake size, but with a sports or experimental model you can incorporate any type and size of air opening. The ideal form of inlet for a model jet would then be what is known as a venturi, which consists of a rounded nozzle opening followed by an integral diffuser. This form of intake gives good results in most flight situations and does not incur a serious pressure loss. The airflow speed at the narrowest point can then be tuned to correspond to the model's expected maximum airspeed.



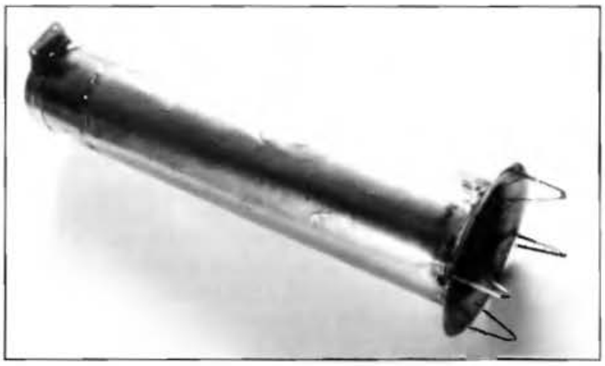
Flow restriction with a sharp-edged intake.

Cooling the fuselage

Since model jet engines are not usually what we might call lightweight, they usually have to be installed close to the model's Centre of Gravity. As a result it is virtually inevitable that delicate parts of the model end up close to the hot exhaust gas flow. Good layouts for jet-engined model aircraft therefore include types with the CG a long way back, and especially flying wings and canards, where the exhaust flow can leave the model quickly without having a chance to burn the tail.

However, for initial experiments I advise keeping to a model of conventional geometry unless you already have experience with flying wings and canards. It is obviously important that the engine should be installed in an open position where it is easily accessible, and as

A more docile model: the author's jet-powered Moturex 2. The fuselage air intake is 70 mm in diameter.



The tail pipe, used to duct the exhaust gases out of the fuselage.

Otto Bruhn's twin-boom at take off.

This construction is very easy to handle. The engine is directly below the wing.

far distant as possible from inflammable balsa wood. A good typical prototype is the Heinkel Salamander, whose engine is mounted above the wing. You can expect to avoid all temperature problems with a model of this configuration.

Concealing the engine inside the model's fuselage presents far more problems, and can therefore only be recommended to the modeller who already has plenty of experience under his belt with jet engines. The main problem is not caused by the engine itself. The maximum temperature of the engine's housing will be about 120° C in the area of the compressor, and up to 200° C at the tail end. The only parts which become really hot are the turbine enclosure, the mounting flange and the

My latest model with V-tail.

Micro-turbine in the tail of a BAe Hawk.

A Fairchild A-10 with two home-built engines.

exhaust cone. The greatest problem is that of ducting the exhaust gas stream outside the model whilst incurring lowest possible losses. A thrust pipe is used which works like an injector, drawing cooling air in with it. Such a system has a greater overall throughput, since the engine moves more air. This can be estimated from the following formula:

$$\dot{m}_G = \dot{m}_T \times \frac{T_A - T_0}{T_S - T_0}$$

The North American F100 Super Sabre is fitted with a fully enclosed Schneider-Sanchez jet engine. The powerful fan of a car vacuum cleaner starts the engine reliably. (Model and photo: Kurt Schreckling)

$\dot{m}_G$ = Total throughput in kg/s
$\dot{m}_T$ = Throughput of the engine in kg/s
T_A = Exhaust gas temperature of the engine in Kelvin
T_S = Temperature at the end of the thrust pipe
T_0 = Inlet temperature

The new throughput must be taken into account when designing the inlet openings, which will result in correspondingly larger cross-sectional areas.

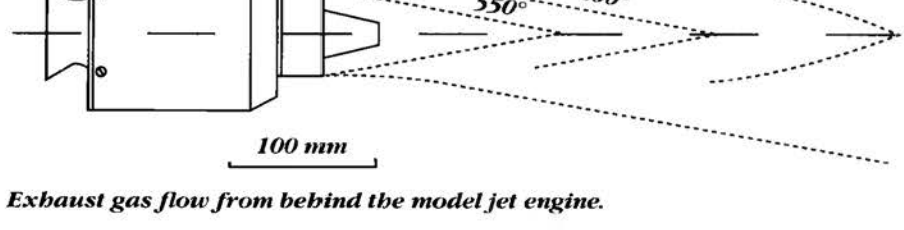
If the engine is concealed inside the fuselage, starting may present problems. With a light headwind flames coming out of the engine may damage the model. When you are starting the engine the thrust pipe also becomes red hot – in the true sense of the expression. You will need a very powerful starter fan in one hand and a fire extinguisher in the other.

As soon as the engine is running the turbulence of the airflow causes cooling air to be mixed into the exhaust gases, and only half a metre "downstream" the temperature is low enough not to burn plywood. Theory tells us that the gas flow expands at an angle of 10° relative to the axis of the flow, although secondary air enters at a slightly lesser angle. The hot core of the jet, i.e. the area in which the full exhaust gas temperature and speed still prevail, extends to a point aft of the engine about three times the diameter of the exhaust cone.

Balsa wood is very susceptible to hot exhaust gases. Since the wood itself contains plenty of oxygen, an imperceptible glow is quickly fanned into life when you open the throttle, and the glow spreads over the wood in narrow snaking lines. A few seconds at full throttle, and the glowing tailplane is engulfed in flames. Endangered areas can be protected by gluing aluminium foil to the surfaces using thinned white glue. Thin aluminium (0.3 mm thick) is another good protective material. A crucial point – especially if you are interested in maintaining friendly relations with your model club's groundkeeper – is the position of the engine relative to the ground. The hot exhaust gases burn the flying site's grass strip in an instant. Initially the grass stays green, but a day later it will start to show a brown discoloration. The jet engine in my Moturex 1 experimental model was inclined slightly down towards the strip at take-off. For several days after my initial flights we could see burned areas with adjoining brown stripes, ending exactly where the model lifted off.

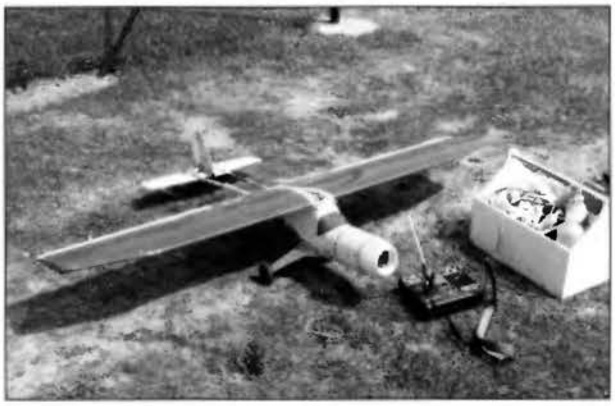
Auxiliary equipment

Unlike piston engines, model jet engines are not completely self-contained, and require a number of additional items of equipment. The primary auxiliary items are the fuel supply system and lubrication system. The fuel pump and controller of a full-size jet engine are mounted directly on the engine, driven by the main shaft, but there seems little prospect of duplicating this arrangement on a model jet engine due to the added complexity. The simplest method is to supply fuel and oil from external sources. For model aircraft use it is clearly vital to have a lightweight, reliable fuel feed system, and we have found geared fuel pumps a good solution. When you are selecting a pump it is essential to check that it can resist the fuels we are likely to use. Metal-geared pumps are certainly preferable. If you are capable of accurate work you will be able to convert a standard fuel pump for use with a turbine. This will necessitate reducing the width of the gears and installing a more suitable motor.



Exhaust gas flow from behind the model jet engine.

Moturex 1 just before take-off. A burned area of grass is already visible. (Photo: Anita van de Goor).



The same model with aileron wings.

Controlling the quantity of fuel pumped to the engine is vitally important. The ideal is to have a regulatory system which varied the flow according to exhaust gas temperature and rotational speed or pressure. A simpler solution, although quite practical for our purposes, is a standard electronic speed controller. The controller has to be adjusted carefully to guarantee a particular idle speed, and above all to limit the maximum rotational speed. I find that variable constant voltage controllers work well, and they are a reasonable choice since the pumping power is so small. With this arrangement a servo operates a potentiometer and an end-point switch. Unfortunately this type of system is not as neat a solution as an ordinary controller, but it offers one crucial advantage: it defines the maximum pump voltage regardless of the initial voltage. This on its own eliminates the problem of freshly charged pump batteries allowing the engine to over-rev. A second pot can be used to set the engine's maximum rotational speed. An externally accessible fuel valve offering fine adjustment is fitted in the fuel circuit between pump and engine.

This is the starting procedure: set the transmitter throttle stick to idle and start the engine on propane. As soon as the gas has ignited and the starter is running, slowly open the fuel valve. The engine revs up, and will reach its idle speed when the valve is fully open. Unless you enjoy unwelcome surprises please remember to set the transmitter stick to zero as soon as the engine stops – bearing in mind that this is not necessary with a piston engine. If you don't, the fuel pump will continue running and will gaily pump the remaining contents of the fuel tank into the engine.

It goes without saying that the fuel tank and the rest of the fuel system in the model must be made of fuel-resistant materials. The fuel tank should have a capacity of at least half a litre, and might even need to be larger if your engine is thirsty or your flying style extravagant. It is not always easy to find space in the model for such a large tank, and you may find it better to make up a custom-designed version from sheet metal to exploit the available space. I strongly recommend using a clunk weight with an integral fuel filter.

The oil tank can simply be a small chemical bottle with a screw-fitting lid. When the engine is in a model I recommend using a mixture of equal parts bicycle oil and synthetic motor oil. To some extent you can control the oil consumption by adding more or less bicycle oil, since this oil is low in viscosity. Consumption should be about 5 ml per minute. However, the engine described here has already survived a number of flights with the oil supply carelessly disconnected.

Starting a jet engine when installed in a model does call for a little practice. There is a danger of the engine overheating temporarily at times when the starter is struggling for power and the oil in the bearings has thickened. Under certain circumstances it is a good idea to keep to hand a pipe made of sheet metal, so that you can deflect the hot gases or flames away from vulnerable wooden parts. You can avoid problems by obtaining a powerful starter fan or, if the engine is easily accessible, a high-revving electric motor. A motor power of 20 Watts is quite sufficient.

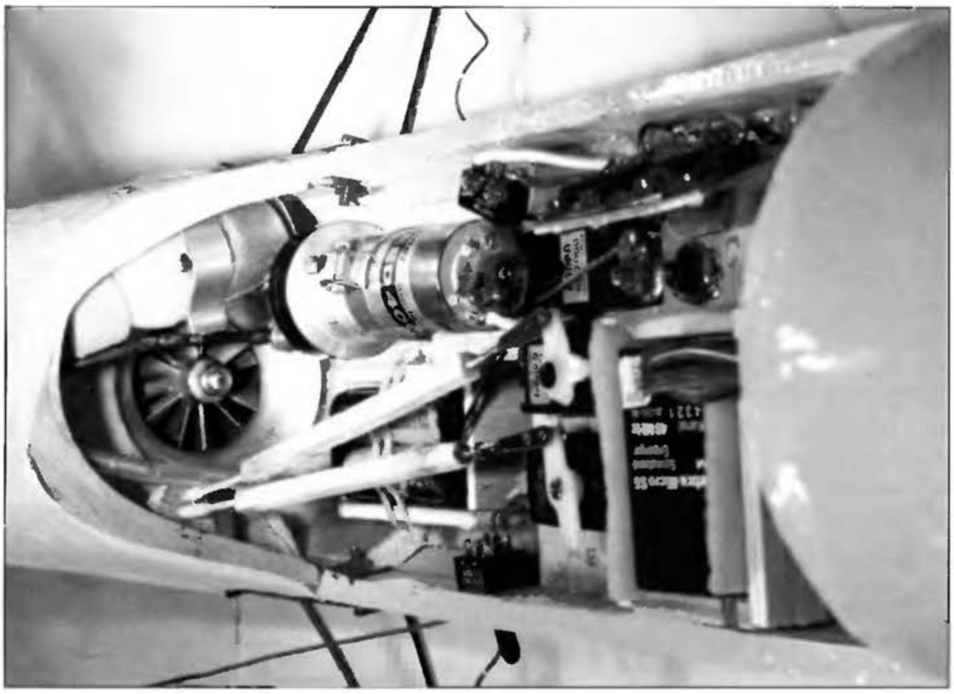
Particular problems encountered in jet-powered flight

Thrust delay

Model jets have a number of characteristics which mark them out from propeller-driven models. These features are similar to those of full-size jet aircraft – as you might reasonably expect.

The most immediately obvious difference to the pilot accustomed to propeller engines is the jet's slight delay in responding to the throttle stick. This phenomenon is due to the inertia of the rotor. At high rotational speeds a great deal of energy is required to accelerate the rotor wheels, and this applies in particular to the jet engine's lower speed range. The force which is acting upon the turbine blades – and which is available to accelerate the turbine – is still small. For this reason the time required to bring the turbine up to speed varies markedly according to the initial speed. Overall the power of the turbine is proportional to the cube of the rotational speed, while the work required to accelerate the rotor is proportional to the square of the speed.

At a rotational speed of 35,000 rpm – corresponding to a thrust of four Newtons – the Micro-Turbine runs up to full throttle in three or four seconds, perhaps a little faster. However, bearing in mind the thermal loads involved in the engine, it is a good idea to handle the throttle stick gently. At the stated speed the work stored in the rotor in the form of rotational energy is around 2000 J, which corresponds roughly to the kinetic energy of a bicycle rider at a speed of 25 km/hr. On average, when you increase the engine's speed from idle to full throttle more than 650 Watts is required to accelerate the rotor alone. The net result is that you have to make allowance for delayed throttle response when the model is in the air, and accelerate rather earlier than usual. However, as soon as you are flying at more than half-throttle you will find that the engine responds to the throttle stick as quickly as a piston engine.



View of the inside of the fuselage. On the right are the fuel pump and oil tank.

The factor which affects a model jet engine's ability to accelerate quickly is the rotor's moment of inertia, the exhaust gas temperature and the compressor surge. In this respect engines with an axial turbine are clearly superior to those with the heavy, high-inertia radial turbine. Kurt Schreckling's FD engines are particularly sprightly; their very light compressor wheels follow the throttle stick virtually like a piston engine. The major factor in the rotor's moment of inertia is the moments of the rotor wheels; the engine's shaft contributes only a few per cent of the rotor's total inertia.

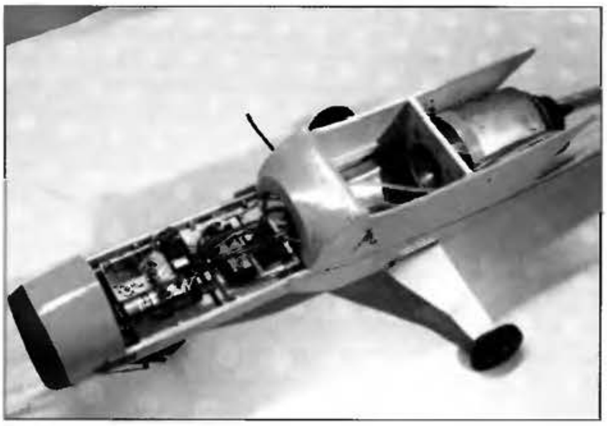
Gyroscopic effects

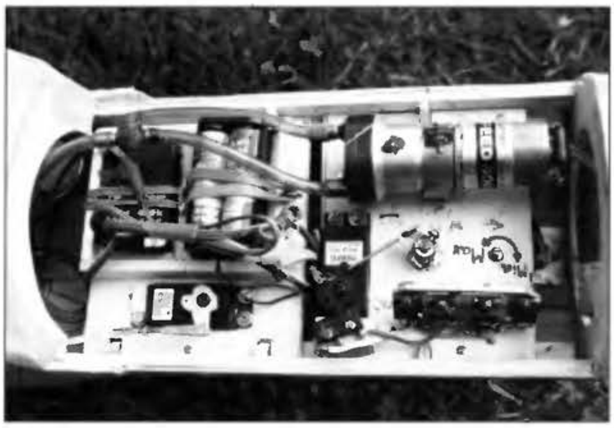
In any rotary system mysterious forces are at work which many people find hard to understand. These gyroscopic forces, as they are known, are omnipresent in our day-to-day lives, although you have to know where to look to find them. For example, they ensure that we don't fall off our bicycles, at least so long as the wheels are going round. Aircraft and ships find their way home with the help of gyro-based navigational systems. In short: gyroscopic forces have a stabilising effect on rotating systems.

The same forces are at work in the spinning rotor system of our model jet engine. Because the rotational speeds are so high the gyroscopic moments are considerable. If you hold your jet-powered model's fuselage in your hand with the engine running and move it (in the language of physics you are forcing a precession upon it and you will clearly feel the gyroscopic moment opposing your effort. You can try the same experiment with a high-revving electric motor.

The system attempts to counteract the original force. The gyroscopic moment acts in the perpendicular direction to what is known as the axis of precession. If we assume that you are flying a model powered by a right-hand rotation jet engine, this means that the model's nose will dip slightly if you fly a left-hand turn, and will rise slightly in a right-hand turn. With a left-hand rotation engine the effect is exactly the opposite. There is no cause to be alarmed. In day-to-day modelling the

Arrangement of auxiliary equipment in the Moturex 2 model. The fuel supply system is installed in the front part of the fuselage.





The Micro-Turbine during the starting procedure. Beneath the wing is the fuel valve which is being opened slowly at this moment. A pressure gauge is still connected to the engine to monitor the settings.

engine's gyroscopic effect is almost imperceptible, as the forces are much too small to have any significant influence on the aircraft.

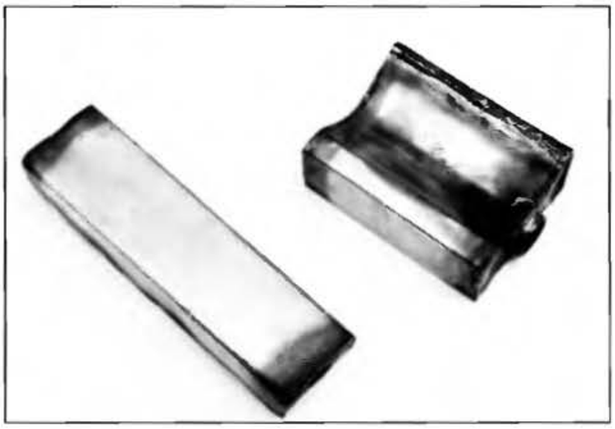
The moment which occurs in a turn or loop varies according to the inertia of the engine's rotor, the rotational speed and the angular velocity of the model in the turn. In a fast loop at full throttle the maximum gyroscopic moment might be one Newton-metre, and that represents no hazard to the model.

Under normal circumstances the stabilising effect of the tail surfaces and the moment of inertia of the model counteract the gyroscopic moment. Serious problems only arise if the model's layout is unsatisfactory. If the engine is mounted close to the model's Centre of Gravity and the tail panels are too small, you could encounter flight conditions - specifically very low airspeeds - in which the model is unable to counteract the gyroscopic forces. For example, if you stall your model in such a way that the tailplane is no longer subject to an airflow, and if one wing stalls first (tip-stalls), the gyroscopic effects could send the model straight into a sort of gyro-stabilised spin. For this reason you should avoid a concentration of masses at the Centre of Gravity when designing your jet model. A good solution is to arrange the engine towards the tail and the rest of the equipment in the nose.

Fault-finding

Every now and again an ordinary piston engine fails to start, and many of us modellers have cursed loud and long at such times. The usual reasons are incorrect carburettor settings, wet glowplugs and blocked fuel lines, and these little problems have driven many a modeller close to insanity. The most pernicious problems are caused by the piston engine's external fuel mixing arrangements (the carburettor) and the ignition system, and in a jet engine both these systems are fundamentally different and usually cause no problem. If you have a jet engine which usually runs well but one day suddenly will not, there is normally a mechanical problem which you will easily be able to recognise.

The main way in which you can avoid problems is to check the engine regularly - especially the bearings and the turbine wheel connection - and replace damaged parts immediately.



Fuel tanks soldered up from sheet metal.

What the sound of the engine tells you

A common problem is the rotor fouling the casing, and the sound of the engine always lets you know that this is happening. If you hear a suspicious scratching noise stop the engine immediately and check the concentricity of the rotor. It can also occur that a normally free-running rotor only fouls the casing at high rotational speeds. This means that the running clearance is too small to allow for the dynamic bending of the shaft. The audible result of this is a distinctive high tone mixed in with the usual engine noise, becoming slightly lower in pitch as the throttle is opened. Usually this type of fouling does not immediately cause the rotor to jam, and the engine continues to spin apparently without protest. However, you will find traces of fouling on the compressor cover or the turbine housing when you dismantle the engine later. You can continue to use the compressor and turbine wheels after such an occurrence provided that they have suffered no major damage. Never allow a model jet engine to continue running if you suspect fouling. If you open the throttle very gradually it may be possible to run up the turbine to high speed, but you then risk wrecking the wheels. You even risk blade fractures if the turbine fouls the casing, as serious and damaging vibration could result.

Similarly, any major imbalance manifests itself in the volume of engine noise. The vibration caused by the imbalance is transmitted to the housing, resulting in a whistling sound at the pitch of the rotational frequency. The whistling sound will be distinctly louder to the side of the engine than immediately in front of or behind it. If you carefully touch the housing with your hand you will be able to feel the vibration. Minor imbalance effects are quite normal, as is a whistle occurring at high rotational speeds. Since the shaft and turbine wheel are only statically balanced, the possibility of dynamic imbalance cannot be excluded entirely. Since the rotating parts are rotationally symmetrical, and since the design of the engine makes it very unlikely that there are major discrepancies in mass distribution, simple static balancing is adequate for model use. If the model jet engine is very well balanced all you will hear under normal circumstances is the hiss of the exhaust gas flow. Naturally the bearings will have a proportionately longer life if the engine is perfectly balanced. After a few hours of operation lubricating oil residues may form deposits on the turbine wheel, causing slight imbalance, but this is not critical.

Exceeding the pressure limit (surging)

This phenomenon occurs primarily in model jet engines fitted with a compressor with radially tipped blades. Under certain circumstances opening the throttle too suddenly may cause the compressor pressure to hunt up and down as the throughput of the compressor is reduced momentarily. This effect, known as compressor surge, is immediately obvious because of the characteristically deep growling sound it causes. If this should happen it is essential to close the throttle without delay to avoid a sudden rise in exhaust gas temperature and consequent damage.

After a fairly long period of operation you may find that the engine's tendency to surge becomes more pronounced, and at the same time the engine no longer produces full thrust. This behaviour is usually a sign that the turbine material is unable to cope with the stresses it encounters in the engine. The result is usually distortion of the turbine blades due to the high centrifugal forces. The angle of the blades usually closes slightly, restricting the open flow cross-sectional area.

This in turn reduces the engine's throughput, and the compressor will then be working very close to its surge limit, especially when the engine is running at high speed. The only remedy in these circumstances is to make a new turbine wheel, and it makes obvious sense to select a better grade of material the second time. The other, temporary recourse is to reduce the full-throttle setting slightly.

A standard problem

Excessively high exhaust gas temperature

Many home-built turbines suffer from overheated, glowing, red-hot turbine wheels. Although you can fly a model using such a hot-running turbine, you are bound to encounter certain problems: materials expand considerably due to the excess heat, and n.g.v. blades may then kink and damage the housing. The glowing turbine housing makes it much more difficult to shield the vulnerable fuselage of the model aircraft. The hot turbine wheel may not be strong enough to withstand the stresses of running at high speed, and the engine as a whole will be slow to respond to the throttle stick. You will have to be very careful with the throttle stick to avoid overheating the engine.

In general terms, then, a model jet engine with a high exhaust gas temperature is a less capable engine. Exactly the opposite applies to full-size aircraft engines: the higher the exhaust gas temperature, the more powerful the engine. The turbine blades which are subjected to the highest temperatures are cooled with air ducted from the final compressor stages, so that the temperature of the turbine blade material is several hundred degrees Kelvin below the actual gas temperature. In small gas turbines and model jet engines this technology is almost certainly too complex, and if we want easy handling the only solution is to strive for low gas temperatures. Several factors affect the gas temperature, but the primary one is the efficiency of the rotor wheels, although it is also important that the compressor and turbine should be accurately matched to each other so that they both work close to their optimum efficiency. Amateur methods and equipment simply do not allow us to diagnose accurately the degree of mismatching between compressor and turbine. As we have already discussed, it is possible to make certain deductions about possible faults from the level of residual swirling motion behind the turbine and from any tendency for the engine to reach its compressor surge limit. However, the best method of reducing an excessively high exhaust gas temperature is to check the overall design using the data which you are able to measure accurately, such as rotational speed and throughput. Use this data in conjunction with the continuity equation to calculate the speeds which are actually occurring, and plot the vector diagrams for the turbine and compressor. This should allow you to detect any significant deviations from the design goals towards which you have been working.

The combustion chamber has a very important influence on exhaust gas temperature. Temperature distribution must be reasonably even. Flames from the turbine, hot spots and acrid, pungent exhaust fumes are good indicators of incomplete combustion. In this case the only remedy is to carry out systematic tests on the combustion chamber. I have already described how the curvature of the "walking sticks" should be adjusted in small increments. It is not advisable to drill further air holes in the combustion chamber at the hot spots. This seldom cures the problem, and more often just wrecks the combustion chamber.

If combustion suddenly worsens, and at the same time the exhaust gas temperature rises, one injector tube might be blocked, perhaps by dirt from the fuel-tank or solder flux residues blocking the fine openings. A fuel filter should always be used – not least to protect the fuel pump.

Motures 2 in action. (Photo: Michael Kamps).

Cleaning urgently required! After an involuntary landing in a field with the turbine running, a few lumps of earth have been sucked inside the engine. Fortunately the compressor wheel is virtually undamaged.

Cleaning the engine

Model jet engines are generally quite easy to look after – assuming that they deign to run at all. Nevertheless, these engines should be opened up now and then for general examination and cleaning. In the course of time dust gets sucked in and combined with the lubricating oil to form a sticky layer which collects in the compressor and housing. This is a good time to check that all screws and other parts are tight. I would recommend that you examine the turbine wheel more closely, preferably using a magnifying glass. Any changes to the blades and signs of cracking are clear signs that the material you have used is not coping well with the stresses. It goes without saying that a damaged wheel must not be re-used.

The lubricating system can be an insidious source of operational problems, as the narrow pipes are readily blocked by minute deposits. This is enough to cause the oil supply system to fail altogether, leading eventually to bearing damage. The normal functioning of the lubrication system can be recognised by tiny explosions behind the turbine: this is caused by burning oil residues. The oil for the front bearing usually makes its way into the open air through leaks in the compressor cover. If the engine's oil consumption falls off, be sure to check the oil pipe. If you can obtain special turbine oil such as Aeroshell 500, do use it. These oils, usually synthetic in nature, produce almost no deposits even at very high temperatures.

Maintenance and repair

Checking the bearings

Maintaining the turbine largely comes down to monitoring the ballraces. These components are subjected to extraordinary stresses in our model jet engine: up to three times their nominal maximum rotational speed. They can only withstand such maltreatment if the heat produced is dissipated by plenty of air from the compressor. As a result, heat from the hot turbine can only reach the bearings once the engine has stopped. This effect results in the inner and outer rings of the turbine bearing exhibiting the characteristic "tarnished" coloration after a few test runs, which might make you think that they are running too hot. However, this should be considered normal for the engine and appears to have little if any effect on the bearings' useful life.

When the engine is running down you should always listen carefully for any trace of rumbling sounds, as these are usually an indication of worn-out bearings. The bearings should then be checked for axial play. Check the condition of the ball cages at the same time. If clearance and play are greater than those of a new bearing, for safety's sake you should install a new bearing.

The useful life of the bearings varies considerably according to the conditions of cooling, rotational speed and lubrication inside the engine. In practice I have found that standard ballraces have survived a whole year in the engine, i.e. several hours of running. The bearing at the compressor end of the engine lasts longer, probably because the rotor's axial thrust exerts an axial load on the bearing, taking up any slack in the race. The operating temperature at the compressor end is also lower. In practice bearings only fail prematurely if the engine is badly out of balance or very dirty.

Bibliography

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Appendix

GTBA - Gas Turbine Builders Association

In 1995 a group of modellers in England formed an association dedicated to the construction of model jet engines. Since its foundation the Gas Turbine Builders Association (GTBA) has achieved a membership worldwide of more than 1700. Articles and contributions are sent out to all members in a regular newsletter, which also includes interesting sources of supply. Once a year a meeting is held in England where members can discuss model gas turbines to their heart's content. The GTBA also maintains its own internet site with numerous links.

Internet: http://www.gtba.co.uk

High-speed hybrid bearings:
GRW GmbH & Co. KG,
Postfach 6360,
D-97013 Wuerzburg,
Germany

Compressor wheels:
Struck Turbotechnik GmbH,
Ernestinenstrasse 115,
D-45141 Essen.
Germany

Cherry, Mike:
Mike's Jet Book
A hands on guide to jet modelling.
Wantage, Oxfordshire: Jets Unlimited

Cohen, H. Rogers, G.F.C., Saravanamuttoo, H.I.H.:
Gas Turbine Theorie, 4th Edition
(this book is very detailed and leaves no technical questions without answer)

Notes

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