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Erian A. Baskharone, D. Lee Hill
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1 Introduction to Gas Turbine Engines

1.1 Definition

A gas turbine engine is a device that is designed to convert the thermal energy of a fuel into some form of useful power, such as mechanical (or shaft) power or a high-speed thrust of a jet. The engine consists, basically, of a gas generator and a power conversion section, as shown in Figures 1.1 and 1.2.

In these figures, the gas generator consists of the compressor, combustor, and turbine sections. The turbine extracts shaft power to, at least, drive the compressor, which is the case of a turbojet. In most other applications, the turbine will extract more shaft work by comparison. The excess amount will be transmitted to a ducted fan (turbofan engine) or a propeller (turboprop engine), as seen in Figure 1.2. On the other hand, the shaft work may also be utilized in supplying direct shaft work or producing electricity in the case of a power plant or an auxiliary power unit (Figure 1.1). The fact, in light of Figures 1.1 through 1.5, is that different types of gas turbine engines result from adding various inlet and exit components to the gas generator. An always interesting component, in this context, is the thrust augmentation devices known as afterburners in a special class of advanced propulsion systems (Figure 1.4).

In principle, gas turbines are exclusively used to power airplanes, due to their high power-to-weight ratio. They have also been used for electric power generation in pipeline compressor drives, as well as propelling trucks and tanks. In fact, it would be unwise to say that all possible turbomachinery applications have already been explored.

1.2 Advantages of Gas Turbine Engines

Of the various means of power production, the gas turbine is, in many ways, the most efficient, due to specific exclusive features. The high power-to-weight ratio makes gas turbines particularly suited for propulsion application. Absence of reciprocating and rubbing members, by comparison to internal combustion engines, means fewer balancing problems and less lubricating oil consumption. Reliability of gas turbines, as a result, is much higher by comparison.

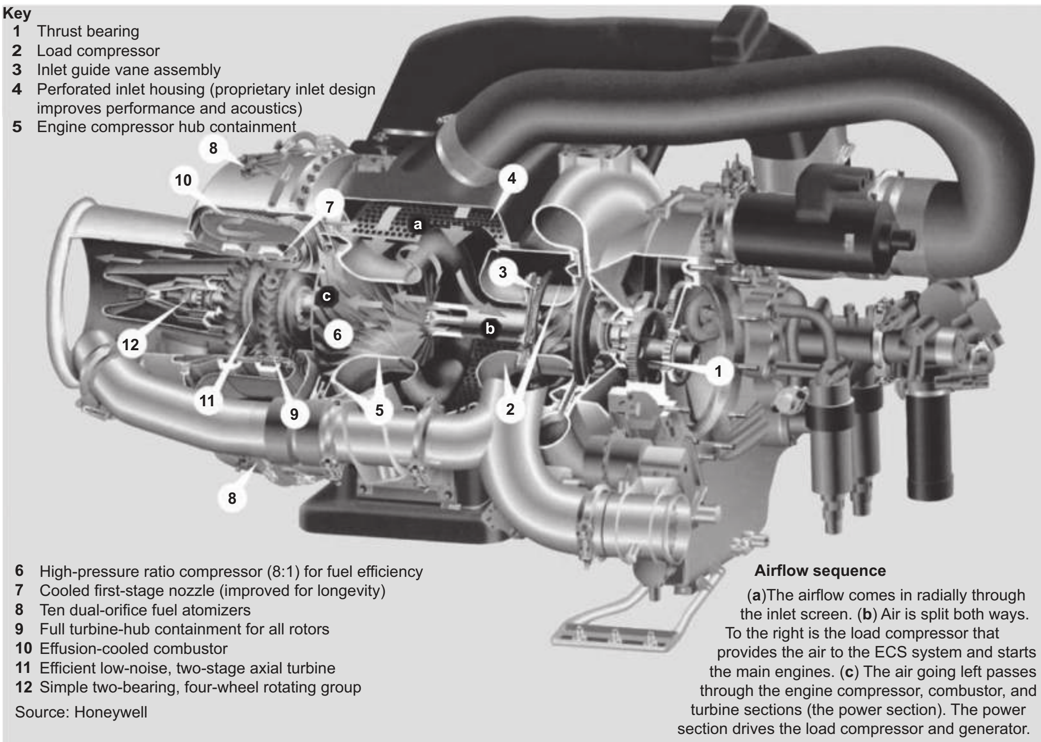
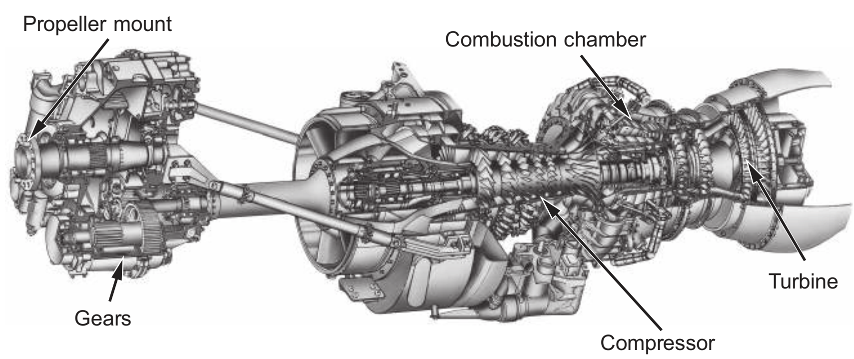


Figure 1.1 Example of an auxiliary power unit (Honeywell 131-9 APU).

Figure 1.2 Example of turboshaft engine (GE CT7-9).



1.3 Applications of Gas Turbine Engines

1.3.1 Power System Applications

This category includes such items as auxiliary power units (Figure 1.1), gas turbine power plants, as well as turbochargers (Figure 1.5). Note, by reference to the latter, that heavy and "bulky" components, such as radial turbines and centrifugal compressors, are typically

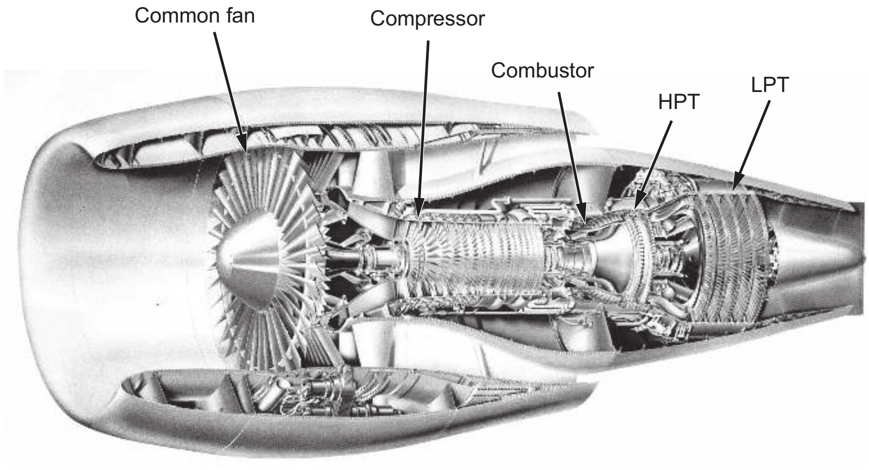


Figure 1.3 Example of a Turbofan engine (GE CF6-6 Engine).

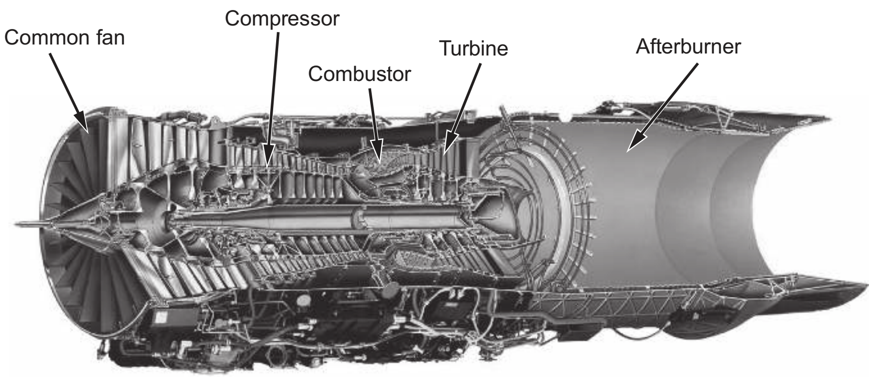


Figure 1.4 A turbofan engine with a bypass ratio of 42%. F-16 turbofan engine (United Technologies).

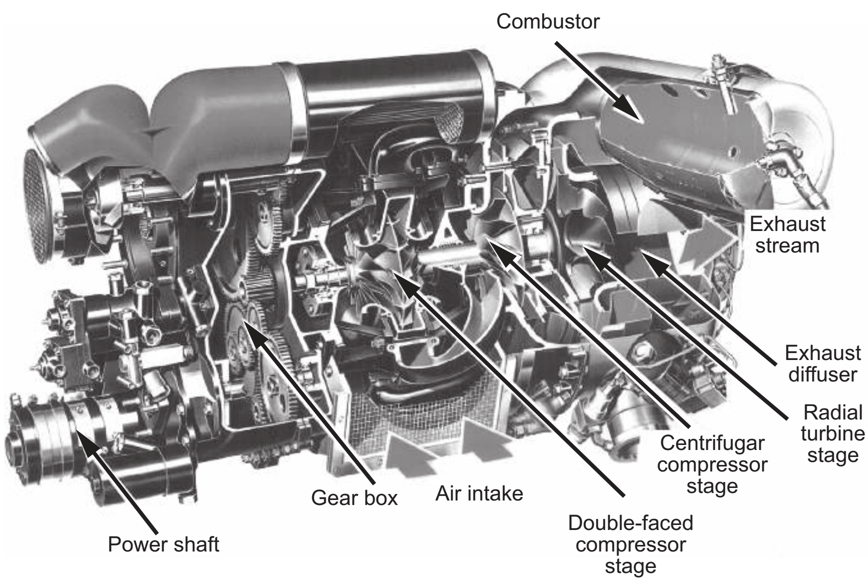


Figure 1.5 Example of the use of radial turbomachinery in a turbocharger. GTCP-85 turbocharger (Garrett Turbine Engine Co.).

tolerated in this type of application, for they are usually ground applications. Although it is not usually classified as such, a turboprop engine (Figure 1.2) belongs to the turboshaft engine category, a phrase that is synonymous with power system applications.

1.3.2 Propulsion Applications

Included in this category are turbojet, turboprop, and turbofan engines, without and with afterburning (Figure 1.4). These are illustrated in Figures 1.2–1.4. With the exception of turboprop engines, the thrust force, in this engine category, is generated by high-speed gases at the exhaust nozzle outlet. In fact, turboprop engines are functionally closer to power system turboshaft engines in the sense that they also provide a net output in the form of propeller-transmitted shaft power, which derives from the propeller.

1.4 The Gas Generator

Referring to Figures 1.1 and 1.2, the engine gas generator is composed of the compressor section, followed by the combustor, and leading to the turbine section. In jet engines, the responsibility of a gas generator is to produce a high-pressure, high-temperature stream of combustion products (predominantly air), which are allowed to expand down to (ideally) the local ambient pressure in an exhaust nozzle. This nozzle gives rise to a high-momentum gas stream generating, in turn, the thrust force that is necessary to propel the airframe. The final outcome in a power system, however, is different, as it is the gas generator's function to transmit shaft work to the power shaft, usually through a gear box, as shown in Figure 1.5. Being a frequent maintenance-needing component, the gear box can often be replaced by a "free turbine" type of arrangement, to obtain the same speed-reduction objective. Typically, the last in the turbine section, the free turbine stage is separately mounted on the inner of a coaxial twin-shaft assembly. One of the desirable features in using of a free turbine is the ease with which the engine can be started. The major drawback, however, is a significant performance deterioration under off-design operation modes.

1.5 Air Intake and Inlet Flow Passage

Attached to the gas generator, on the upstream end, is an air-intake section, which substantially differs from one engine category to another. In auxiliary power units (Figure 1.1), and turbochargers (Figure 1.5), the air-intake section is normally covered by a fine-mesh screen. This has the function of protecting the engine, particularly the turbine rotors, from the erosion effects that can be imparted by the solid objects, such as sand particles, in the inlet airstream.

As for propulsion systems, the majority of air-intake sections are as simple as annular (Figure 1.3). An exception to this rule is shown in Figure 1.2, for a typical turboprop engine.

In this case, the inlet section appears like a "smiling mouth," a clearly odd shape, that is primarily caused by the existence of the propeller in this region. As shown in the figure, a cross-section conversion, ultimately leading to a perfect annular duct, quickly follows. Upstream the compressor section, in turbofan engines, is a single- or multistage ducted fan that, by definition, is a smaller compressor in the sense of pressure ratio. The fan may partially exist in the "core" flow stream (Figure 1.3) or the secondary bypass duct (Figure 1.4).

1.6 Engine Exhaust Component

In a turboshaft engine, e.g., the turboprop in Figure 1.2 and the turbocharger in Figure 1.5, the engine typically ends with an exhaust diffuser. This device converts the incoming kinetic energy into a pressure rise before releasing it to the local ambient pressure. Typically an annular cross-section duct, the exhaust diffuser may, in part, rely on what is termed the "dump" effect, which is a result of abruptly ending the center body. While this sudden area enlargement does cause a pressure rise, it is perhaps on of the most undesirable diffusion means for the aerodynamic degradation that it imparts in this sensitive engine segment.

Aside from turboprop engines, propulsion systems will obviously have to end with a flow-accelerating device, namely one or more nozzles. As is well known, it is the converging–diverging DeLaval nozzle that is uniquely capable of producing the highest exit kinetic energy. Under normal operating conditions, the nozzle(s) can then produce supersonic exit velocity. Referring to the turbofan engine in Figure 1.3, as an example, a viable exhaust system may very well be composed of two separate annular nozzles. Of these, the inner nozzle handles the core (or primary) flow stream. The outer nozzle, on the other hand, concerns the secondary (or the bypass duct) flow stream. Returning to Figure 1.3, note that the two exhaust nozzles here are both of the converging (or subsonic) type. In many other turbofan configurations, a single "mixer" nozzle is utilized for both primary and secondary flow streams. The decision to leave these flow streams separate or to mix them is by no means obvious. Such a decision will typically be based on such variables as the secondary-to-primary total-to-total pressure ratio, at the point where the two streams can join one another, as well as the bypass ratio. There is, however, an acoustic incentive in mixing these two flow streams, for reducing the engine noise. In this case, it is notably less.

1.7 Multispool Engine Arrangements

If the gas turbine is required to operate under fixed-speed, fixed-load types of conditions, then the single-shaft arrangement (whereby all rotating components spin at the same speed) may be suitable. In this case, flexibility of operation (i.e., the rapidity with which the machine can lend itself to changes of load and rotational speed) is not important.

However, when flexibility in operation is of primary importance, which is typically the case, the use of a mechanically independent (or free) power turbine becomes desirable. In this twin-shaft arrangement in Figure 1.1, the high-pressure turbine derives the upstream compressor. Such a coaxial shaft arrangement could theoretically alleviate the need for an expensive and rather *bulky gear box in turboshaft engines where the net power output is to be delivered at low speed. An example here is a turboprop engine, where the load is naturally the propeller, a component that spins at a small fraction of the core engine.

Twin shaft (or twin spool) configurations are particularly critical in large-scale electricity-generating units in the turboshaft category of gas turbines. In this case, the free turbine is designed to run at the alternator speed, again eliminating the need for an expensive speed-reduction gear box, or making it possible to considerably reduce its size. Note that an additional advantage here is that the starter unit need only be sized to run over the gas generator. Nevertheless, the free turbine engine configuration is known to cause major performance degradation under off-design operation modes.

1.8 Thermodynamic Cycle in a Single-Combustor Engine

Composing a conceptual Brayton-type cycle, the sequence of thermodynamic events in a simple turbojet engine is sketched on the Mollier enthalpy–entropy (h–s) diagram in Figure 1.6. For reference purposes, the ideal cycle is shown first, where all of the compression and expansion processes are isentropic, and no total (or stagnation) pressure loss occurs

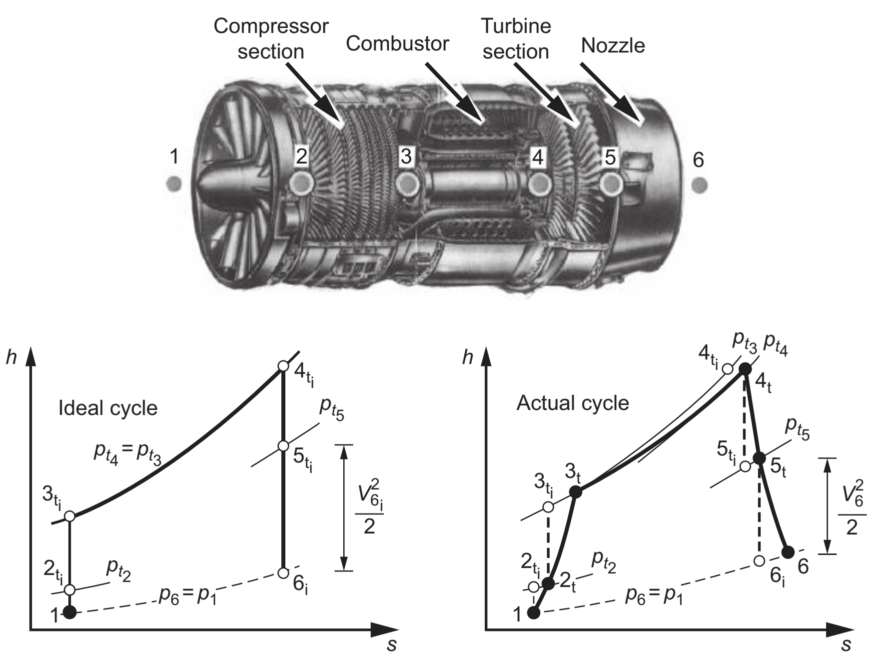


Figure 1.6 Brayton thermodynamic cycle for a typical single-spool turbojet engine. Subscript "i" refers to an ideal state, or the end state of an isentropic process. Subscript "t" refers to a total (stagnation) property, or a state that is defined by its total properties.

over the combustor. The real-life sequence of processes is separately shown in the same figure. As seen, the principle of entropy production, a quantitative interpretation of the Second Law of Thermodynamics, is clearly represented in this figure. This is exclusively applicable to the compressor and turbine flow processes, where the ideal (isentropic) flow processes are shown alongside of the real-life process. Note that the net useful outcome of the engine is the production of a high-velocity gases (products of combustion), which are responsible for propelling the airframe. Referring to Figure 1.6, this velocity is identified as V_6. As would be expected, the ideal-cycle "theoretical" operation gives rise to a higher V_6 magnitude by comparison. Finally, note that the combustor-exit/turbine-inlet total temperature (T_{t4}) is maintained fixed in this entire figure. The reason is that this particular variable is a strong function of, among others, the turbine metallurgical strength and shaft speed. In practice, this temperature is therefore treated as a design constraint.

1.9 Importance of Metallurgical Progress

Since its inception, and for more than six decades now, gas turbine engines have been under virtually uninterrupted development and upgrade. Design refinements have progressively been at a pace that is proportional to advancements in the "strength-of-materials" area. These metallurgical advancements have been focused on and continually implemented in the turbine area. The reason is that turbine stages, especially the earlier ones, are exposed to a critically high temperature (typically above 1,400 K), while spinning at a high-speed exceeding, in some applications, a magnitude of 100,000 rpm. Combined, these factors simply constitute a recipe for a harsh mechanical environment. Nowadays, however, ceramic turbine rotors are capable of spinning at more than 120,000 rpm and under a temperature that is as high as 1,800 K. As a result, turbomachinists find it much easier to maximize the turbine power output to levels that in the past were simply unthinkable.

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2 Overview of Turbomachinery Nomenclature

A brief introduction to gas turbine engines was presented in Chapter 1. Review of the different engines included in this chapter reveals that most of these engine components are composed of "lifting" bodies, termed airfoil "cascades," some of which are rotating, while others are stationary. These are all, by necessity, bound by the hub surface and the engine casing (or housing), as shown in Figures 2.1–2.5. As a result, the problem becomes one of the internal-aerodynamics type, as opposed to such traditional external-aerodynamics topics as "wing theory" and others. Referring, in particular, to the turbofan engines in Chapter 1 (e.g., Figure 1.3), these components may come in the form of ducted fans. These, as well as compressors and turbines, can be categorically summed up under the term "turbomachines." Being unbound, however, the propeller of a turboprop engine (Figure 1.2) does not belong to the turbomachinery category.

The preceding listed turbomachines, however, are no more than a subfamily of a more inclusive category. These only constitute the turbomachines that commonly utilize a compressible working medium, which is totally, or predominantly, air. In fact, a complete list of this compressible-flow subfamily should also include such devices as steam turbines, which may utilize either dry (superheated) or wet (liquid/vapor) steam mixture with high quality (or dryness factor). On the other hand, there exists a separate incompressible-flow turbomachinery classification, where the working medium may be water or, for instance, liquid forms of oxygen or hydrogen, as is the case in the Space Shuttle main engine turbopumps. This subcategory also includes power-producing turbomachines, such as water turbines. Presented next is a summary of turbomachinery classifications in accordance with some specific criteria, beginning with the very definition of a turbomachine.

2.1 Definition of a Turbomachine

A turbomachine is a device where mechanical energy, in the form of shaft work, is transferred either to or from a continuously flowing fluid, by the dynamic action of rotating blade rows.

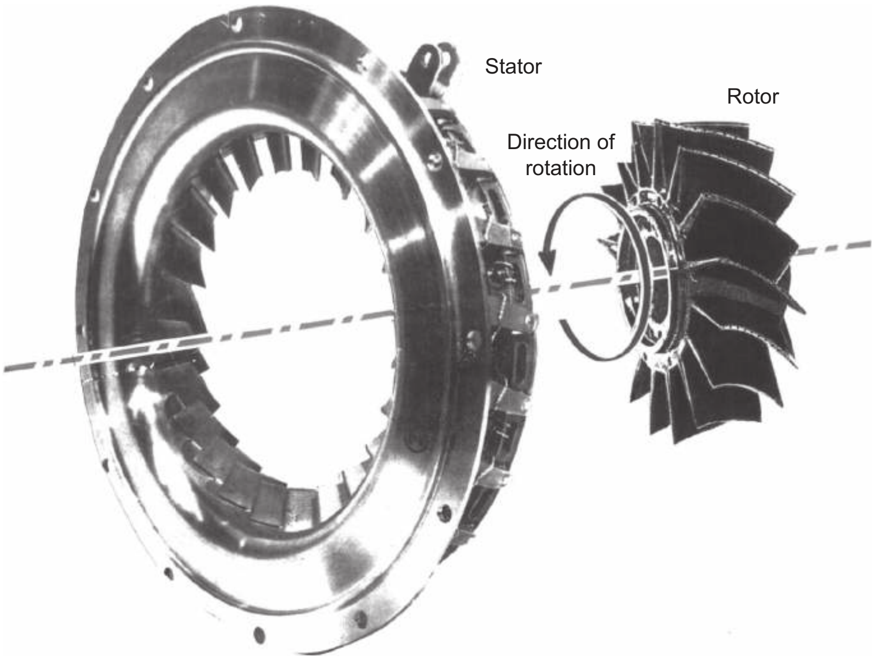

Figure 2.1 A typical axial-flow turbine stage.

2.2 General Classification of Turbomachines

2.2.1 By Their Functions

Functions by which turbomachines are classified include the following:

- Work-absorbing turbomachines, such as compressors and fans.
- Work-producing turbomachines, generally known as turbines.

Figures 2.2 and 2.3 show examples of these two turbomachinery categories.

2.2.2 By the Nature of the Working Medium

Turbomachines are also classified by the nature of their working medium:

- Compressible-flow turbomachines, where the incoming fluid is totally air, as in fans and compressors, or the products of combustion as in gas turbines. In the latter category, and in the absence of an afterburner, the working medium will still be treated as predominantly air.
- Incompressible-flow turbomachines, where the working medium may be water (hydraulic pumps) or any single-phase substance in the liquid form.

2.2.3 By the Type of the Meridional Flow Path

Using a cylindrical frame of reference, the projection of a turbomachine onto the axial-radial (z–r) plane is called the meridional view (also termed the meridional flow path).

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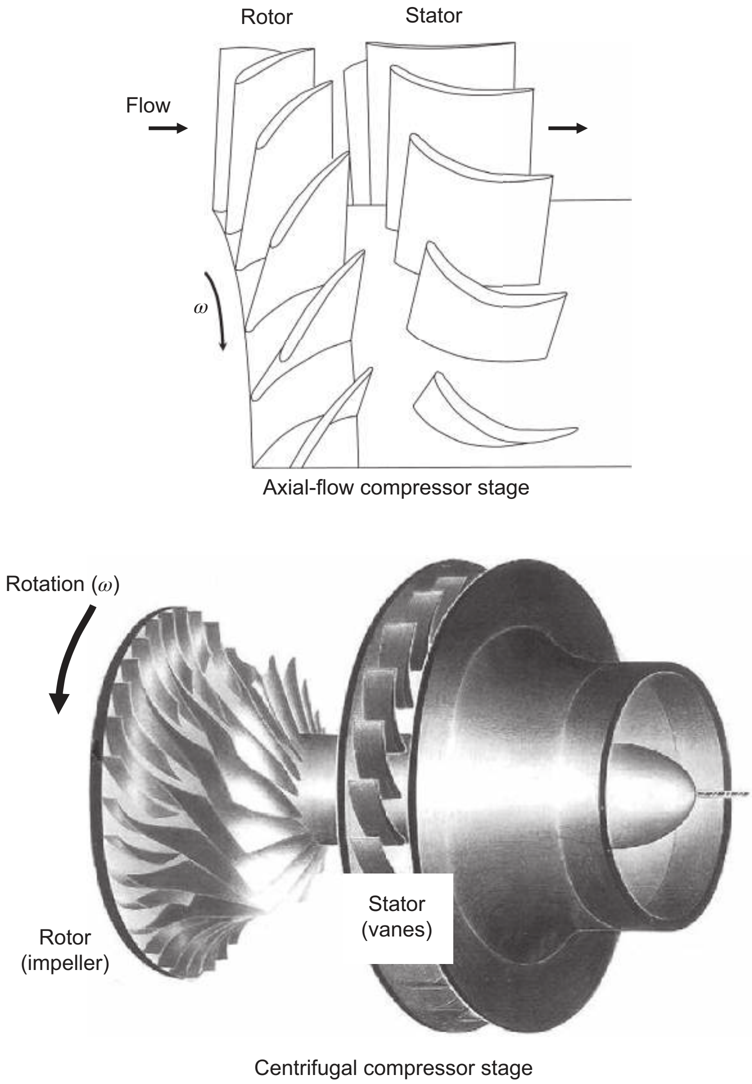

Figure 2.2 Comparison between axial and centrifugal compressor stages.

Referring to the two compressor examples in Figure 2.4 and the corresponding turbine examples in Figure 2.5, it is only the meridional projection of the rotating blades, which are relevant in this particular classification. Should the rotor flow path remain (exactly or nearly) parallel to the axis of rotation, the entire stator/rotor assembly (termed a “stage”) is said to be of the axial-flow type. However, should the meridional flow path change direction from axial to radial, or vice versa, the “stage” is referred to as a centrifugal compressor, or a radial turbine, as shown in Figures 2.4 and 2.5, respectively.

It is perhaps fitting to emphasize the fact that terms such as “purely” axial, or “purely” radial meridional-view flow direction represent ideally perfect flow guidedness by the end-wall. These terms imply the total lack of such real-life flow effects as viscosity and secondary