2 INTERNAL COMBUSTION TURBOMOTORS

2.1 GAS TURBINES

2.1.1 OPERATING PRINCIPLES

In its simplest and most common form (Figure 2.1.1), a gas turbine (GT), also called combustion turbine, is composed of three elements:

- a compressor, usually centrifugal or axial, which is used to compress the ambient air at a pressure between 10 and 30 bar in modern machines;
- a combustion chamber in which fuel is injected under pressure, combusted with air previously compressed (the latter in large excess in order to limit the exhaust gases temperature at the turbine inlet);
- a turbine, usually axial, in which are expanded the high temperature gases exiting the combustion chamber. A significant proportion (60-70%) of the work recovered on the shaft of the turbine is used to drive the compressor.

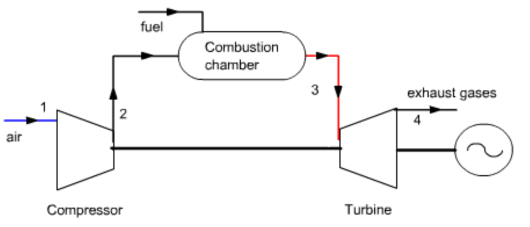

Figure 2.1.1: Sketch of a gas turbine

In this form the gas turbine engine is a continuous stream internal combustion engine. Note that the gas turbine term comes from the working fluid state, which remains gaseous, and not the fuel used, which can be both gaseous and liquid (gas turbines typically use natural gas or light petroleum distillates). There are also closed cycle gas turbines, used for special applications, including nuclear, as we shall see below and in Chapter 7 of Part 4. Of course, then it is an external combustion engine.

To achieve compression ratios r of 20 or 30, the **compressor** is multistage, with sometimes intermediate cooling to reduce the work consumed. Axial rotors are made of a stack of discs, either mounted on a central shaft, or drum assembled on their periphery. The materials used are aluminum or titanium alloys for the first stages and steel alloys and refractory alloys for last stages that can withstand temperatures up to 500 °C.

The **combustion chamber** is normally constructed of refractory alloy. Various types will be presented later.

In gas turbine open cycle, the main technological constraints are at the first stages of the **expansion turbine**, through which flow the exhaust gas at high temperature.

The parts most at risk are especially rotor blades, which are very difficult to cool and in addition particularly sensitive to abrasion. It is therefore important to use a very clean fuel (no particles and chemicals that may form acids), and limit the temperature depending on the mechanical characteristics of the blades.

The materials used for turbine blades are refractory alloys based on nickel or cobalt, and manufacturers intend to make use of ceramics in the future.

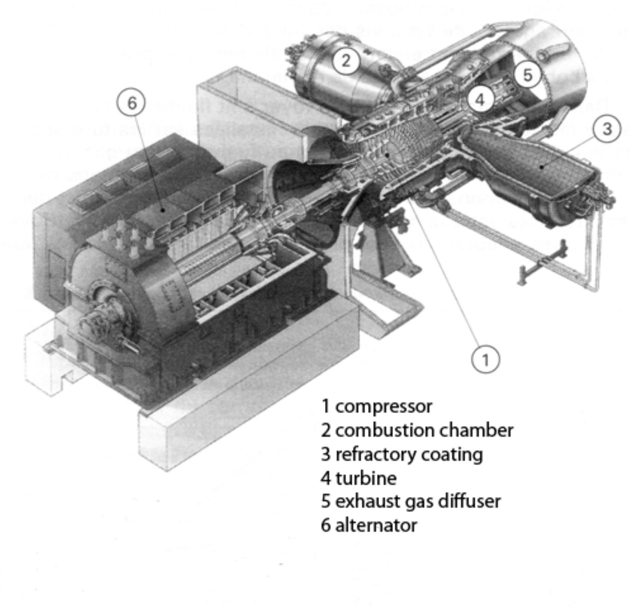

Figure 2.1.2: Siemens gas turbine, Extrait de Techniques de l'Ingénieur, Génie Energétique

As the cycle efficiency is itself an increasing function of temperature, major technological developments have been devoted to the fabrication, first of efficient cooling systems of the blades, and second of materials resistant at high temperatures. For half a century, there has been a gradual increase (about 20 °C per year) of the turbine inlet temperature, now reaching 1300 to 1500 °C.

Two broad categories of gas turbines are generally distinguished: industrial gas turbines, heavy and robust, but of average performance (efficiency η between 28 and 38%), and gas turbines derived from aviation or "aeroderivative" much more efficient and light (η between 35 and 42%), but also more expensive. The capacities of the first range from tens of kW (microturbines) to several hundreds of MW, while those of aeroderivative machines are generally between a few hundred kW to tens of MW, corresponding to those of aircraft engines. We shall indeed see in section 2.2.2 that most jet engines used in aviation today are in fact variations of the gas turbine open cycle. The aviation market has helped fund major technological development programs on these engines, which led to the development of highly efficient gas turbines, which could supplant industrial gas turbines, or allow hybrid turbine design of enhanced efficiencies and low cost, including components of existing jet engines for high pressure compressor and turbine sections, and industrial parts for low-pressure sections.

Early gas turbines were manufactured at the beginning of the twentieth century, in France by the Société Anonyme des Turbomoteurs in Paris and in Switzerland by the Brown Boweri company in Neuchatel. The net work produced by these machines is equal to the difference between the useful work done by the turbine and the work required to compress the air. In the early achievements, it was very low, and it was not until the 1930s that industrial applications have really started to grow, thanks to the improved performance of compressors and turbines, mainly due to advances in the understanding of gas flows, which continue today with 3D modeling.

For thirty five years, gas turbines have been experiencing a very strong development in many applications: air transport, power generation, cogeneration, driving machines (compressors and pumps), marine propulsion, where they make a growing breakthrough. Arguments in their favor include their small size, excellent power to weight ratio, good performance and low emissions of pollutants.

Among other advantages of gas turbines, we can mention:

- their startup is very fast: while it takes 24 hours to start up some steam plants, a gas turbine reaches its rated speed in 15 to 20 minutes, and capacity can be modulated very rapidly between the full load and 20 to 30% of this value;
- auxiliary equipment is small and cheap, and there is no need of water for cooling the cycle, since the exhaust gases are released into the atmosphere. In addition, the construction time on site is reduced, because the machine is assembled in factory.

Investment costs range from 350 Euros/kW for machines between 1 and 10 MW to approximately 180 Euros/kW for units larger than 50 MW. The price per kW installed, however, is higher because of auxiliary equipment and infrastructure. For electricity generation, it varies between 300 and 450 Euros/kW.

Their main drawback is the use of clean fuels, which is therefore generally expensive. Also note that their performance depends significantly on site conditions, and degrades when the outside temperature rises or when the pressure drops.

2.1.2 EXAMPLES OF GAS TURBINES

2.1.2.1 Industrial Gas Turbines

Siemens gas turbine of Figure 2.1.2 is characterized by silo combustion chambers (multi-fuel, emission control, radiative protection of turbine blades).

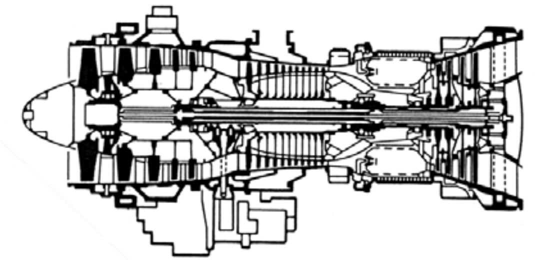

Figure 2.1.3: Rolls Royce SM1C, Reproduced courtesy of Rolls -Royce plc

2.1.2.2 Aeroderivative gas turbines

Rolls Royce SM1C two shaft turbine (Figure 2.1.3) (marine propulsion) has a capacity of 20 MW, a compression ratio r = 22 (5 + 11 stages of compression, 2 + 2 expansion). Its turbine inlet temperature is 740 °C.

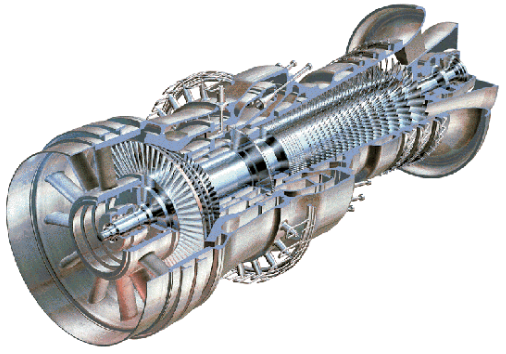

Figure 2.1.4: Alstom Power GT24/26

The Alstom Power GT24/26 gas turbine of Figure 2.1.4 is a new generation of aero-derivative turbine, in the sense that, although developed using aviation techniques, there is no equivalent turbojet, given its high capacity (180/260 MW) and its combustion mode (sequential). Its characteristics are as follows: r = 30 (22 stages of compression, 1 + 4 expansion), turbine inlet temperature 1255 °C; $\eta = 37.5\%$. The GT 24 has a rotation speed of 3600 rpm to provide electricity at 60 Hz, while the GT 26 rotates at 3000 rpm (50 Hz). Designed with equivalent mechanical stress in the blades, their capacities are respectively 180 and 260 MW, and their masses (with their bases) of approximately 225 and 370 tons.

Figures 1.1.4 and 1.1.5 presented in chapter 1 give an idea of the approximate size of a power plant based on this gas turbine: a base of 50 m by 70 m and a height of 25m.

2.1.3 MAJOR TECHNOLOGICAL CONSTRAINTS

2.1.3.1 Combustion chamber

The combustion chamber of a gas turbine, especially those derived from aviation, must satisfy severe constraints:

- ensure complete combustion of fuel;
- reduce emissions of pollutants;
- minimize pressure drop (which represents an increase in compression work);
- ensure good stability of the turbine inlet temperature;
- occupy as small a volume as possible while allowing proper cooling of the walls.

The diagram in Figure 2.1.5 shows a section of a flame tube combustion chamber, very commonly encountered in practice.

The compressed air exiting the compressor enters on the left side. It splits into two streams, one that provides wall cooling, the other entering directly into the combustion chamber, where it serves as oxidizer to the fuel injected in the central part. Given the low excess air locally, the flame reaches a high temperature (up to 2500 K) in the primary zone. Through holes at the periphery of the flame tube, the outside air is mixed with exhaust gases in the transitional zone, where temperature drops around 2000 K, and in the dilution zone, where one seeks to achieve a gas flow temperature as stable as possible to avoid the risk of local or momentary overheating.