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Michael Casey , Chris Robinson
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1 Introduction to Radial Flow Turbocompressors

1.1 Overview

1.1.1 Introduction

In this chapter, the subject of the book is introduced to the reader. Classifications of different types of turbomachine and different types of compressor are reviewed, to define precisely what is meant by a radial flow turbocompressor. This first chapter also considers the basic operating principle of turbocompressors, known as the Euler turbine equation, which is valid for all turbomachines. The function of the components of a single-stage compressor are introduced, and the many different forms of single-stage and multistage compressors are described. An overview of different types of impeller is provided.

Centrifugal compressors have become ubiquitous over the twentieth century across a wide range of applications due to their inherent robustness, good efficiency and broad operating range. Numerous applications of radial flow turbocompressors are described in this chapter whereby the special aerodynamic features that are relevant to their design for each application are highlighted. The wide range of applications explains why the book is devoted to this relatively narrow part of the wide field of turbomachines. Even small gains of efficiency, improvements in operating range and an increase in swallowing capacity are welcomed across all industrial applications.

Some comments are provided in the chapter on the effect of renewable energy on the applications of radial compressors. The future of centrifugal compressors seems equally bright with the present focus on environmental goals, including the future decarbonisation of power generation and transportation, with a possible shift to a hydrogen economy. There is ever-increasing pressure to produce higher-efficiency gas turbines at increased cycle pressure ratios for aviation propulsion and ground-based power generation, which also favour the use of centrifugal or axial-centrifugal machines.

Aspects of the history of turbomachines are also given together with a short overview of some other useful books on this topic.

1.1.2 Learning Objectives

- Define what is meant by a turbomachine.
- How does a turbocompressor differ from other rotary compressors?

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- Define the differences between turbines and compressors, axial and radial machines and thermal and hydraulic turbomachines.
- Know the basic operating principle of a turbomachine based on the Euler turbine equation.
- Be able to identify various applications of radial flow turbocompressors.
- Have a broad knowledge of the history of turbomachinery with emphasis on radial flow turbocompressors.
- Be aware of other useful books on the same subject matter.

1.2 Definition of Turbomachinery

Turbomachines are rotating machines used to change the state of a working fluid – liquids in pumps, gases in compressors and one or the other in turbines. Pumps, fans, ventilators and blowers are used to transport fluids; turbines and wind turbines extract energy from a fluid stream. Turbochargers, propellers and jet engines constitute part of propulsion or transportation devices. This wide remit means that turbomachines span almost all industrial sectors and play a vital role in many of them. They are often only a small part of a more complex system, which typically imposes the requirements for and constraints on their design. There is a huge range of types, sizes and speeds, with large economic significance in numerous applications. In addition, the technological and scientific interest of fluid dynamics, thermodynamics and mechanics makes turbomachinery a highly worthwhile subject of engineering study.

Turbomachinery is fundamentally linked to energy conversion in its many forms. Most electrical power is currently generated by steam turbines in nuclear and coal-fired plants, but even modern solar or biomass power plants use small steam or gas turbines for energy conversion. Natural gas is the fuel most commonly used for land-based gas turbine power plants, and nowadays these are often combined with a steam turbine which, in turn, obtains its heat source from the hot exhaust gases of the gas turbine. Water turbines in hydroelectric schemes and wind turbines use renewable energy sources for power generation.

Turbomachinery plays an equally important role in the transportation industry – the gas turbine jet engine is used for propulsion in nearly all aircraft; turbochargers are widely used in ground transportation and as an integral part of diesel propulsion in nearly all ships, lorries and diesel cars and, increasingly, in gasoline-fuelled vehicles. Pumps are the world’s most ubiquitous turbomachines, found everywhere where liquid needs to be transported. Compressors and pumps are important to chemical processes, to the use of industrial gases and in the oil and gas industries. Compressors and ventilators are key components in air conditioning, cooling and refrigeration equipment. Turbomachinery can even be found in the medical industry, where pumps are deployed for blood circulation, ventilation-assist fans are used in the treatment of sleep apnoea and in other clinical applications. The drive powering a high-speed dental drill is, in fact, generally a tiny high-speed air-driven turbine.

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The distinguishing feature of a turbomachine is that energy is transferred continuously to or from a fluid by the aerodynamic action of the flow around rotating blades in an open system. Different aspects of this are discussed later in this chapter.

1.2.1 Open System

The definition of an open system is discussed in Chapter 2 on the thermodynamics of energy transfer. To explain a turbomachine as part of an open system, it is useful to make a simple comparison between the work-producing processes in a gas turbine and those of an internal combustion engine. In the gas turbine, the energy transfer takes place through the continuous aerodynamic forces of the gas passing through the flow channels of a machine which is open at both ends. There are no valves or movable plates to force the flow to pass forwards through the machine or to stop the flow from reversing direction, as is the case in a reciprocating machine.

The different parts of the gas turbine process take place continuously in separate components which are open at both ends and are specifically designed to achieve high efficiency for each purpose: the intake, the compressor, the combustion chamber and the turbine and, in a jet engine, the outlet nozzle. Work is produced in the rotor blade rows of the turbine, and this is used as motive power to drive the compressor. The excess power not needed by the compressor is then available to drive a generator or to provide thrust for an aero engine.

In the internal combustion engine, similar processes take place but the energy is transferred by the intermittent operation of forces acting on the pistons in a closed cylinder, which are forced to change direction regularly. There are valves which open and close to trap gas in the cylinder and to allow it to enter and leave during the different expansion and compression processes. These variable processes take place in the same component but at different times, and the work transfer is intermittent. In a two-stroke engine, there is one power stroke every two strokes of the piston in a single revolution of a shaft; in a four-stroke engine, two shaft revolutions are needed for each power stroke.

In a gas turbine, there are no strokes, since each blade passage provides more or less continuous flow and ensures that the forces acting on the shaft, with the exception of the small variations due to the interaction of the moving and stationary blade rows, are steady. Because of this, a turbomachine basically has only one moving part. This rotates rather than oscillates, and has high reliability and a long lifetime. The continuous rotating motion applies relatively simple mechanical loads, and the rotors may achieve high rotational speeds, resulting in high power density – turbomachines that are generally light in weight for a given power.

1.2.2 Continuous Energy Transfer by Flow over Blades Rotating around an Axis

Turbomachines differ from positive displacement devices in that they effect a continuous energy transfer. In the case of positive displacement machines, the work is transferred discontinuously by changing the volume of a trapped mass of fluid, releasing it and then intermittently repeating the process. Most positive displacement machines are reciprocating – as in a piston engine – but some, such as screw compressors, liquid ring compressors and sliding vane blowers, may have rotary motion and be nearly continuous in operation.

The limitations of the intermittent power and mass flow capability associated with reciprocating machinery explains the fact that the largest diesel engine (for container ships) has a power output of about 80 MW, compared with typically 1600 MW for the largest single-shaft steam turbines. In contrast to discontinuous operation, a large energy flux can be obtained in turbomachines and hence high gas flow rates require only comparatively small components. In addition, rotary motion is a natural characteristic of turbomachinery and does not require complex oscillating connecting rods from the machine crankshaft to a rotating shaft.

A categorisation of different compressor types is given in Figure 1.1. The piston compressor comprises a reciprocating piston and associated valves and operates on the same principle as a bicycle pump. A diaphragm compressor comprises a flexible diaphragm which is moved by means of a hydraulic system. The movement of the diaphragm draws the process gas into a chamber enclosed by the diaphragm and then forces it under pressure through a valve. Another possibility, often used for vacuum applications, is to use a jet of gas at high pressure in an ejector to transfer its momentum to a stream of gas at low pressure.

Screw compressors use two helical screws, both known as rotors, which mesh to enclose a small volume of gas. Gas enters at the suction end of the casing and moves through the threads of the screws as they rotate and is then forced at pressure out of the exit of the compressor casing. The rotary lobe compressor also consists of two rotors that have two or three lobes. The rotors rotate such that air is sucked into the inlet and is forced out of the discharge by the lobes. The liquid-ring compressor has a vaned

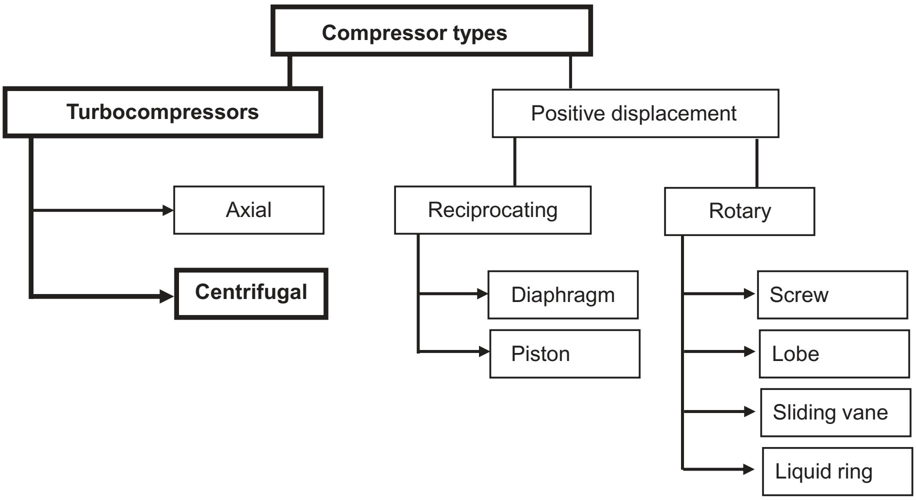

Figure 1.1 Categories of different compressor types.

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impeller rotating eccentrically within a cylindrical casing. Liquid (usually water) within the casing is centrifuged outwards and provides a liquid ring that seals the space between the impeller blades and the casing. The eccentric impeller results in a periodic variation of the volume enclosed by the vanes and the liquid ring; this draws air into the casing and delivers it at a higher pressure. A sliding vane compressor also has an eccentric rotor, but the blades themselves are able to move within the rotor to seal the casing. The blades are held in close contact with the outer shell under the action of the centrifugal force, and the sealing between the vanes and the casing is improved by the injection of a lubricating oil over the entire length of the blade. The main drawback of positive displacement compressors is that the compression cycle is discrete: the gas comes in bursts rather than smoothly and continuously.

On a timescale of the order of seconds, the time-averaged properties within a turbomachine can be considered as a smooth and continuous steady flow process, at least at the usual stable operating points. However, the forces acting on a blade are not steady at very small timescales (milliseconds). The aerodynamic interaction of the motion of adjacent blade rows leads to small, unsteady variations in pressure at frequency with which the blades and vanes pass each other. In fact, these variations can force blade vibrations, and if they are not under control the mechanical damage can severely interfere with the life and aerodynamic function of the machine. In fact, a classical analysis by Dean (1959), clarified by Hodson et al. (2012), shows that the equations describing the change in enthalpy for a fluid particle in a turbomachine require a time variation in pressure. Conveniently, for most analyses the design engineer is concerned with the mean, time-averaged performance and may consider the smooth operation to be steady.

1.2.3 Aerodynamic

The truly key feature of a turbomachine is the aerodynamic forces acting on the blades. It is the motion of the fluid compared to the motion of the machine that is primary. The actual motion of the fluid in a positive displacement machine is, by contrast, generally less well ordered and is secondary to the motion of the components – such as pistons or valves. As the flow passes over the blade surface of a turbomachine, an aerodynamic lift force is generated, similar to the lift force on an aircraft wing. If the blades are moving in the direction of this force, then there is a transfer of work between the fluid and the shaft. This is the essence of turbomachinery, and a good understanding of fluid dynamics is therefore one of the key building blocks in the design of good turbomachines.

As an example of the importance of aerodynamic forces, it is useful to consider the work input into an Archimedean screw. This rotating machine acts as a pump to raise water to a higher level (or as a water turbine when the water is flowing downhill), but it is not a turbomachine because the work input is not related to an aerodynamic force. Instead, it is due to work done against gravitation to lift the weight of the water as it periodically fills and empties from a section of the screw.

Similarly, one can distinguish between undershot and overshot water wheels. In an overshot water wheel, the water enters at the top of the wheel and the weight of the water held in each bucket provides the necessary torque. This is not a turbomachine as long as the small impulse from the water entering and leaving the buckets can be neglected. An undershot wheel, by contrast, makes use of the kinetic motion of the fluid to provide a force on the paddle blades. The head of water must first be converted into kinetic energy or the wheel needs to be mounted in a fast-running stream. The undershot water wheel is considered to be a turbomachine as its operation is due to an aerodynamic force from the motion of the water acting on the blades. In this case, however, it is a drag force and not an aerodynamic lift force, which is more normal in turbomachines.

The range of types and sizes of turbomachines is vast. Common examples in rough order of increasing size are: high-speed dental drills, computer cooling fans, hair dryers, ventilation fans, turbochargers for cars, water pumps, blowers for air compression, compressors and turbines for helicopter engines, turbochargers for ships' diesel engines, turbines and compressors in aero engines and industrial gas turbines, water turbines, steam turbines and wind turbines in the power generation industry. If world records are considered, wind turbines are the largest (having a rotor tip diameter above 200 m), Francis turbines are the most powerful in terms of the energy from a single blade row (with a power of 800 MW from a single impeller with a diameter of between 5 and 10 m), and the steam turbine is the most powerful turbomachine on a single shaft.

Practical radial turbocompressors can be found in a range of applications with impeller diameters, D_2, of between 10 mm and 2000 mm, and an impeller tip-speed, u_2, of between 100 and 700 m/s. An overview is provided in Figure 1.2. Low-pressure compressors with low tip-speeds are known as fans and medium-pressure compressors as blowers. While

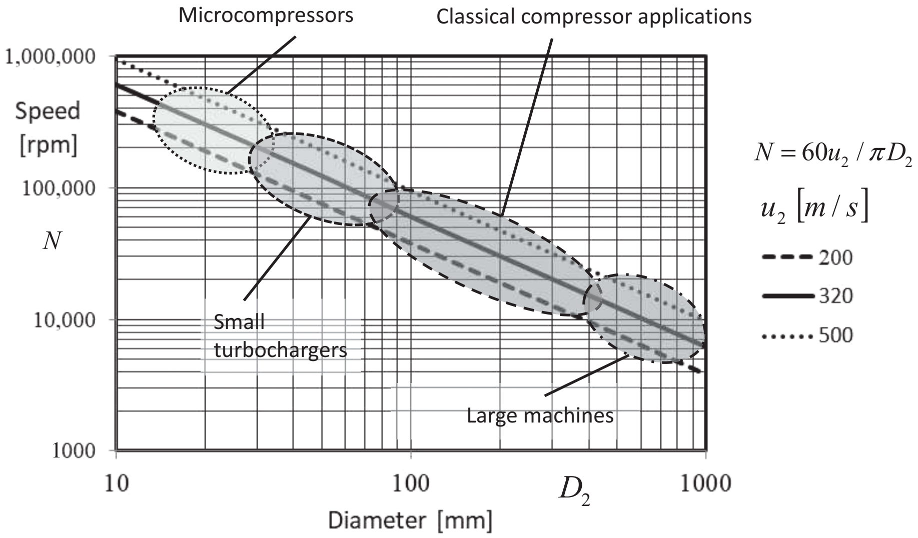

Figure 1.2 An overview of the range of size and rotational speed of radial flow turbocompressors.

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most of the fundamental principles of design can be comfortably applied across the range of size and tip-speed, some aspects do not scale. For example, the tip clearance of open impellers is one of the key factors limiting the efficiency of small stages, and the blade thickness tends to become larger relative to the diameter at small size due to manufacturing constraints. In many applications at the larger sizes, it may be more efficient – and may reduce the outer dimensions – to use a smaller axial compressor or an axial-centrifugal compressor. Large centrifugal machines are often preferred, however, as they are more robust and have much wider operating characteristics.

1.2.4 Principle of Operation

An understanding of the fact that machines of such a broad range of power density and application operate on the same single physical principle is the key to effective turbomachinery design. The unifying theoretical system is the Euler turbine equation, first derived from Newton’s second law by the polymath Leonhard Euler (1707–1783) in the eighteenth century.

Newton showed that a force is needed to generate a change in the speed of an object, and the change in speed is proportional to, and along the direction of, the applied force. Euler extended this and deduced that the torque acting on a turbomachinery shaft is related to the forces causing a change in the angular momentum of the gas by a change in its circumferential velocity between the inlet and outlet of a blade row. This is illustrated in Section 2.2 and discussed in detail in most other chapters. When the Euler turbine equation is applied to the gas passing from the inlet (station 1) to outlet (station 2) across a rotor blade row, it gives the specific shaft work (the mechanical work per unit mass flow on the shaft) in terms of the changes in the circumferential component of the gas velocity (c_u) and the blade speed (u) as

$$w_{s12} = u_2 c_{u2} - u_1 c_{u1} = \Delta(u c_u). \tag{1.1}$$

The individual blade rows guide the fluid as it passes through the flow channels and produce a change in direction of the swirling flow relative to the circumferential direction. It is this change in angular momentum across a rotor which creates work on the shaft: such that the principle of a turbomachine can be thought of as a machine in which the blades cause a change in the swirl of the flow. The addition of swirl in a rotor blade row of a compressor is usually followed by its removal in a downstream stator row, and so a turbomachine usually has at least two blade rows.

Not only is the Euler turbomachinery equation universally applicable, it also combines great simplicity and elegance. Furthermore, it is formidably potent: as it is based on a control volume approach, it determines the work of the machine simply from the changes between the mean conditions at inlet and outlet of a rotor with no knowledge of the inner workings of the blade row. It is immediately clear from the dimensions of this equation, for example, that the work done per unit mass on the fluid in a compressor is proportional to the product of two velocities and thus to the square of the blade speed. Therefore, for compressors with high pressure ratios, high blade tip-speeds are required.

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In all turbomachines, at least one blade row rotates, which means that a fundamental aspect of the application of the Euler turbomachinery equation is the consideration of the flow in the blade rows, both in an inertial system relative to the moving blades and in the absolute frame of reference. The stator vanes guide the direction of the flow in the absolute frame, while the rotor blades guide the relative flow in the rotating coordinate system. An important aspect is then the relationship between flow in the absolute coordinate system, as seen by an observer outside the machine, and the flow in a relative coordinate system that rotates with the rotor. This approach was first formulated in the theory of steam turbines by Aurel Stodola (1859–1942) (Stodola, 1905). The transformation of velocity vectors from one system to the other requires vector addition of velocities. At each point in the flow through a turbomachine, the absolute velocity, c, and the relative velocity, w, can be identified and combined through the local circumferential blade speed, u, with a so-called Galilean transformation between the two inertial systems:

$$\vec{c} = \vec{w} + \vec{u}\,. \tag{1.2}$$

The Galilean transformation of velocities leading to velocity triangles is discussed in Section 2.2.5.

Another simple description of the principle of operation of a compressor is sketched in Figure 1.3, which depicts the change in the nondimensional absolute velocity and static pressure through a 2D compressor stage. The absolute gas velocity, c, increases through the impeller along together with the static pressure. At the impeller outlet, the absolute gas velocity almost reaches the tip-speed of the impeller. The deceleration of the gas in the downstream diffuser leads to a further rise in pressure. The proportion of the pressure rise in the impeller to that in the whole stage, in this case about 60%, is called the degree of reaction.

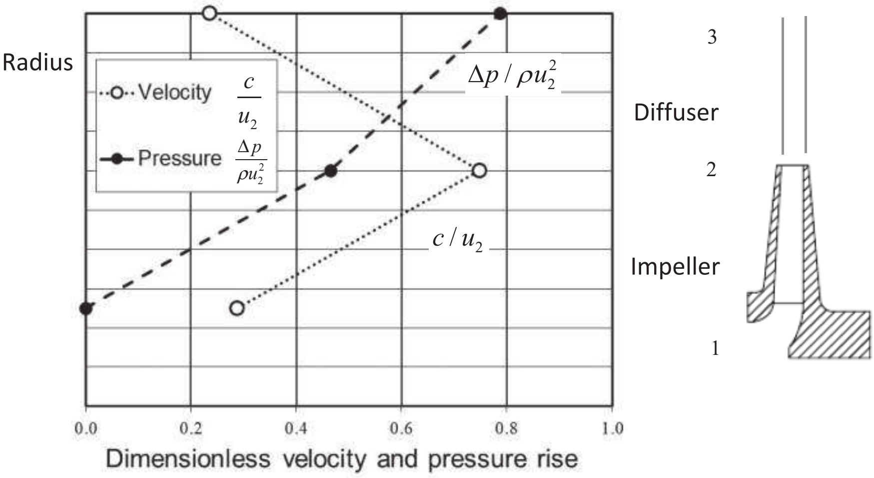

Figure 1.3 Dimensionless absolute gas velocity and pressure rise in a 2D compressor stage.

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The aerodynamic forces and the stresses resulting from high-speed rotation must be safely carried by the blades and by the other mechanical elements. In addition, the blades need to stay attached to the rotor. Special attention must be given to the sealing between the rotating elements and the stationary elements. Some of the unsteady stresses in turbomachinery blade rows are associated with vibration phenomena from blade row interactions and flow instabilities, both of which may lead to material failure by fatigue. Stress analysis, vibration analysis, the selection of materials and the mechanical component design for safe operation are key aspects in the integration of turbomachinery components into actual products and are introduced in Chapter 19 of the book.

1.3 Classification of Turbomachines

1.3.1 Power Consuming and Power Producing Machines

There are many ways to classify turbomachines. This book covers only a fraction of the many categories of turbomachinery, as it deals with thermal and not hydraulic machines, radial and not axial machines, compressors and not turbines, and only includes machines enclosed within a casing, as explained in this section.

The most fundamental classification is into machines which add energy to a fluid and those which extract energy from a fluid: work-absorbing machines and work-producing machines. The addition or extraction of energy is usually achieved at the expense of the fluid pressure. Turbines have an output of shaft work from the machine which they obtain by converting the internal energy of the fluid into rotational energy of the shaft. In all turbines, except wind turbines, the pressure falls as rotational kinetic energy is generated in upstream components, and this energy is then extracted by the rotor blades. Compressors (and pumps) require work input to the shaft to generate a pressure (or head) rise. The work is first converted into static pressure or enthalpy rise and an increase in kinetic energy in a rotor blade row. The kinetic energy is then converted into a further pressure rise by a stator blade row. In some low-cost applications, such as ventilator fans, the downstream stator is not present and the exit kinetic energy is simply discarded.

1.3.2 Thermal and Hydraulic Machines

The distinguishing feature of a thermal turbomachine, as opposed to a hydraulic turbomachine, is that the working fluid is compressible. The gas undergoes a marked change in volume with the density and temperature changes that occur as it passes through the machine. In a hydraulic machine, the fluid (usually cold water) is effectively incompressible and the density remains constant: the fluid then has the same volume, and very nearly the same temperature, at the inlet and the outlet of the machine. Thermodynamics is not relevant to the performance analysis in this case.

A multistage pump has similar impellers in all of its stages as there is no difference in the volume flow at different positions in the machine. On the other hand, a multistage compressor requires that the flow channel of the stages is adapted to

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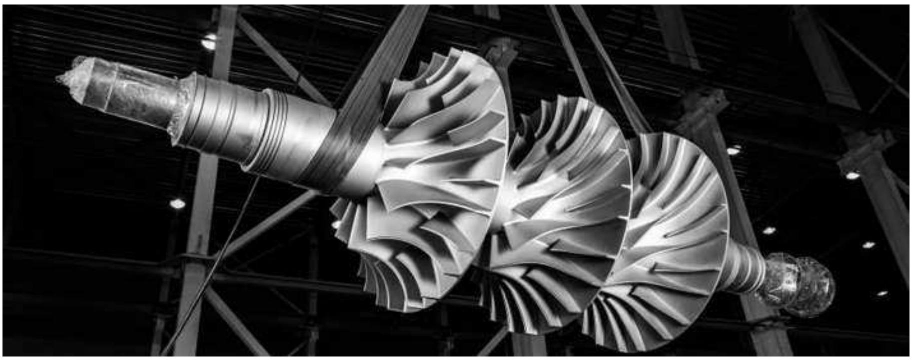

Figure 1.4 The shaft of a three-stage air compressor with open impellers manufactured by Entenmach RPC LCC, Saint Petersburg, Russia. (image by courtesy of Entenmach)

account for the decrease in volume of the gas being compressed, which means that different impellers with narrower flow channels are needed on the passage through the machine. Figure 1.4 from Neverov and Liubimov (2018) shows this for a multistage machine with three different open impellers of the same diameter on the same shaft. The amount of volume compression for a given pressure rise is also a function of the gas properties of the fluid being compressed so that different impellers are also needed for different gases. The manufacturer of multistage pumps needs to develop a single stage that can be used at each position in a multistage machine as the volume flow does not change through the machine, whereas the compressor manufacturer needs to develop or adapt separate stages for each location.

A limiting case in respect of thermal turbomachinery is a low-speed ventilator where the density change is almost negligible and so these machines may be regarded as incompressible. The large changes in temperature and density in high-speed turbomachines can only be properly accounted for by the theory of compressible gas dynamics. This is another key building block to understanding the design and operation of turbocompressors and is covered in Chapter 6 of the book.

1.3.3 Acceleration and Deceleration of the Flow

The addition or extraction of energy is usually made at the expense of the fluid pressure; compressors generate a pressure rise, whereas turbines cause a pressure drop. Furthermore, whether the static pressure rises or falls through the machine is an important difference. In compressors and ventilators, the static pressure usually rises in the direction of flow, whereas it usually drops in the direction of flow in turbines. It is fundamentally difficult to persuade a fluid to move ’uphill’ against rising pressure. This means that the basic aerodynamic design of compressors is generally more problematic and more affected by aerodynamic limits than that of turbines.

Compressor blade rows generally experience decelerating flow as the flow gives up its kinetic energy to produce a static pressure rise. This tends to cause the slow-