APPLIED THERMODYNAMICS

Gas Turbine Engines
(Module IV)

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List of Topics

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Lecture 1

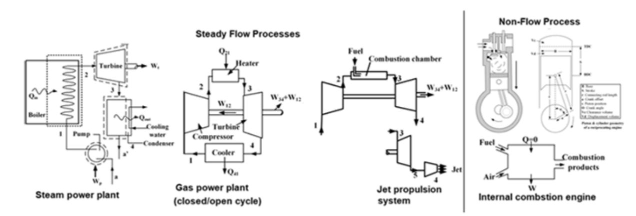
Gas Turbine Engine – Components and Thermal Circuit Arrangement

- Gas Turbine System
- Working Feasibility
- Thermodynamic Feasibility
- Gas Turbine Engine vs Internal Combustion Engine
- Thermal Circuits for Gas Turbine Systems
- Aircraft Propulsion
- Industrial Gas Turbines

Gas Turbine System

Background:

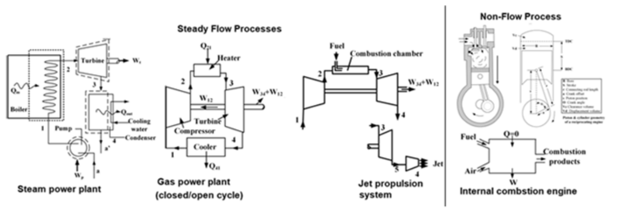
- There are various means of producing mechanical power through different working fluids e.g. 'water' in hydro-power plants, 'steam' in steam power plant, 'fuel-air mixture' in reciprocating engines and gas turbine engines.
- Reciprocating engines involve "non-flow processes" accomplished in a cylinder fitted with a reciprocating piston. Gas turbine engines are analogous to steam power plants in which individual processes are "steady-flow processes" carried in separate components.



Gas Turbine System

Background:

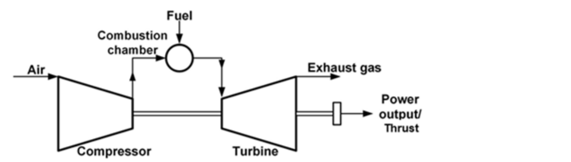
- All the above methods of power generation have relative merits and disadvantages. Their importance is realized with an overall efficiency of 30-40%, for instance, a steam plant producing over 1000 MW power, have efficiencies in the order of 40%.
- Gas turbine engines began to compete successfully with other counterparts in middle of 1950 (after second world war) with intention of generating 'shaft-power' from a 'turbojet engine' used for aircraft propulsion.



Gas Turbine System

Background:

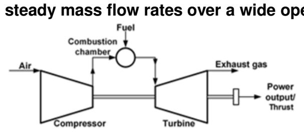
- The main use of present day applications of 'gas-turbine engine' include aircraft propulsion, marine propulsion and electric power generation (natural gas as fuel).
- A "constant-pressure" combustion is considered in open gas turbine cycle.
- For expansion of gases in a turbine, a 'pressure ratio' should be provided which is achieved through compression of working fluid.
- If there is no losses in either component, then power developed by the turbine is equal to that absorbed by the compressor. When coupled together, the combination would no more than turn itself.



Gas Turbine System

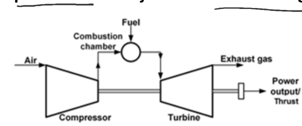
Background:

- The applications require the much higher power to be developed by the turbine. Hence, the additional energy must be added to raise the temperature of working fluid prior to the expansion.
- When the working fluid is 'air', a suitable means is to initiate combustion through a fuel for compressed air.
- The expansion of hot working fluid produces greater power output from the turbine so that it is able to provide reasonable power in addition to driving the compressor.
- Thus, the use of constant pressure combustion with a rotary compressor driven by a rotary turbine, mounted on a common shaft, gives the ideal combinations with steady mass flow rates over a wide operating range.



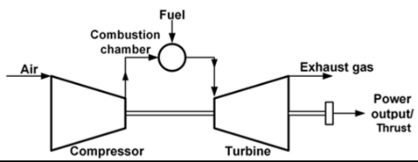
Working Feasibility

- In practice, the losses in the thermal cycle mostly occurs both at compressor and turbine which in turn increases the power absorbed by the compressor and decreases the power delivered by the turbine.
- The addition of fuel results useful power in the circuit but there is a limit to the rate of fuel that can be supplied for a given flow rate of air. The maximum fuel-air ratio governs the working temperature.
- This working temperature should be within the allowable temperature of the highly stressed turbine blade. This value depends on the creep strength of materials used in construction of turbine blades and required working life.
- Hence, there are two main factors affecting the gas turbine engine all-round performance: component efficiency and turbine working temperature.



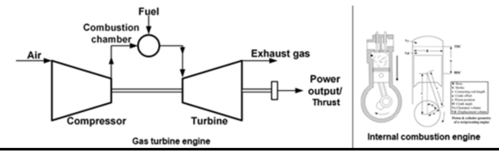
Thermodynamic Feasibility

- There are two possible systems of combustion for heat addition processes: constant pressure and constant volume. Thermodynamically, constant volume combustion is efficient.
- With heat addition at constant volume, it is necessary to isolate the combustion chamber from compressor and turbine. So, the combustion phenomena would be intermittent (difficulties smooth operation).
- In constant pressure cycle, the combustion is a continuous process without need of mass flow regulation and capability of handling higher flow rates.
- An advanced gas turbine engine can operate with pressure ratios up to 35 with component efficiencies of 85-90% and turbine inlet temperatures exceeding 1650 K.



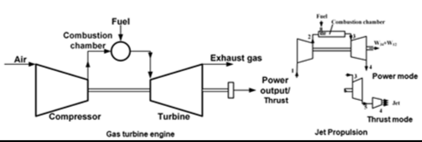
Gas Turbine Engines vs Internal Combustion Engines

- IC engines are reciprocating type (piston-cylinder device) while GT engines use rotary compressors and turbines.
- Combustion process in IC engines occurs either at constant volume (SI engines) or at constant pressure (CI engines).
- All the processes in IC engines occur in a single component while different components are linked together in a gas turbine unit.
- For performance enhancement of a gas turbine unit, additional components (such as intercoolers between compressors, reheat combustion chambers between turbines, after burners etc.) becomes a necessity. They add to complexity, weight and cost.



Gas Turbine Engines vs Internal Combustion Engines

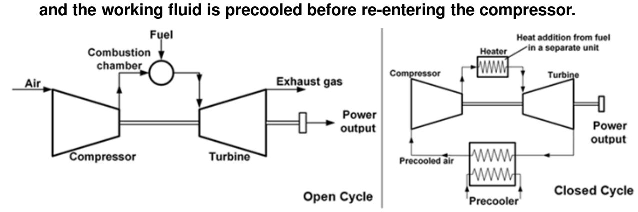
- The way in which the components are linked to together affects the maximum overall efficiency, but also with power output, rotational speed and torque.
- The gas turbine engines are extremely versatile prime mover to perform variety of functions – electric power generation, mechanical drive systems, jet propulsion to supply the process heat and compressed air.
- The components of gas turbine unit can be linked together to produce either "shaft power" in electric power generation/mechanical drive systems or "thrust" in aircraft propulsion system.
- The inefficiencies in the compression and expansion process becomes greater for smaller stand-alone gas turbine units. Thus, a heat exchanger is frequently used to improve cycle efficiency so as to compete for economy with small oil/petrol engine.



Thermal Circuits for Gas Turbine Systems

<u>Open cycle vs closed cycle</u>:

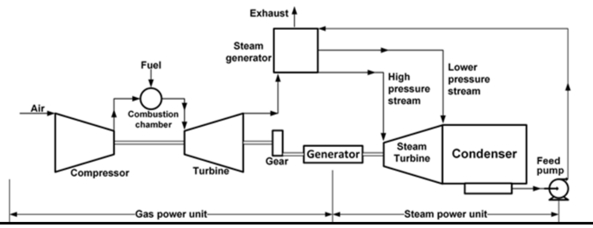
- Universally, an open cycle gas turbine is well-accepted. The fresh atmospheric air is drawn to the circuit continuously and energy is added by the combustion of the fuel in the working fluid itself. The products of combustion are expanded in the turbine and exhausted to the atmosphere.
- The air or any other gas is repeatedly circulated through the machine in a closed cycle. Thus, fuel can not be burnt in the working fluid. So, necessary energy is added in a heater wherein the fuel is burnt in a separate air stream and the working fluid is precooled before re-entering the compressor.



Thermal Circuits for Gas Turbine Systems

Combined gas and steam cycle:

- A combined cycle involving gas and steam power unit have ability for electric power generation with thermal efficiencies up to 60% as compared to individual units where thermal efficiencies are limited up to 40%.
- The gas turbine exhaust (at 500-600°C) can be used to raise steam in a "waste heat boiler / heat recovery steam generator" and further utilized in a steam turbine to drive electric generator. This method of power generation is referred as "cogeneration or combined heat and power".



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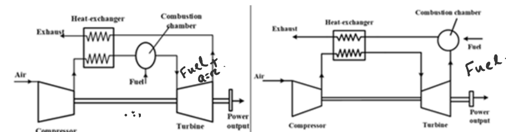
Thermal Circuits for Gas Turbine Systems

Open cycle single-shaft arrangement:

- When a gas turbine engine is required to operate at fixed-speed and fixed-load condition (base load power generation), a single shaft arrangement is suitable.
- The engine can not adopt itself with the changes in the load and rotational speed. The high inertia due to drag of the compressor is reduces the danger of over-speeding in the event of electric load loss.
- A heat exchanger can be added to the circuit to improve thermal efficiency at low pressure ratio operation.
- A combustion chamber can be placed before the turbine so that the combustion products expand in the turbine. The other option is to place after the turbine so that products combustion constituents do not erode/corrode the turbine blades.



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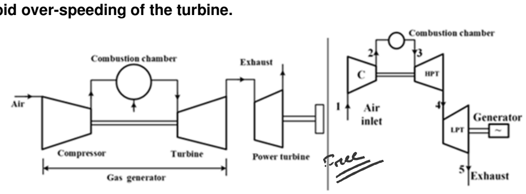
Thermal Circuits for Gas Turbine Systems

Open cycle with twin-shaft arrangement:

- When a gas turbine engine is required to operate at variable-speed and variable-load condition, mechanically independent (or free) power turbine is desirable.
- In twin-shaft arrangement, the high pressure turbine drives the compressor and the combination acts as "gas generator" flow low-pressure "power turbine".
- The turbine for gas generator assembly runs at same speed with that of compressor while power turbine is designed to run at generator speed.
- A twin-shaft engine has a significant advantage in ease of starting compared to single-shaft unit. On the other hand, shedding of electrical loads can lead to rapid over-speeding of the turbine.



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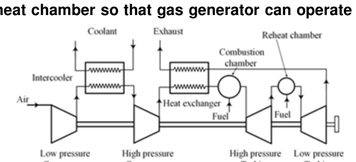
Thermal Circuits for Gas Turbine Systems

Open cycle with reheat and intercooling arrangement:

- The performance of gas turbine can be improved substantially by reducing the work of compression and /or increasing work of expansion.
- At a given compressor pressure ratio, the power required per unit quantity of working fluid is directly proportional to the inlet temperature. So, if the compression is achieved through two or more stages with intermediate intercooling, then it is possible to reduce the work of compression.
- The turbine output can be increased by dividing the expansion into two/more stages and reheating the gas to a maximum possible temperature.
- A complex cycle can have possibility of varying power output by controlling the fuel supply at reheat chamber so that gas generator can operate at its optimum condition.



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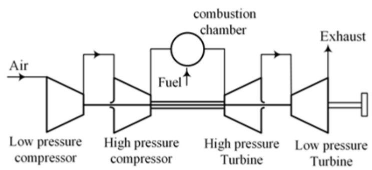
Thermal Circuits for Gas Turbine Systems

Open cycle with multi-spool arrangement:

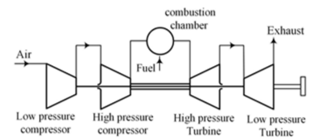
- In order to obtain high thermal efficiency without a heat exchanger, a high pressure ratio is required. But the compression process puts a limitation.
- Generally, compressors in gas turbine engines are rotary in nature because of larger flow handling capacity. At full power, the density at the outlet is much higher than inlet. On the other hand, the densities at the exit of compressor is too low at rotational speeds below the design value.
- This un-stability due to aerodynamic vibration leads to flow reversal at low power and overheating of turbines (known as 'flame out') at full power. It is very severe when the pressure ratio is more than 8 in a single compressor.



Thermal Circuits for Gas Turbine Systems

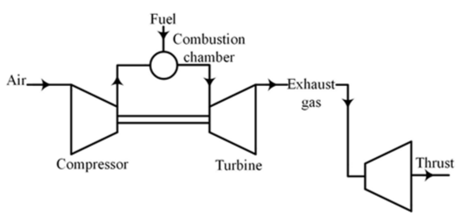
Open cycle with multi-spool arrangement:

- One of the method is to overcome this problem is to split the compressor into one or more section, permitting them to run at different rotational speeds.
- With mechanically independent compressors, each one will have its own turbine. The low-pressure compressor is driven by low-pressure turbine and the high-pressure compressor is driven by high-pressure turbine.
- The power may be taken from either the low-pressure shaft or from a separate turbine. Such arrangement is known as twin-spool engine and it is justified when cycle pressure ratio is above 35.
- Although, the 'spools' are mechanically independent, their speeds are related aerodynamically. The spool arrangement is very common for aircraft engines.



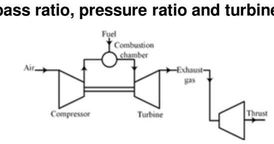
Aircraft Propulsion

- The greatest impact of gas turbine has been seen in aircraft propulsion.
- A simple "turbojet engine" has a turbine that produces enough power to drive the compressor and the gas leaving the turbine at high pressure and temperature is expanded to atmospheric pressure in a propelling nozzle .
- For lower speed aircrafts (less than 200 m/s), a combination of propeller and exhaust jet provides best propulsive efficiency (Turboprop engine).
- A turboshaft engine is used in helicopters use free-turbine turboprop with power turbine driving the helicopter main/tail rotor unit.



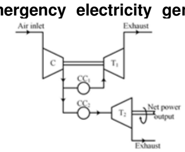
Aircraft Propulsion

- At high subsonic speeds (~ 280 m/s), a propulsive jet of smaller mass flow but higher velocity is achieved by a "turbofan (or bypass) engine".
- A part of air is delivered by a low-pressure compressor or fan bypasses the rest to the core of the engine (high-pressure compressor, combustion chamber and turbine) to form an annular propulsive jet of cooler air surrounding hot jet.
- It results in a let of lower velocity which not only provides a better propulsive efficiency but also significantly reduces exhaust noise.
- Heat exchangers has no place for aircraft propulsion units (bulky & weight).
- In airline applications, the fuel consumption has paramount importance, requiring high bypass ratio, pressure ratio and turbine inlet temperature.



Industrial Gas Turbine

- The life span for an industrial plant is about 100,000 hours without major overhaul. The limitations of size and weight is no longer a concern. The aircraft power plant makes effective use of kinetic energy of gases leaving the turbine which is not the essential requirement of industrial gas turbine.
- The availability of fully-developed aircraft engine offered attractive possibility of "aero-derivative" engines through substitution of power turbine in place of exhaust nozzle.
- Modifications are required to burn natural gas/diesel in the combustion chamber.
- Aero-derivative gas turbines are widely used for applications for gas/oil transmission pipelines, peak-load and emergency electricity generation, naval propulsion etc.



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THANK YOU

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