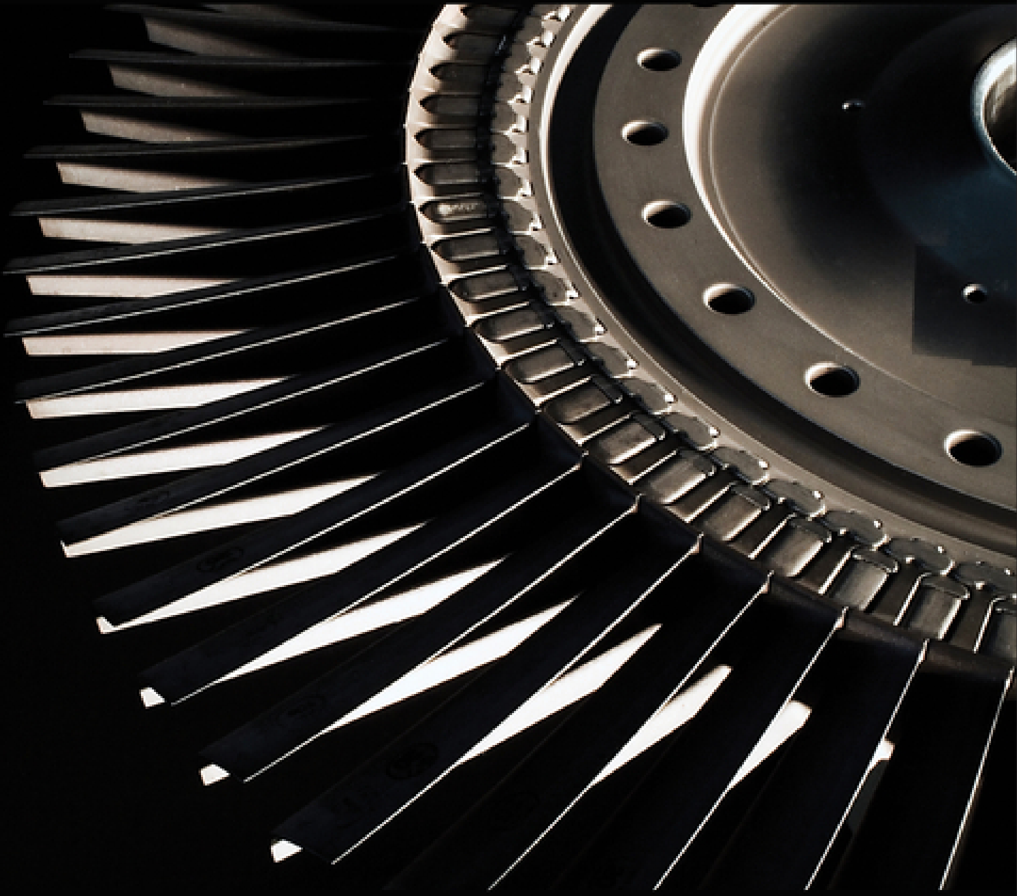
PRINCIPLES OF TURBOMACHINERY

SECOND EDITION

SEPPO A. KORPELA



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Seppo A. Korpela
The Ohio State University

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To my wife Terttu,
to our daughter Liisa,
and to the memory of our
daughter Katja

CONTENTS

Foreword

Turbomachines are important machines in our industrial civilization. Steam turbines are used to generate electricity at central station power plants, whether fueled by coal or uranium. Gas turbines and axial compressors are found in jet engines. Aero-derivative gas turbines are used to generate electricity with natural gas as fuel. Same technology is used to drive centrifugal compressors for transmission of natural gas across continents. Blowers and fans are in use for mine and industrial ventilation. Large pumps provide feed-water to boilers and move wastewater in sanitation plants. Hydraulic turbines generate electricity from water stored in reservoirs, and wind turbines do the same from the blowing wind.

This is a textbook on turbomachines. It aims for a unified treatment of the subject matter, with consistent notation and concepts. Chapter 4 is new to this edition. It consists of an account of droplet laden flows of steam that is relevant to the flow in the low pressure end of a steam turbine. It is quite specialized and ought to be left for an advanced course, or later self-study. Similarly, the new section on oblique shocks in Chapter 3 is included as background material for understanding phenomena in transonic compressors. Those with a background on thermodynamics and gas dynamics, may just glance through Chapter 2 and early parts of Chapter 3. Some sample computer codes are given in the text. They are based on MATLAB and its equivalent GNU-OCTAVE. The latter is free software and tailored to be compatible with MATLAB. In the Appendix B is a script that can be used in the calculations of air with variable specific heats. The program XSTEAM by Magnus Holmgren is used when the properties of steam are needed. It is available from Mathworks website. https://www.mathworks.com/matlabcentral/profile/authors/870351-magnus-holmgren.

Acknowledgments

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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 and 8.1 are by courtesy of MAN Diesel & Turbo SE, and Figures 5.12 and 5.13 are published by permission of BorgWarner Turbo Systems. Figure 3.11 is courtesy of Professor D. Papamaschou; Figures 11.3 and 11.11 are published under the GNU Free Documentation licenses with original courtesy of Voith Siemens Hydro. The Figure 11.9 is reproduced under the Gnu Free Documentation licence, with the original photo by Audrius Meskauskas. Figure 11.5 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 4.10, 7.16, 8.6, 8.7, and 8.17. Figure 5.11 is published under agreement with NASA. The *Journal of the Royal Aeronautical Society* granted permission to publish Figure 7.11. Figures 7.19 and 7.20 are published under the Crown Stationary Office's Open Government Licence of UK. Figure 3.8 has been adapted from J. H. Keenan, *Thermodynamics*, MIT Press and Figure 10.6 from O. E. Balje, *Turbo* *machines – A guide to Selection and Theory*. Permission to use Figures 13.13 and 13.15 from *Wind Turbine Handbook* by T. Burton, N. Jenkins, D. Sharpe, and E. Bossanyi has been granted by John Wiley & Sons.

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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.

About the Companion Website

This book is accompanied by a companion website:

www.wiley.com/go/Korpela/PrinciplesTurbomachinery_2e

The website contains Solutions Manual for Principles of Turbomachinery

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 33% of world's energy mix, coal's share is 30%, and that of natural gas is 24%, for a total of 87%. Hydropower contributes 7%, and nuclear's share is about 4%, and these increase the total from these sources to 98%. The final 2% is supplied by wind, geothermal energy, waste products, and solar energy [101]. Most of the 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 [61].

1.1.1 Energy conversion of fossil fuels

Over the last two centuries, engineers have 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.

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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 aforementioned methods, 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 and compressors, 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 in hydraulic turbines *inlet guide vanes*.

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 in the program of study of mechanical engineering.

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. During the year 2016, coal provided 30%, and nuclear fuels 20%, of the electricity production in the United States. For the world, the corresponding numbers are 40% and 11%, 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

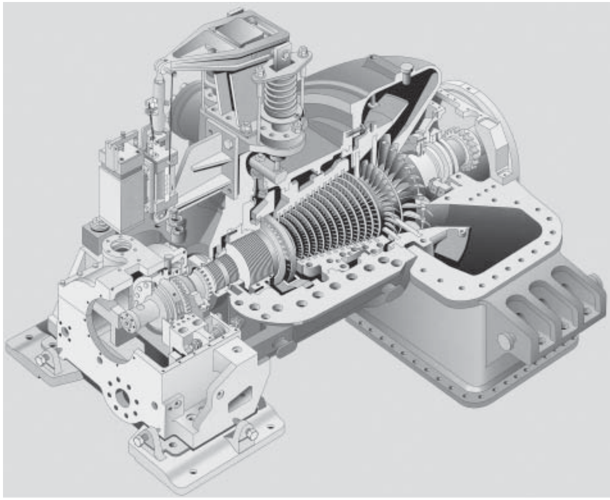

Figure 1.1 The Siemens SST-600 industrial steam turbine with a capacity of up to 100 MW. Source: Courtesy Siemens press picture, Siemens AG.

in this turbine. Each stage consists of a set of rotor blades, preceded by a set of stator vanes. 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 near $540\ ^\circ\mathrm{C}$, and its pressure is close to $140\ \mathrm{bar}$. Angular speed of the shaft is generally in the range 3500–15000 rpm (rev/min). In this turbine, there are five bleed locations for the steam. The steam extracted from the bleeds enters feed-water heaters and from them 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. Critical pressure for steam is $220.9\ \mathrm{bar}$, and its critical temperature is $373.14\ ^\circ\mathrm{C}$. In an ultra-supercritical plant, the boiler pressure can reach $600\ \mathrm{bar}$ and turbine inlet temperature, $620\ ^\circ\mathrm{C}$.

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 become important in electricity production. Their use in combined cycle power plants has increased the plant's 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, and they now account for 34% of the electricity production. Unfortunately, production from the old natural gas fields of North America is strained, even if new resources have been developed from shale deposits. Projections show increasing use of natural gas in the energy mix in the United States, although it is still unclear how long the new deposits last since these wells deplete rapidly.

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

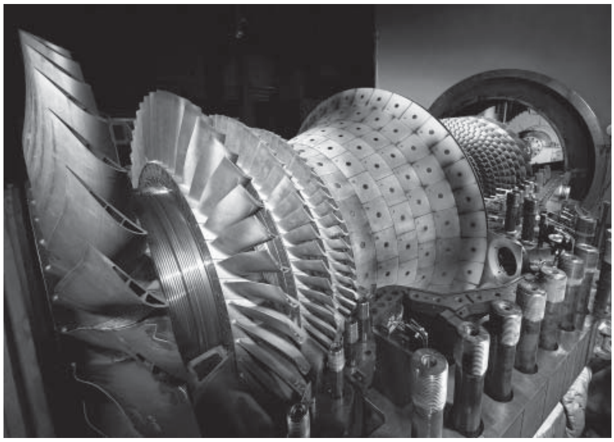

Figure 1.2 An open rotor and combustion chamber of an SGT5-4000F gas turbine. Source: Courtesy Siemens press picture, Siemens AG.

blades, with thermal barrier coatings 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.

1.1.4 Hydraulic turbines

In those areas of the world with large rivers, water turbines are used to generate electric 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 2016 was 1064000 MW, but generation was 451000MW; therefore, their ratio, called a *capacity factor*, comes to 0.38.

With the completion of the 22500-MW Three Gorges Dam, China has now the world's largest installed capacity of 319000 MW and generated 28000 MW of power, based on year 2014 statistics. Canada, owing to its expansive landmass, is the world's second largest producer of hydroelectric power, with generation at 44000 MW from installed capacity of 76000 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 43000 MW from an installed capacity of 89000 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 12600 MW of power at full capacity. Of nearly the same size is Venezuela's Guri dam power plant with a rated capacity of 10200 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 282 billion kilowatt-hours (kwh) a year, or

33000 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 2015, its installed wind turbine's capacity was 45000 MW. It was exceeded only by China and the United States. China's installed capacity was 145400 MW and that of the United States was 74500 MW. They were followed by India and Spain with installed capacity of 27100 MW in India and 23000 MW in Spain. Although Denmark has fallen from the leaders, it still generates a larger percentage of its energy from wind than the others.

For the world, the capacity factor for wind power averages about 0.20, thus even lower than for hydropower. But for the United States, it is about 0.32, and wind constitutes about 2% of the country's total energy needs. 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. In addition to Texas, there are tight gas formations in North Dakota, Colorado, Pennsylvania, and Ohio. 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.

Russia has 18% of world's natural-gas reserves, and much of its gas is transported to Europe through Ukraine. China has constructed a natural-gas pipeline to transmit the gas produced in the western provinces to the eastern cities. Extensions to Turkmenistan have been completed, and extensions to Iran are in the planning stage. Both have large natural-gas reserves.

Another important application of compressors is in the jet engines as previously mentioned.

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 feed-water heaters, from which the water is pumped to boilers. Pumps are also used for cooling water flows in these power plants.

Figure 1.3 A centrifugal pump. Source: Courtesy Schmalenberger GmbH.

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 $100\ \mathrm{m^3/h}$, with a $20\ \mathrm{m}$ increase in its head.

In the mining industry, blowers circulate fresh air into mines and exhaust stale and 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.

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 air conditioner 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 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 200 years. Compressors developed as advances were made in aircraft propulsion during the last century.

1.2.1 Water power

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 BCE.

Overshot waterwheel came into use in the hilly regions of Rome during the second century CE. 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 Conqueror's *Domesday Book* of 1086, the number of watermills in England is said to have been 5684. By 1700, about 100000 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 [1], 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 wheel and 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 guide vanes to direct the flow tangentially to the blades. In 1835, Fourneyron 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 11000-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 CE, where these vertical axis windmills were still in use in recent times [39]. 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 [82]. 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 *post-mills*. This restriction was removed in a *tower mill* in which only the platform, affixed to the top of the mill, was free to rotate. The blades were connected to a wind shaft, 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 of the spar supporting a blade from mid-cord to quarter-cord position and to introduce a nonlinear twist and leading edge camber to the blade [82]. The blades were positioned at a steep angle to the wind and made use of the lift

(a) (b)

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

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-cord blades is about 1 m 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.

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 1 kW at windspeed of 7 m/s [82]. The windmill shown in the figure is an 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 period 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 [80]. 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 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 CE, 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 that 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,