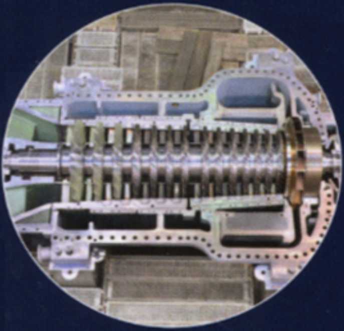
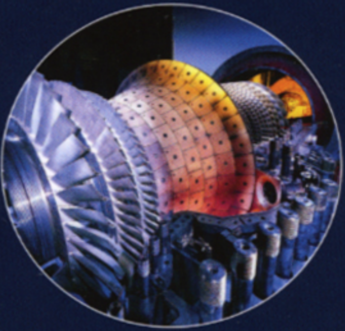
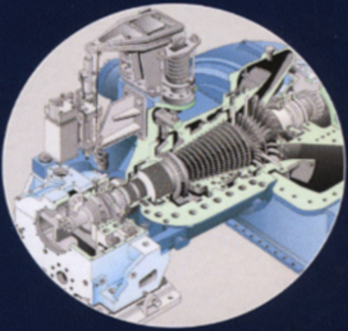
PRINCIPLES OF TURBOMACHINERY

SEPPO A. KORPELA

WILEY

Principles of Turbomachinery

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Seppo A. Korpela
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To my wife Terttu,
to our daughter Liisa,
and to the memory of our
daughter Katja

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Foreword

Turbomachinery is a subject of considerable importance in a modern industrial civilization. Steam turbines are at the heart of central station power plants, whether fueled by coal or uranium. Gas turbines and axial compressors are the key components of jet engines. Aeroderivative gas turbines are also used to generate electricity with natural gas as fuel. Same technology is used to drive centrifugal compressors for transmitting this natural gas across continents. Blowers and fans are used for mine and industrial ventilation. Large pumps are often driven with steam turbines to provide feedwater to boilers. They are used in sanitation plants for wastewater cleanup. Hydraulic turbines generate electricity from water stored in reservoirs, and wind turbines do the same from the flowing wind.

This book is on the principles of turbomachines. It aims for a unified treatment of the subject matter, with consistent notation and concepts. In order to provide a ready reference to the reader, some of the developments have been repeated in more than one chapter. This also makes possible the omission of some chapters from a course of study. The subject matter becomes somewhat more general in three of the later chapters.

Acknowledgments

The subject of turbomachinery occupied a central place in mechanical engineering curriculum some half a century ago. In the early textbooks fluid mechanics was taught as a part of a course on turbomachinery, and many of the pioneers of fluid dynamics worked out the many technical issues related to these machines. The field still draws substantial interest. Today the situation has been turned around, and books on fluid dynamics introduce turbomachines in one or two chapters. The same relationship existed with thermodynamics and steam power plants, but today an introduction to steam power plants is usually found in a single chapter in an introductory textbook on thermodynamics.

The British tradition on turbomachinery is long and illustrious. There W. J. Kearton established a center at the University of Liverpool nearly a century ago. His book *Steam Turbine Theory and Practice* became a standard reference source. After his retirement J. H. Horlock occupied the Harrison Chair of Mechanical Engineering there for a decade. His book *Axial Flow Compressors* appeared in 1958 and its complement, *Axial Flow Turbines*, in 1966. Whereas Horlock's books are best suited for advanced workers in the field, at University of Liverpool, S. L. Dixon's textbook *Fluid Mechanics and Thermodynamics of Turbomachinery* appeared in 1966, and its later editions continue in print. It is well suited for undergraduates. Another textbook in the British tradition is the *Gas Turbine Theory* by H. Cohen and G. F. C. Rogers. It was first published in 1951 and in later editions still today. At a more advanced level are R. I. Lewis's *Turbomachinery Performance Analysis* from 1996, N. A. Cumpsty's *Compressor Aerodynamics* published in 1989, and the *Design of Radial Turbomachines* by A. Whitfield and N. C. Baines in 1990.

More than a generation of American students learned this subject from D. G. Sheppard's *Principles of Turbomachinery* and later from the short *Turbomachinery—Basic Theory and Applications* by E. Logan, Jr. The venerable A. Stodola's *Steam and Gas Turbines* has been translated to English, but many others classic works, such as W. Traupel's *Thermische Turbomaschinen* and the seventh edition of *Strömungsmachinen*, by Pfleiderer and Petermann, require a good reading knowledge of German.

I am indebted to all the above mentioned authors for their fine efforts to make the study of this subject enjoyable.

My introduction to the field of turbomachinery came thanks to my longtime colleague, the late Richard H. Zimmerman. After working on other areas of mechanical engineering for many years, I returned to this subject after Reza Abhari invited me to spend a summer at ETH in Zurich. There I also met Anestis Kalfas, now also at the Aristotle University of Thessaloniki. I am grateful to both of them for sharing their lecture notes, which showed me how the subject was taught at the institutions of learning where they had completed their studies and how they have developed it further. I am grateful to my former student and friend,V. Babu, a professor of Mechanical Engineering of the Indian Institute of Technology, Madras, for reading the manuscript and making many helpful suggestions for improving it. Undoubtedly some errors have remained, and I will be thankful for readers who take the time to point them out by e-mail to me at the address: korpela.1@osu.edu.

I am grateful for permission to use graphs and figures from various published works and wish to acknowledge the generosity of the various organization for granting the permission to use them. These include Figures 1.1 and 1.2 from Siemens press photo, Siemens AG; Figure 1.3, from Schmalenberger Strömungstechnologie AG; Figures 1.6 and7.1 are by courtesy of MAN Diesel & Turbo SE, and Figures 4.12 and 4.11 are published by permission of BorgWarner Turbo Systems. Figure 3.7 is courtesy of Professor D. Papamaschou; Figures 10.3 and 10.11 are published under the GNU Free Documentation licenses with original courtesy of Voith Siemens Hydro. The Figure 10.9 is reproduced under the Gnu Free Documentation licence, with the original photo by Audrius Meskauskas. Figure 1.5 is also published under Gnu Free Documentation licence, and so is Figure 1.4 and by permission from Aermotor. The Institution of Mechanical Engineers has granted permission to reproduce Figures 3.14, 6.16, 7.5, 7.6, and 7.16. Figure 4.10 is published under agreement with NASA. The *Journal of the Royal Aeronautical Society* granted permission to publish Figure 6.11. Figures 6.19 and 6.20 are published under the Crown Stationary Office's Open Government Licence of UK. Figure 3.11 has been adapted from J. H. Keenan, *Thermodynamics*, MIT Press and Figure 9.6 from O. E. Balje, *Turbo machines A guide to Selection and Theory.* Permission to use Figures 12.13 and 12.15 from *Wind Turbine Handbook* by T. Burton, N. Jenkins, D. Sharpe, and E. Bossanyi has been granted by John Wiley & Sons.

I have been lucky to have Terttu as a wife and a companion in my life. She has been and continues to be very supportive of all my efforts.

S. A. K.

CHAPTER 1

INTRODUCTION

1.1 ENERGY AND FLUID MACHINES

The rapid development of modern industrial societies was made possible by the large-scale extraction of fossil fuels buried in the earth's crust. Today oil makes up 37% of world's energy mix, coal's share is 27%, and that of natural gas is 23%, for a total of 87%. Hydropower and nuclear energy contribute each about 6% which increases the total from these sources to 99%. The final 1% is supplied by wind, geothermal energy, waste products, and solar energy. Biomass is excluded from these, for it is used largely locally, and thus its contribution is difficult to calculate. The best estimates put its use at 10% of the total, in which case the other percentages need to be adjusted downward appropriately [54].

1.1.1 Energy conversion of fossil fuels

Over the the last two centuries engineers invented methods to convert the chemical energy stored in fossil fuels into usable forms. Foremost among them are methods for converting this energy into electricity. This is done in steam power plants, in which combustion of coal is used to vaporize steam and the thermal energy of the steam is then converted to shaft work in a steam turbine. The shaft turns a generator that produces electricity. Nuclear power plants work on the same principle, with uranium, and in rare cases thorium, as the fuel.

Principles of Turbomachinery. By Seppo A. Korpela

Oil is used sparingly this way, and it is mainly refined to gasoline and diesel fuel. The refinery stream also yields residual heating oil, which goes to industry and to winter heating of houses. Gasoline and diesel oil are used in internal-combustion engines for transportation needs, mainly in automobiles and trucks, but also in trains. Ships are powered by diesel fuel and aircraft, by jet fuel.

Natural gas is largely methane, and in addition to its importance in the generation of electricity, it is also used in some parts of the world as a transportation fuel. A good fraction of natural gas goes to winter heating of residential and commercial buildings, and to chemical process industries as raw material.

Renewable energy sources include the potential energy of water behind a dam in a river and the kinetic energy of blowing winds. Both are used for generating electricity. Water waves and ocean currents also fall into the category of renewable energy sources, but their contributions are negligible today.

In all the methods mentioned above, conversion of energy to usable forms takes place in a *fluid machine*, and in these instances they are *power-producing* machines. There are also *power-absorbing* machines, such as pumps, in which energy is transferred into a fluid stream.

In both power-producing and power-absorbing machines energy transfer takes place between a fluid and a moving machine part. In *positive-displacement machines* the interaction is between a fluid at high pressure and a reciprocating piston. Spark ignition and diesel engines are well-known machines of this class. Others include piston pumps, reciprocating and screw compressors, and vane pumps.

In *turbomachines* energy transfer takes place between a *continuously flowing fluid stream and a set of blades rotating about a fixed axis*. The blades in a pump are part of an *impeller* that is fixed to a shaft. In an axial compressor they are attached to a compressor *wheel*. In steam and gas turbines the blades are fastened to a disk, which is fixed to a shaft, and the assembly is called a turbine *rotor*. Fluid is guided into the rotor by *stator vanes* that are fixed to the *casing* of the machine. The inlet stator vanes are also called *nozzles*, or *inlet guidevanes*.

Examples of power-producing turbomachines are steam and gas turbines, and water and wind turbines. The power-absorbing turbomachines include pumps, for which the working fluid is a liquid, and fans, blowers, and compressors, which transfer energy to gases.

Methods derived from the principles of thermodynamics and fluid dynamics have been developed to analyze the design and operation of these machines. These subjects, and heat transfer, are the foundation of *energy engineering*, a discipline central to modern industry.

1.1.2 Steam turbines

Central station power plants, fueled either by coal or uranium, employ steam turbines to convert the thermal energy of steam to shaft power to run electric generators. Coal provides 50% and nuclear fuels 20% of electricity production in the United States. For the world the corresponding numbers are 40% and 15%, respectively. It is clear from these figures that steam turbine manufacture and service are major industries in both the United States and the world.

Figure 1.1 shows a 100-MW steam turbine manufactured by Siemens AG of Germany. Steam enters the turbine through the nozzles near the center of the machine, which direct the flow to a rotating set of blades. On leaving the first stage, steam flows (in the sketch toward the top right corner) through the rest of the 12 stages of the high-pressure section in this turbine. Each stage consists of a set rotor blades, preceded by a set of stator vanes.

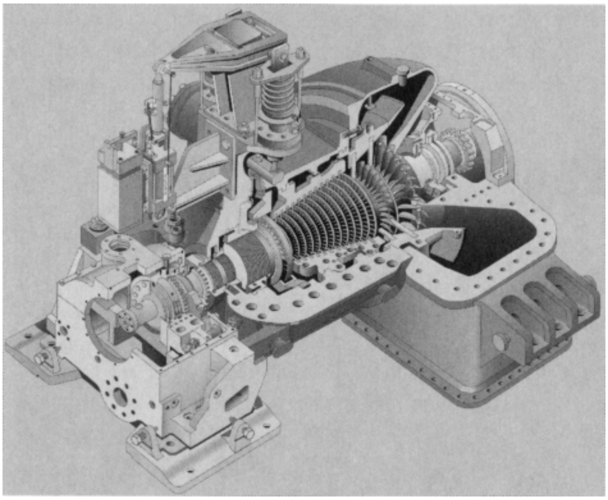

Figure 1.1 The Siemens SST-600 industrial steam turbine with a capacity of up to 100-MW. (Courtesy Siemens press picture, Siemens AG.)

The stators, fixed to the casing (of which one-quarter is removed in the illustration), are not clearly visible in this figure. After leaving the high-pressure section, steam flows into a two-stage low-pressure turbine, and from there it leaves the machine and enters a condenser located on the floor below the turbine bay. Temperature of the entering steam is up to 540°C and its pressure is up to 140 bar. Angular speed of the shaft is generally in the range 3500–15,000 rpm (rev/min). In this turbine there are five bleed locations for the steam. The steam extracted from the bleeds enters feedwater heaters, before it flows back to a boiler. The large regulator valve in the inlet section controls the steam flow rate through the machine.

In order to increase the plant efficiency, new designs operate at supercritical pressures. In an ultrasupercritical plant, the boiler pressure can reach 600 bar and turbine inlet temperature, 620°C. Critical pressure for steam is 220.9 bar, and its critical temperature is 373.14°C.

1.1.3 Gas turbines

Major manufacturers of gas turbines produce both jet engines and industrial turbines. Since the 1980s, gas turbines, with clean-burning natural gas as a fuel, have also made inroads into electricity production. Their use in combined cycle power plants has increased the plant overall thermal efficiency to just under 60%. They have also been employed for stand-alone power generation. In fact, most of the power plants in the United States since 1998 have been fueled by natural gas. Unfortunately, production from the old natural gas-fields of North America is strained, even if new resources have been developed from shale deposits. How long they will last is still unclear, for the technology of gas extraction from shale deposits is new and thus a long operating experience is lacking.

Figure 1.2 shows a gas turbine manufactured also by Siemens AG. The flow is from the back toward the front. The rotor is equipped with advanced single-crystal turbine blades, with a thermal barrier coating and film cooling. Flow enters a three-stage turbine from an annular combustion chamber which has 24 burners and walls made from ceramic tiles. These turbines power the 15 axial compressor stages that feed compressed air to the combustor. The fourth turbine stage, called a *power turbine*, drives an electric generator in a combined cycle power plant for which this turbine has been designed. The plant delivers a power output of 292-MW.

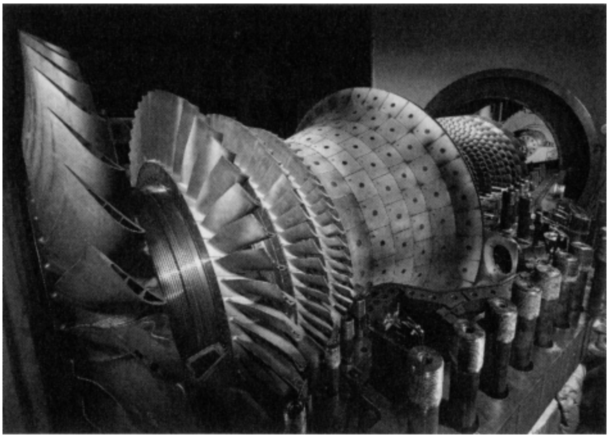

Figure 1.2 An open rotor and combustion chamber of an SGT5-4000F gas turbine. (Courtesy Siemens press picture, Siemens AG.)

1.1.4 Hydraulic turbines

In those areas of the world with large rivers, water turbines are used to generate electrical power. At the turn of the millennium hydropower represented 17% of the total electrical energy generated in the world. The installed capacity at the end of year 2007 was 940,000 MW, but generation was 330,000 MW, so their ratio, called a *capacity factor*, comes to 0.35.

With the completion of the 22,500-MW Three Gorges Dam, China has now the world's largest installed capacity of 145,000 MW, which can be estimated to give 50,000 MW of power. Canada, owing to its expansive landmass, is the world's second largest producer of hydroelectric power, with generation at 41,000 MW from installed capacity of 89,000 MW. Hydropower accounts for 58% of Canada's electricity needs. The sources of this power are the great rivers of British Columbia and Quebec. The next largest producer is Brazil, which obtains 38,000 MW from an installed capacity of 69,000 MW. Over 80% of Brazil's energy is obtained by water power. The Itaipu plant on the Paraná River, which borders Brazil and Paraguay, generates 12,600 MW of power at full capacity. Of nearly the same size is Venezuela's Guri dam power plant with a rated capacity of 10,200 MW, based on 20 generators.

The two largest power stations in the United States are the Grand Coulee station in the Columbia River and the Hoover Dam station in the Colorado River. The capacity of the Grand Coulee is 6480 MW, and that of Hoover is 2000 MW. Tennessee Valley Authority operates a network of dams and power stations in the Southeastern parts of the country. Many small hydroelectric power plants can also be found in New England. Hydroelectric power in the United States today provides 289 billion kilowatthours (kwh) a year, or 33,000 MW, but this represents only 6% of the total energy used in the United States. Fossil fuels still account for 86% of the US energy needs.

Next on the list of largest producers of hydroelectricity are Russia and Norway. With its small and thrifty population, Norway ships its extra generation to the other Scandinavian countries, and now with completion of a high-voltage powerline under the North Sea, also to western Europe. Norway and Iceland both obtain nearly all their electricity from hydropower.

1.1.5 Wind turbines

The Netherlands has been identified historically as a country of windmills. She and Denmark have seen a rebirth of wind energy generation since 1985 or so. These countries are relatively small in land area and both are buffeted by winds from the North Sea. Since the 1990s Germany has embarked on a quest to harness its winds. By 2007 it had installed wind turbines on most of its best sites with 22,600 MW of installed capacity. The installed capacity in the United States was 16,600 MW in the year 2007. It was followed by Spain, with an installed capacity of 15,400 MW. After that came India and Denmark.

The capacity factor for wind power is about 0.20, thus even lower than for hydropower. For this reason wind power generated in the United States constitutes only 0.5% of the country's total energy needs. Still, it is the fastest-growing of the renewable energy systems. The windy plains of North and South Dakota and of West and North Texas offer great potential for wind power generation.

1.1.6 Compressors

Compressors find many applications in industry. An important use is in the transmission of natural gas across continents. Natural-gas production in the United States is centered in Texas and Louisiana as well as offshore in the Gulf of Mexico. The main users are the midwestern cities, in which natural gas is used in industry and for winter heating. Pipelines also cross the Canadian border with gas supplied to the west-coast and to the northern states from Alberta. In fact, half of Canada's natural-gas production is sold to the United States.

Russia has 38% of world's natural-gas reserves, and much of its gas is transported to Europe through the Ukraine. China has constructed a natural-gas pipeline to transmit the gas produced in the western provinces to the eastern cities. Extensions to Turkmenistan and Iran are in the planning stage, as both countries have large natural-gas resources.

1.1.7 Pumps and blowers

Pumps are used to increase pressure of liquids. Compressors, blowers, and fans do the same for gases. In steam power plants condensate pumps return water to feedwater heaters, from which the water is pumped to boilers. Pumps are also used for cooling water flows in these power plants.

Figure 1.3 shows a centrifugal pump manufactured by Schmalenberger Strömungstechnologie GmbH. Flow enters through the eye of an impeller and leaves through a spiral volute. This pump is designed to handle a flow rate of $100\,\mathrm{m}^3/\mathrm{h}$, with a $20\,\mathrm{m}$ increase in its head.

In the mining industry, blowers circulate fresh air into mines and exhaust stale, contaminated air from them. In oil, chemical, and process industries, there is a need for large blowers and pumps. Pumps are also used in great numbers in agricultural irrigation and municipal sanitary facilities.

Figure 1.3 A centrifugal pump. (Courtesy Schmalenberger GmbH.)

Offices, hospitals, schools and other public buildings have heating, ventilating, and air conditioning (HVAC) systems, in which conditioned air is moved by large fans. Pumps provide chilled water to cool the air and for other needs.

1.1.8 Other uses and issues

Small turbomachines are present in all households. In fact, it is safe to say that in most homes, only electric motors are more common than turbomachines. A pump is needed in a dishwasher, a washing machine, and the sump. Fans are used in the heating system and as window and ceiling fans. Exhaust fans are installed in kitchens and bathrooms. Both an airconditioner and a refrigerator is equipped with a compressor, although it may be a screw compressor (which is not a turbomachine) in an air-conditioner. In a vacuum cleaner a fan creates suction. In a car there is a water pump, a fan, and in some models a turbocharger. All are turbomachines.

In addition to understanding the fluid dynamical principles of turbomachinery, it is important for a turbomachinery design engineer to learn other allied fields. The main ones are material selection, shaft and disk vibration, stress analysis of disks and blades, and topics covering bearings and seals. Finally, understanding control theory is important for optimum use of any machine.

In more recent years, the world has awoken to the fact that fossil fuels are finite and that renewable energy sources will not be sufficient to provide for the entire world the material conditions that Western countries now enjoy. Hence, it is important that the machines that make use of these resources be well designed so that the remaining fuels are used with consideration, recognizing their finiteness and their value in providing for some of the vital needs of humanity.

1.2 HISTORICAL SURVEY

This section gives a short historical review of turbomachines. Turbines are power-producing machines and include water and wind turbines from early history. Gas and steam turbines date from the beginning of the last century. Rotary pumps have been in use for nearly 200 years. Compressors developed as advances were made in aircraft propulsion during the last century.

1.2.1 Water power

It is only logical that the origin of turbomachinery can be traced to the use of flowing water as a source of energy. Indeed, waterwheels, lowered into a river, were already known to the Greeks. The early design moved to the rest of Europe and became known as the *norse mill* because the archeological evidence first surfaced in northern Europe. This machine consists of a set of radial paddles fixed to a shaft. As the shaft was vertical, or somewhat inclined, its efficiency of energy extraction could be increased by directing the flow of water against the blades with the aid of a *mill race and a chute*. Such a waterwheel could provide only about one-half horsepower (0.5 hp), but owing to the simplicity of its construction, it survived in use until 1500 and can still be found in some primitive parts of the world.

By placing the axis horizontally and lowering the waterwheel into a river, a better design is obtained. In this *undershot waterwheel*, dating from Roman times, water flows through the lower part of the wheel. Such a wheel was first described by the Roman architect and engineer Marcus Vitruvius Pollio during the first century B.C.

Overshot waterwheel came into use in the hilly regions of Rome during the second century A.D. By directing water from a chute above the wheel into the blades increases the power delivered because now, in addition to the kinetic energy of the water, also part of the potential energy can be converted to mechanical energy. Power of overshot waterwheels increased from 3 hp to about 50 hp during the Middle Ages. These improved overshot waterwheels were partly responsible for the technical revolution in the twelfth–thirteenth century. In the William the Conquerer's *Domesday Book* of 1086, the number of watermills in England is said to have been 5684. In 1700 about 100,000 mills were powered by flowing water in France [12].

The genius of Leonardo da Vinci (1452–1519) is well recorded in history, and his notebooks show him to have been an exceptional observer of nature and technology around him. Although he is best known for his artistic achievements, most of his life was spent in the art of engineering. Illustrations of fluid machinery are found in da Vinci's notebooks, in *De Re Metallica*, published in 1556 by Agricola [3], and in a tome by Ramelli published in 1588. From these a good understanding of the construction methods can be gained and of the scale of the technology then in use. In Ramelli's book there is an illustration of a mill in which a grinding wheel, located upstairs, is connected to a shaft, the lower end of which has an enclosed impact wheel that is powered by water. There are also illustrations that show windmills to have been in wide use for grinding grain.

Important progress to improve waterwheels came in the hands of the Frenchman Jean Victor Poncelet (1788–1867), who curved the blades of the undershot waterwheel, so that water would enter tangentially to the blades. This improved its efficiency. In 1826 he came up with a design for a horizontal wheel with radial inward flow. A water turbine of this design was built a few years later in New York by Samuel B. Howd and then improved by James Bicheno Francis (1815–1892). Improved versions of Francis turbines are in common use today.

About the same time in France an outward flow turbine was designed by Claude Burdin (1788–1878) and his student Benoît Fourneyron (1802–1867). They benefited greatly from the work of Jean-Charles de Borda (1733–1799) on hydraulics. Their machine had a set of guidevanes to direct the flow tangentially to the blades of the turbine wheel. Fourneyron in 1835 designed a turbine that operated from a head of 108 m with a flow rate of 20 liters per second (L/s), rotating at 2300 rpm, delivering 40 hp as output power at 80% efficiency.

In the 1880s in the California gold fields an impact wheel, known as a *Pelton wheel*, after Lester Allen Pelton (1829–1918) of Vermillion, Ohio, came into wide use.

An axial-flow turbine was developed by Carl Anton Henschel (1780–1861) in 1837 and by Feu Jonval in 1843. Modern turbines are improvements of Henschel's and Jonval's designs. A propeller type of turbine was developed by the Austrian engineer Victor Kaplan (1876–1934) in 1913. In 1926 a 11,000-hp Kaplan turbine was placed into service in Sweden. It weighed 62.5 tons, had a rotor diameter of 5.8 m, and operated at 62.5 rpm with a water head of 6.5 m. Modern water turbines in large hydroelectric power plants are either of the Kaplan type or variations of this design.

1.2.2 Wind turbines

Humans have drawn energy from wind and water since ancient times. The first recorded account of a windmill is from the Persian-Afghan border region in 644 A.D., where these vertical axis windmills were still in use in more recent times [32]. They operate on the principle of drag in the same way as square sails do when ships sail downwind.

In Europe windmills were in use by the twelfth century, and historical research suggests that they originated from waterwheels, for their axis was horizontal and the masters of the late Middle Ages had already developed gog-and-ring gears to transfer energy from a horizontal shaft into a vertical one. This then turned a wheel to grind grain [68]. An early improvement was to turn the entire windmill toward the wind. This was done by centering a round platform on a large-diameter *vertical post* and securing the structure of the windmill on this platform. The platform was free to rotate, but the force needed to turn the entire mill limited the size of the early *postmills*. This restriction was removed in a *towermill* found on the next page, in which only the platform, affixed to the top of the mill, was free to rotate. The blades were connected to a windshaft, which leaned about 15° from the horizontal so that the blades would clear the structure. The shaft was supported by a wooden main bearing at the *blade end* and a thrust bearing at the *tail end.* A band brake was used to limit the rotational speed at high wind speeds. The power dissipated by frictional forces in the brake rendered the arrangement susceptible to fire.

Over the next 500 years, to the beginning of the industrial revolution, progress was made in windmill technology, particularly in Great Britain. By accumulated experience, designers learned to move the position the spar supporting a blade from midcord to quarter-chord position, and to introduce a nonlinear twist and leading edge camber to the blade [68]. The blades were positioned at a steep angles to the wind and made use of the lift force, rather than drag. It is hard not to speculate that the use of lift had not been learned from sailing vessels using *lanteen sails* to tack.

A towermill is shown in Figure 1.4a. It is seen to be many meters tall, and each of the four quarter-chord blades is about one meter in width. The blades of such mills were covered with either fabric or wooden slats. By an arrangement such as is found in window shutters today, the angle of attack of the blades could be changed at will, providing also a braking action at high winds.

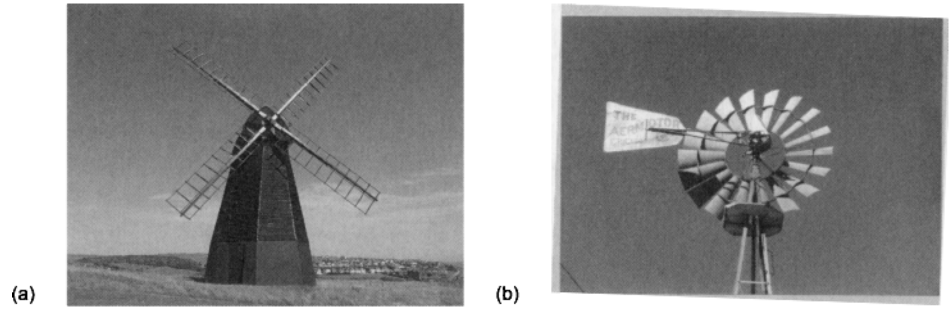

Figure 1.4 A traditional windmill (a) and an American farm windmill (b) for pumping water.

The American windmill is shown in Figure 1.4b. It is a small multibladed wind turbine with a vertical vane to keep it oriented toward the wind. Some models had downwind orientation and did not need to be controlled in this way. The first commercially successful wind turbine was introduced by Halladay in 1859 to pump water for irrigation in the Plains States. It was about 5 m in diameter and generated about one kilowatt (1 kW) at windspeed of 7 m/s [68]. The windmill shown in the figure is a 18-steel-bladed model by Aermotor Company of Chicago, a company whose marketing and manufacturing success made it the prime supplier of this technology during the 1900–1925.

New wind turbines with a vertical axis were invented during the 1920s in France by G. Darrieus and in Finland by S. Savonius [66]. They offer the advantage of working without regard to wind direction, but their disadvantages include fluctuating torque over each revolution and difficulty of starting. For these reasons they have have not achieved wide use.

1.2.3 Steam turbines

Although the history of steam to produce rotation of a wheel can be traced to Hero of Alexandria in the year 100 A.D., his invention is only a curiosity, for it did not arise out of a historical necessity, such as was imposed by the world's increasing population at the beginning of the industrial revolution. Another minor use to rotate a roasting spit was suggested in 1629 Giovanni de Branca. The technology to make shafts and overcome friction was too primitive at this time to put his ideas to more important uses. The age of steam began with the steam engine, which ushered in the industrial revolution in Great Britain. During the eighteenth century steam engines gained in efficiency, particularly when James Watt in 1765 reasoned that better performance could be achieved if the boiler and the condenser were separate units. Steam engines are, of course, positive-displacement machines.

Sir Charles Parsons (1854–1931) is credited with the development of the first *steam turbine* in 1884. His design used multiple turbine wheels, about 8 cm in diameter each, to drop the pressure in *stages* and this way to reduce the angular velocities. The first of Parson's turbines generated 7.5 kW using steam at inlet pressure of 550 kPa and rotating at 17,000 rpm. It took some 15 years before Parsons' efforts received their proper recognition.

An impulse turbine was developed in 1883 by the Swedish engineer Carl Gustav Patrik de Laval (1845–1913) for use in a cream separator. To generate the large steam velocities he also invented the supersonic nozzle and exhibited it in 1894 at the Columbian World's Fair in Chicago. From such humble beginnings arose rocketry and supersonic flight. Laval's turbines rotated at 26,000 rpm, and the largest of the rotors had a tip speed of 400 m/s. He used flexible shafts to alleviate vibration problems in the machinery.

In addition to the efforts in Great Britain and Sweden, the Swiss Federal Institute of Technology in Zurich [Eidgenössische Technische Hochschule, (ETH)] had become an important center of research in early steam turbine theory through the efforts of Aurel Stodola (1859–1942). His textbook *Steam and Gas Turbines* became the standard reference on the subject for the first half of last century [75]. A similar effort was led by William J. Kearton (1893–?) at the University of Liverpool in Great Britain.

1.2.4 Jet propulsion

The first patent for gas turbine development was issued to John Barber (1734–c.1800) in England in 1791, but again technology was not yet sufficiently advanced to build a machine on the basis of the proposed design. Eighty years later in 1872 Franz Stolze (1836–1910) received a patent for a design of a gas turbine power plant consisting of a multistage axial-flow compressor and turbine on the same shaft, together with a combustion chamber and a heat exchanger. The first U.S. patent was issued to Charles Gordon Curtis (1860–1953) in 1895.

Starting in 1935, Hans J. P. von Ohain (1911–1998) directed efforts to design gas turbine power plants for the Heinkel aircraft in Germany. The model He178 was a fully operational jet aircraft, and in August 1939 it was first such aircraft to fly successfully.

During the same timeframe Sir Frank Whittle (1907–1996) in Great Britain was developing gas turbine power plants for aircraft based on a centrifugal compressor and a turbojet design. In 1930 he filed for a patent for a single-shaft engine with a two-stage axial compressor followed by a radial compressor from which the compressed air flowed into a straight-through burner. The burned gases then flowed through a two-stage axial turbine on a single disk. This design became the basis for the development of jet engines in Great Britain and later in the United States.

Others, such as Alan Arnold Griffith (1893–1963) and Hayne Constant (1904–1968), worked in 1931 on the design and testing of axial-flow compressors for use in gas turbine power plants. Already in 1926 Griffith had developed an aerodynamic theory of turbine design based on flow past airfoils.

In Figure 1.5 shows the De Havilland Goblin engine designed by Frank Halford in 1941. The design was based on the original work of Sir Frank Whittle. It is a turbojet engine with single-stage centrifugal compressor, and with can combustors exhausting the burned combustion gases into a turbine that drives the compressor. The remaining kinetic energy leaving the turbine goes to propulsive thrust.

Since the 1950s there has been continuous progress in the development of gas turbine technology for aircraft power plants. Rolls Royce in Great Britain brought to the market its Olympus twin-spool engine, its Dart single-spool engine for low-speed aircraft, and in

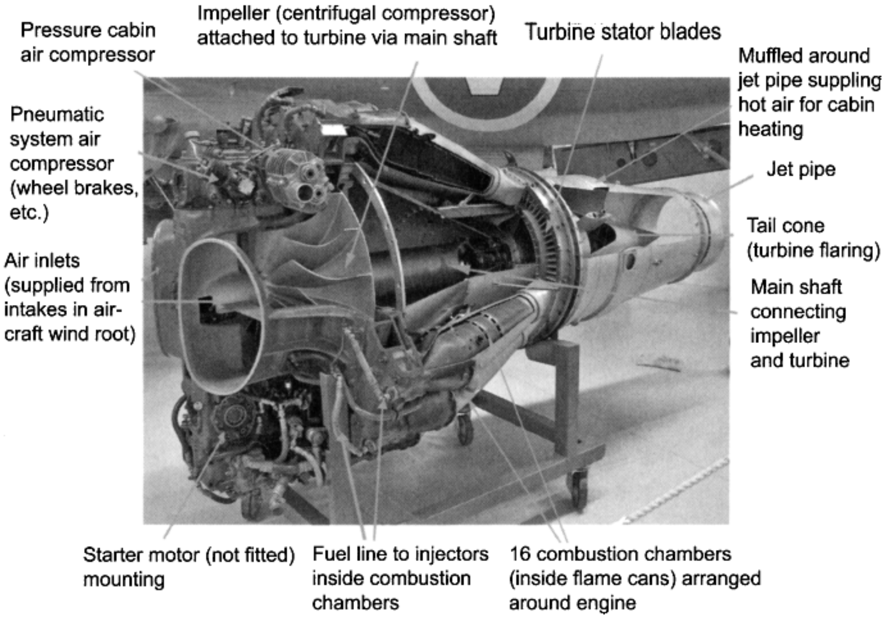

Figure 1.5 De Havilland Goblin turbojet engine.

1967 the Trent, which was the first three-shaft turbofan engine. The Olympus was also used in stationary power plants and in marine propulsion.

General Electric in the United States has also a long history in gas turbine development. Its I-14, I-16, I-20, and I-40 models were developed in the 1940s. The I-14 and I-16 powered the Bell P-59A aircraft, which was the first American turbojet. It had a single centrifugal compressor and a single-stage axial turbine. Allison Engines, then a division of General Motors, took over the manufacture and improvement of model I-40. Allison also began the manufacture of General Electric's TG series of engines.

Many new engines were developed during the latter half of the twentieth century, not only by Rolls Royce and General Electric but also by Pratt and Whitney in the United States and Canada, Rateau in France, and by companies in Soviet Union, Sweden, Belgium, Australia, and Argentina. The modern engines that power the flight of today's large commercial aircraft by Boeing and by Airbus are based on the Trent design of Rolls Royce, or on General Electric's GE90 [7].

1.2.5 Industrial turbines

Brown Boveri in Switzerland developed a 4000-kW turbine power plant in 1939 to Neuchatel for standby operation for electric power production. On the basis of this design, an oil-burning closed cycle gas turbine plant with a rating of 2 MW was built the following year.

Industrial turbine production at Ruston and Hornsby Ltd. of Great Britain began by establishment of a design group in 1946. The first unit produced by them was sold to Kuwait Oil Company in 1952 to power pumps in oil fields. It was still operational in

1991 having completed 170,000 operating hours. Industrial turbines are in use today as turbocompressors and in electric power production.

Pumps and compressors

The centrifugal pump was invented by Denis Papin (1647–1710) in 1698 in France. To be sure, a suggestion to use centrifugal force to effect pumping action had also been made by Leonardo da Vinci, but neither his nor Papin's invention could be built, owing to the lack of sufficiently advanced shop methods. Leonhard Euler (1707–1783) gave a mathematical theory of the operation of a pump in 1751. This date coincides with the beginning of the industrial revolution and the advances made in manufacturing during the ensuing 100 years brought centrifugal pumps to wide use by 1850. The Massachusetts pump, built in 1818, was the first practical centrifugal pump manufactured. W. D. Andrews improved its performance in 1846 by introducing double-shrouding. At the same time in Great Britain engineers such as John Appold (1800–1865) and Henry Bessemer (1813–1898) were working on improved designs. Appold's pump operated at 788 rpm with an efficiency of 68% and delivered 78 L/s and a head of 5.9 m.

The same companies that in 1900 built steam turbines in Europe also built centrifugal blowers and compressors. The first applications were for providing ventilation in mines and for the steel industry. Since 1916 compressors have been used in chemical industries, since 1930 in the petrochemical industries, and since 1947 in the transmission of natural gas. The period 1945–1950 saw a large increase in the use of centrifugal compressors in American industry. Since 1956 they have been integrated into gas turbine power plants and have replaced reciprocating compressors in other applications.

The efficiencies of single stage centrifugal compressors increased from 70% to over 80% over the period 1935–1960 as a result of work done in companies such as Rateau, Moss-GE, Birmann-DeLaval, and Whittle in Europe and General Electric and Pratt & Whitney in the United States. The pressure ratios increased from 1.2 : 1 to 7 : 1. This development owes much to the progress that had been made in gas turbine design [26].

For large flow rates multistage axial compressors are used. Figure 1.6 shows such a compressor, manufactured by Man Diesel & Turbo SE in Germany. It has 14 axial stages followed by a centrifugal compressor stage. The rotor blades are seen in the exposed rotor. The stator blades are fixed to the casing, the lower half of which is shown. The flow is from right to left. The flow area decreases toward the exit, for in order to keep the axial velocity constant, as is commonly done, the increase in density on compression is accommodated by a decrease in the flow area.

1.2.6 Note on units

The Système International (d'Unités) (SI) system of units is used in this text. But it is still customary in some industries English Engineering system of units and if other reference books are consulted one finds that many still use this system. In this set of units mass is expressed as pound (lbm) and foot is the unit of length. The British gravitational system of units has *slug* as the unit of mass and the unit of force is pound force (lbf), obtained from Newton's law, as it represents a force needed to accelerate a mass of one slug at the rate of one foot per second squared. The use of slug for mass makes the traditional British gravitational system of units analogous to the SI units. When pound (lbm) is used for mass, it ought to be first converted to slugs (1 slug = 32.174 lbm), for then calculations follow smoothly as in the SI units. The unit of temperature is Fahrenheit or Rankine. Thermal