THE POTENTIAL OF VALVELESS PULSEJETS FOR SMALL UAV PROPULSION APPLICATIONS

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Abstract

It is shown that the possibility appears to exist of propelling very small UAVs by means of valveless, or aerovalved, pulsejets. Such engines do not incorporate any moving parts. The ignition and auxiliary starting-air systems remain on the ground and, hence, are disconnected from the engine once it has started because the intake air flow is then induced automatically by the engine, due to internal wave action, with reignition for each cycle occurring due to residual hot gases remaining in the combustion zone from the previous cycle. The types of pulsejet studied centered around that of the now classical SNECMA/Lockwood aerovalved design, a design that has proved most effective from the performance viewpoint. A thrust-augmenter-flow-rectifier was added to each unit to redirect into a downwind direction, and amplify the thrust due to, the backflows emerging from the upwind-directed inlets of the SNECMA/Lockwood style pulsejets. It was deduced that in terms of thrust/weight ratio and thrust/unit frontal area the aerovalved pulsejets are competitive with small, centrifugal-compressor type, turbojets. Simplicity and hence low first cost are other advantages. The poor specific fuel consumption of the pulsejets implies that they are most suitable for missions of short duration.

Introduction

In the writer's opinion the most general, and potentially useful, application of valveless, or aerovalved, pulse-combustors in the field of flight propulsion is as pressure-gain combustors for otherwise conventional gas-turbine engines in which such combustors are substituted for conventional steady-flow combustors. Installations of this type offer the possibility of achieving a stagnation-pressure increase between the compressor outlet and turbine inlet as has already been demonstrated experimentally on a very small gas-turbine unit[1,2]. However a more restrictive, but potentially useful, application for valveless pulse-combustor technology appears to be as pulsejets for small unmanned air vehicles (UAVs). The advantages of pulsejets for such roles relate to extreme simplicity, reflected in a low first cost, and, for short duration missions requiring a low thrust level, performances that will be shown to be competitive with those of other more sophisticated air-breathing propulsors.

A valveless pulsejet does not require an ignition system during normal operation although this is required, together with an auxiliary air supply, to initiate engine starting. Hence both of these systems will be ground-based for ground launched UAVs and will not, therefore, be carried with the pulsejet. Furthermore a simple hydrocarbon fuel is all that is required to sustain engine operation. Each successive engine cycle is ignited from residual hot gas remaining, from previous cycles, in the combustion zone. Combustion takes place, substantially in the combustion zone, by deflagration.

Figure 1 shows the basic geometry, in terms of combustion-zone diameter D, of a single-inlet-port valveless pulsejet of the SNECMA-Lockwood type that has been shown to be most effective from the thrust performance viewpoint[3]. An alternative, shorter, configuration developed at the University of Calgary is illustrated in Fig. 2. The reduction in overall length from 16.77 D to 10.01 D is due to the use of four inlets which serves to reduce the duration of the pre-combustion mixing of air, fuel and high temperature residual products of combustion from the previous cycle. The use of multiple inlets tends, in general terms, relative to a single inlet configuration, to result in a lower specific fuel consumption but also, unfortunately, in a lower thrust per unit of frontal area[4,5]. Both of the configurations of Fig. 1 and 2 result in a heavy inlet backflow which, for a pulsejet application, must be re-directed, or rectified, into the direction of the tailpipe

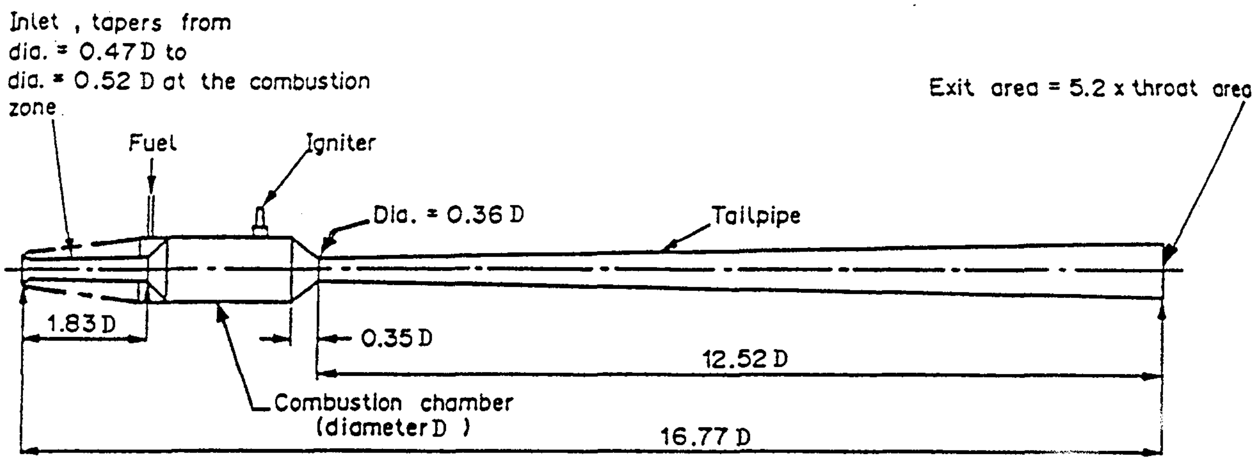

Fig. 1 Geometry of a SNECMA/Lockwood single inlet valveless pulsejet: D is the internal diameter of the combustion zone. The flow-rectifier is omitted.

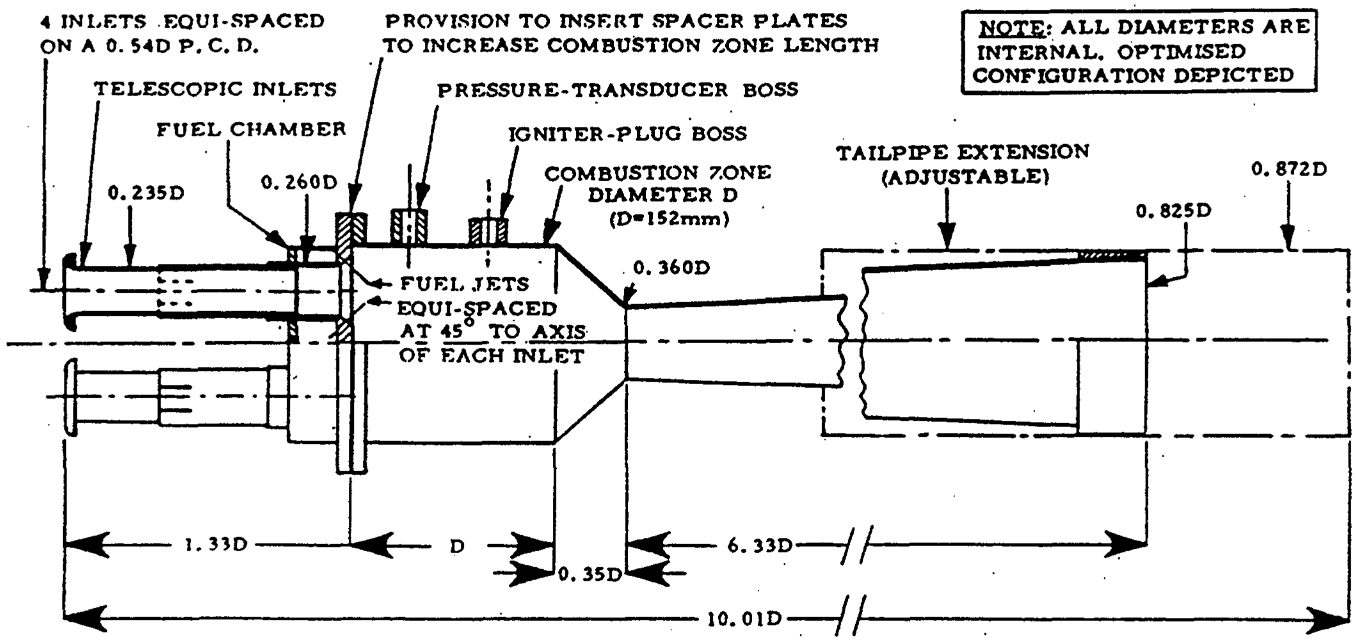

Fig. 2 Geometry of an optimized four-inlet valveless pulsejet: D is the internal diameter of the combustion zone. The flow-rectifier is omitted.

outflow.

Theoretical Treatment

The theoretical prediction of pulse-combustor, or pulsejet, performance was carried out using a computerized method-of-characteristics like procedure based on the simultaneous solution of the hyperbolic partial differential equations representing, in a time dependent flow field, the one-space-dimensional continuity, momentum and energy conservation conditions. A solution for a single-inlet combustor obtained in this manner, due to Cronje[6], is presented graphically in Fig. 3. In this diagram the pressure is normalized by division by the surroundings pressure, the velocity U is normalized by the surroundings acoustic velocity a_0. The negative U apparent at the inlet indicates a backflow. The abscissa of the diagram, z, represents a dimensionless time unit defined to be time multiplied by a_0 and divided by a reference length ℓ equal to the length of the combustion zone. It was found that the theoretical pressure trace was very close to the pressure signal recorded experimentally at full-throttle operation.

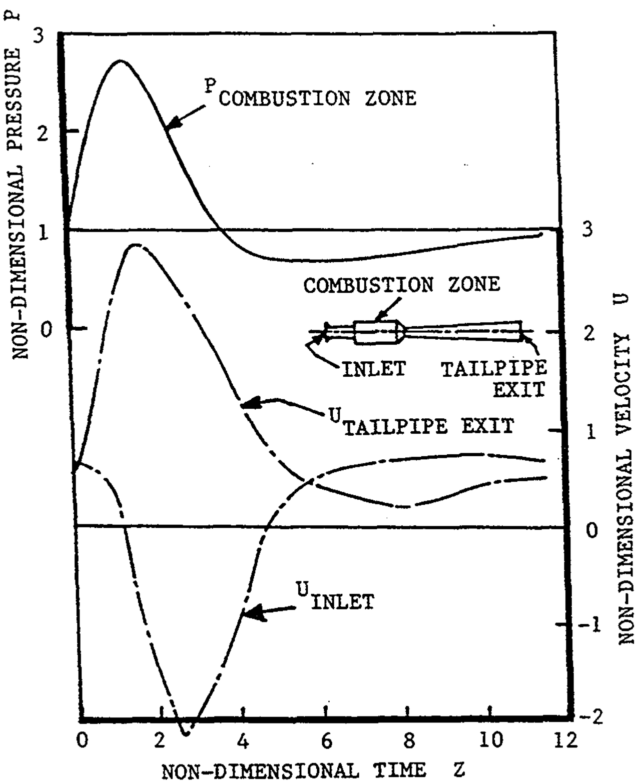

Fig. 3 Theoretically derived plot of normalized pressure P (pressure divided by ambient pressure) and normalized velocity U (gas velocity divided by acoustic velocity at ambient conditions) versus dimensionless time Z (elapsed time multiplied by acoustic velocity at ambient conditions divided by the combustion zone length) for a single inlet SNECMA/Lockwood pulsejet.

A particular difficulty with performance prediction relates to modelling the combustion process. Cronje employed an empirical heat-release rate model[6]. An alternative is to employ an overall reaction-rate model due to Clarke and Craigen[7]. A detailed description of a numerical simulation of a pulse-combustor employing the Clarke and Craigen reaction rate model is available elsewhere[8].

Flow Rectification

The substantial reverse flow from the inlet apparent in Fig. 3 is confirmed by experiment as indicated in Fig. 4 showing data obtained from tests of a four-inlet pulsejet of the type shown in Fig. 2. The device developed at the University of Calgary to "catch" and re-direct the intake backflow has been termed a thrust-augmenter flow rectifier. It serves not only to re-direct the intake backflow but also, by virtue of entraining additional flow from the surroundings, augmenting the intake thrust as otherwise measurable, without the flow rectifier, by means of an inlet plate-type thrust meter. Figure 5 is a diagram of the thrust-augmenter flow rectifier and Fig. 6 shows that the tailpipe plus the re-directed intake thrust exceed, slightly, the arithmetic sums of the inlet backflow plus the tailpipe thrust, as recorded from thrust plates, without the use of flow rectification.

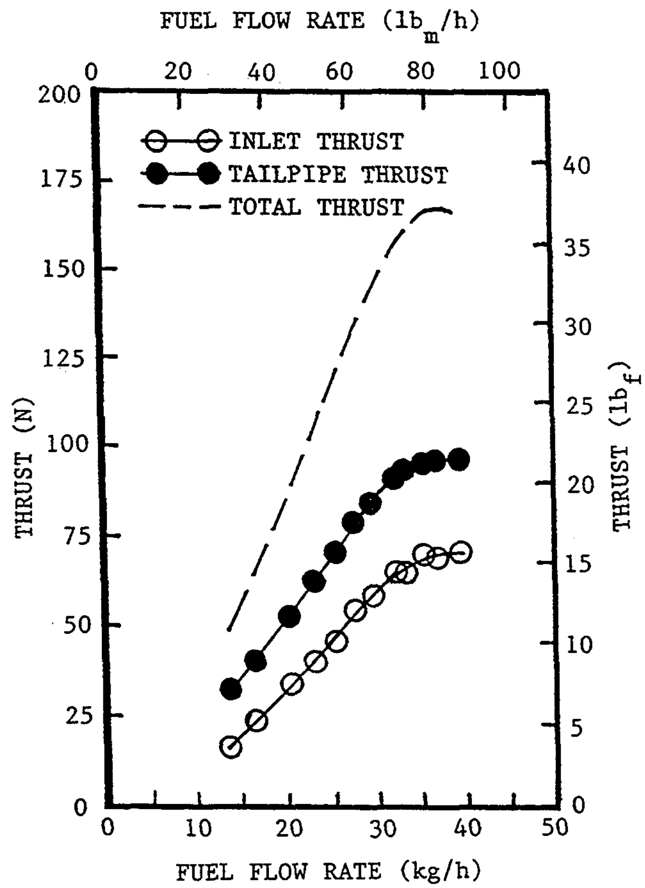

Fig. 4 The necessity for a flow rectifier as illustrated by the performance of a four-inlet pulsejet without flow rectification.

Alternatives to the device shown in Fig. 5 include an inlet offering a high flow resistance to back flow with a low resistance to inflow. However such a device behaves somewhat in the manner of a leaky non-return valve and hence involves substantial flow irreversibilities. A more attractive alternative employs a simple return bend, but without the thrust augmenting capability. Such an arrangement was used on the SNECMA Escopette pulsejet. Yet another alternative is to add a 180° bend in the tailpipe. By this means the inlet is directed rearwards. The SNECMA Écrevisse pulsejet employs an arrangement of this type[9].

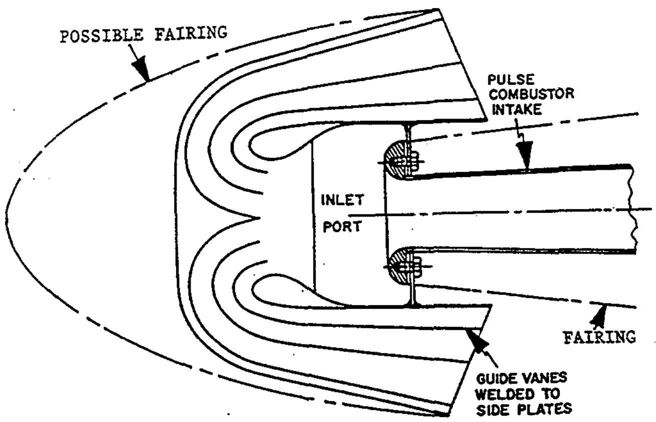

Fig. 5 Cross-section of a double-exit flow-rectifier of the thrust-augmenter type coupled to the single inlet of a SNECMA/Lockwood pulsejet.

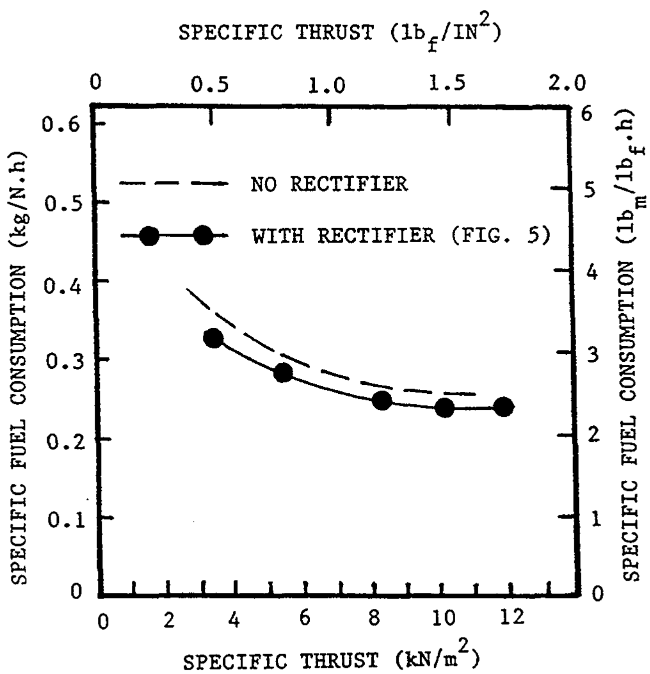

Fig. 6 Performance of a thrust-augmenter flow-rectifier installed on a small single-inlet SNECMA/Lockwood type pulsejet.

Fuel Systems

There is particular convenience in employing pressurized, liquified, gaseous fuels, such as propane or butane gas, for pulsejets intended for short range missions. This implies that complete, fuelled, engines are storable and it should be possible to specify a long shelf life. The larger units operating on propane or butane will require a fuel vaporizer heated by pulsejet waste heat, in the manner of a hot-air-balloon burner-vaporizer, to supply the fuel with the latent heat of vaporization. The thrust of a pulsejet is regulated by control of the fuel supply only over a mass flow range of about 3:1, or more, giving a range of thrust of about 4:1 between the maximum to minimum thrust levels. The performance curves presented in Fig. 4 and 6 were obtained by regulating the fuel supply only.

Alternatively liquid fuels such as gasoline or kerosene are also usable. They can be supplied by means of a pressurized fuel system or by means of a carburetter equipped with a non-return valve. Two of the performance curves shown in Figs. 7 and 8 were obtained using the latter system with gasoline fuel.

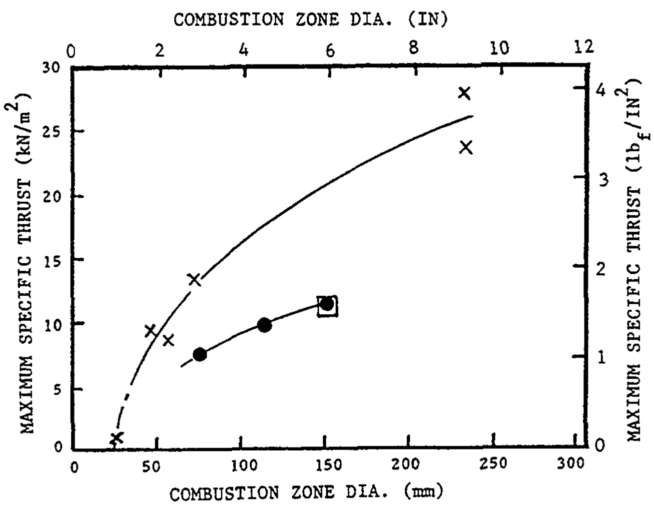

Fig. 7 Maximum specific thrust at SLS conditions versus combustion zone diameter:
x x SNECMA/Lockwood type pulsejets
• • Carburetted SNECMA/Lockwood pulsejets
□ Four-inlet pulsejet.

Unit Size and Specific Performance

It has been found experimentally that the specific thrust (thrust per unit combustor cross-sectional area) increases with increasing combustion zone diameter as indicated in Fig. 7 and that specific fuel consumption decreases, although less dramatically, with an increase in combustion zone diameter as shown in Fig. 8. These findings are supportable on the basis of an analytical study[10]. Essentially the reasoning hinges on the sensitivities of non-steady flows to boundary layer influences and hence to flow Reynolds numbers as they influence, primarily, internal friction losses and secondarily heat losses to the surroundings. Non-steady, and reversing, flows tend to "scrape off" boundary layers and re-establish new, growing, boundary layers. Thus the larger units suffer less performance degradation due to this cause than geometrically similar smaller ones. Additional experimental evidence suggests that the smallest operable pulsejet has a combustion zone diameter of almost 22 mm (≈ 0.87 in).

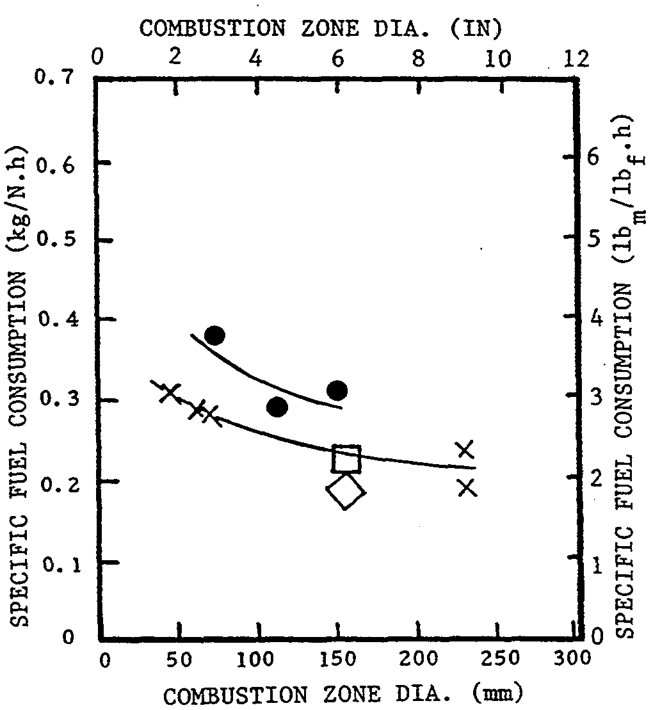

Fig. 8 SFC for maximum thrust at SLS conditions versus combustion zone diameter:
x x SNECMA/Lockwood type pulsejets
• • Carburetted SNECMA/Lockwood pulsejets
□ Four-inlet pulsejet
◇ Four-inlet pulsejet, 85% max. thrust.

Unit operating frequency depends, primarily, upon unit length and varies but little with thrust level although it does tend to increase very slightly, as the fuel supply is increased from the minimum to the maximum value. For units of approximately 1500 mm (≈ 60 in) length operating frequency at maximum thrust is about 200 Hertz. Operating frequency is, to a first approximation, inversely proportional to unit overall length.

Pulsejet Specifications

The data presented in Figs. 7 and 8 plus the output of a design exercise allows the approximate specifications of flight-weight pulsejets to be derived. These specifications are presented in summary form in Table 1 for four units, three of the single inlet type and one of the four inlet variety.

Table 1 Aerovalved-pulsejet specifications with flow rectifier

PROPERTY	INTERNAL DIAMETER			
	SINGLE INLET			4 INLETS
	76 mm (3 in)	152 mm (6 in)	228 mm (9 in)	152 mm (6 in)
Overall length (excluding rectifier): mm, (in)	1278 (50.3)	2556 (100.6)	3834 (150.9)	1526 (60.1)
Max. SLS thrust: N, (lb_f)	64 (14.4)	389 (87.6)	1075 (241.7)	199 (44.6)
SFC at max. thrust: kg/N.h, ($lb_m/lb_f.h$)	0.29 (2.84)	0.23 (2.25)	0.21 (2.05)	0.22 (2.15)
Minimum SFC kg/N.h, ($lb_m/lb_f.h$)	0.29 (2.84)	0.23 (2.25)	0.21 (2.05)	0.18* (1.76)*
Thrust/weight ratio (estimated)	4.2	7.0	8.5	6.0
Max. Thrust/ combustion zone csa: kN/m^2, (lb_m/in^2)	14.0 (2.04)	21.3 (3.09)	26.2 (3.80)	10.9 (1.58)
Max. Thrust/length from top line: N/m, (lb_m/ft)	50.1 (3.44)	152.2 (10.4)	280.4 (19.22)	130.4 (8.91)

* At 85% maximum thrust

Comparison With Other Propulsors

Approximate comparisons of valveless, or aerovalved, pulsejets with other, more conventional, air breathing propulsion technologies are presented in Fig. 9 and 10 in terms of specific fuel consumption versus sea-level static thrust and thrust/weight ratio versus sea-level static thrust respectively[11].

It can be seen from Fig. 9 that the specific fuel consumption of aerovalved pulsejets is substantially higher than for other air-breathing propulsors. This serves to emphasize the disadvantage of pulsejets for long duration missions. However, it appears that for very low thrust levels commercially produced turbo-machinery is not available and, if it became available[12], it would, presumably, be of higher first cost than a pulsejet of equal thrust.

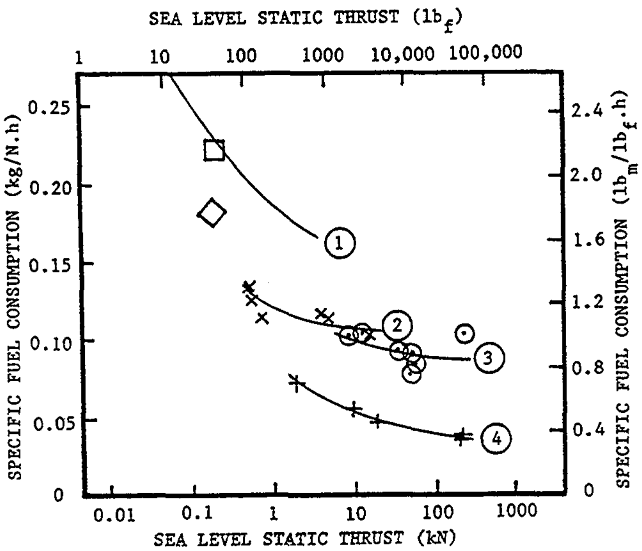

Fig. 9 SFC versus maximum SLS thrust:

1. **Single inlet aerovalved pulsejets**
   □ Four-inlet pulsejet
   ◇ Four-inlet pulsejet, 85% max. thrust
2. **Pure jets with centrifugal compressors X**
3. **Pure jets with axial-flow compressors ⊙**
4. **Best economy turbofans +.**

In terms of thrust-to-weight ratio carefully designed aerovalved pulsejets offer significant advantages, at low thrust levels, compared with available turbo-machinery as can be seen from Fig. 10. In terms of thrust/weight ratio multiple inlet units offer no advantages over the longer single-inlet units. The advantage of, for equal combustion-zone diameters, the reduced length of multiple-inlet pulsejets is offset by virtue of their lower thrust per unit of frontal area. However, in the most general sense the aerovalved pulsejets compare favourably in terms of thrust/frontal area with small gas-turbine jet units equipped with centrifugal compressors. This is the type of gas-turbine likely to be used for low-thrust level applications and hence to compete with the pulsejets.

It is not currently possible to compare the performance of the aerovalved pulsejets described here with engines of the pulse-detonation wave variety as definitive performances for units of this type do not yet appear to be available. In any case it seems to be necessary to carry oxygen on board to initiate, in a short distance, the detonation wave in such units hence they are not, in the truest sense, air-breathing propulsors.

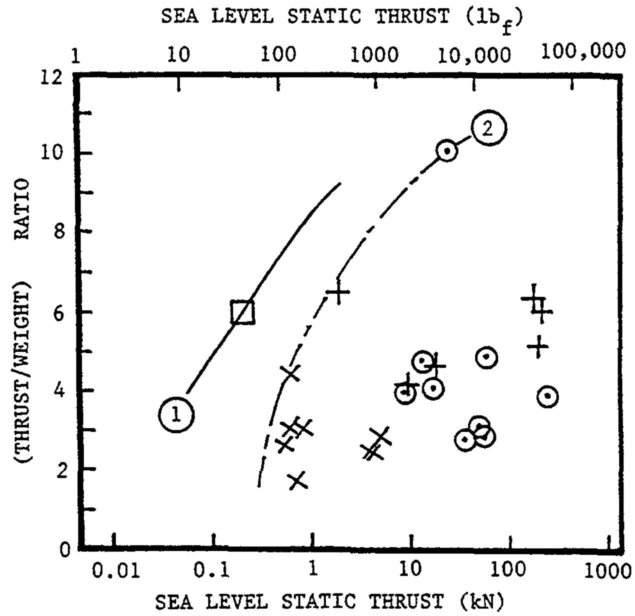

Fig. 10 Thrust-to-weight ratio versus maximum SLS thrust:

1. **Aerovalved pulsejets (4-inlet □)**
2. **Gas-turbine envelope curve (code as for Fig. 9).**

Influence of Flight Speed

The nature of the influence of flight speed on the performance of an aerovalved pulsejet depends, to a major extent, on the care taken with engine installation. Figure 11 shows the performance, predicted by SNECMA[9], of carefully installed pulsejet of the SNECMA Écrevisse type operating up to a flight Mach number of 0.8. An engine of this type was subsequently used as the sole propulsion unit of a UAV that achieved a flight Mach number of 0.85.

The writer's own experience with aerovalved pulsejets operating under simulated flight conditions is minimal since most of his work has been directed at the development of pulse, pressure-gain, combustors for use in gas turbines. However a very rudimentarily installed, early, aerovalved pulsejet of his design has been tested,

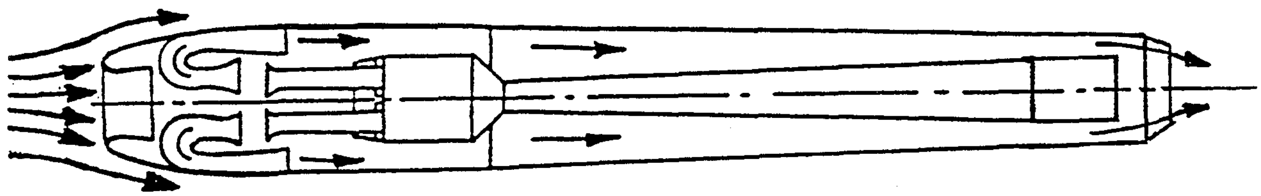

Fig. 12 A carefully faired, shrouded, four-inlet aerovalved pulsejet with four asymmetric thrust-augmenter flow rectifiers (diagrammatic: to scale).

under simulated flight conditions, up to a Mach number of 0.3 without problems. This engine which was very lightly loaded compared with the units described here could be expected to be more sensitive to flight Mach number than the highly loaded pulsejets under discussion. It appears, from the experiences of other workers, that the engine inlet should be shielded from the direct impingement of ram air at high subsonic Mach numbers. The flow rectifier (Fig. 5) tends, in any case, to offer such shielding. A more elaborate engine installation is illustrated diagrammatically in Fig. 12.

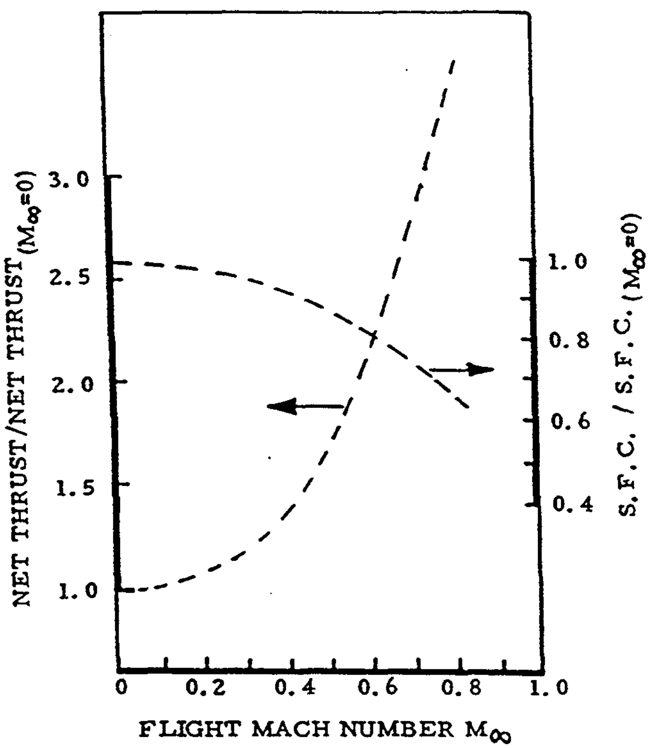

Fig. 11 Influence of flight Mach number on the performance of a carefully installed SNECMA Écrevisse aerovalved pulsejet (Results due to SNECMA[9]).

Conclusions

Valveless, or aerovalved, pulsejets do not incorporate any moving components and are amenable to thrust modulation solely by variation of the fuel supply rate. The great simplicity of aerovalved pulsejets suggests their use in expendable UAVs such as target drones, etc.

The generally high specific fuel consumption of pulsejets, is in large measure, a consequence of their very low charge pre-compression prior to combustion. This inhibits direct competition with turbo-machinery type air-breathing propulsors at high thrust levels. A more than 20% reduction in pulsejet specific fuel consumption is possible, at about 85% of maximum thrust, by employing pulsejets with multiple inlet passages. In comparison with small turbojets with centrifugal compressors aerovalved pulsejets are competitive in terms of thrust per unit cross-sectional area.

It is, therefore, concluded that aerovalved pulsejets are most suitable for small UAVs requiring maximum thrust thrusts of up to about 800 N (≈ 180 lb_f). The shorter the duration of the mission the greater the relative benefit of selecting an aerovalved pulsejet. The high specific fuel consumption of pulsejets mitigates against missions of long duration.

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