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Introduction

1.1 Introduction to the Study of the Aerothermodynamics of Turbomachinery

Turbomachinery refers to a machine which has one or more stator and rotor blade rows. It is able to transfer potential or thermal energy either to or from the fluid (especially gas) flow. Turbomachinery has been widely used in different industries, playing important roles in national economies and defense, as follows:

In conventional *power* plants and nuclear power stations, which account for more than 80% of all electrical power generated, gas turbines are used in combined-cycle and power plants. In hydro-electrical power generation plants large hydraulic turbines are installed. In fields, on and off shore and on islands wind turbines are used to generate electricity. The above-mentioned machines belong to the category of turbomachinery.

Gas turbines, compressors and fans are used in *aero-engines* (for aircraft and helicopters). The turbojet, turbofan and turboprop engines play a dominant role over other kinds of engines in the aero industry.

Rocket engines with fuel and liquid oxidant pumps are used in missiles and for space exploration purposes. The turbines and the centrifugal pumps with inducers installed in rocket engines are also turbomachines.

As an application to *shipping*, steam turbine power plants and supplementary facilities (fire protection pump and electric generators, and so on) are installed in large commercial ships and nuclear submarines. More and more gas turbine power plants are used in naval surface warships. Careful hydrodynamic design of the low-noise propellers used for submarines is an important way to protect against sonar detection.

In some *trucks, cars and trains* gas turbines are also applied. Important devices, such as hydraulic coupling, torque converters and brakes, and so on, are designed using advanced turbomachinery theory.

A great number of gas turbines, compressors and pumps are applied in *other industries*, such as gas and petroleum transmission, the food, paper and metallurgy industries, chemical processes, water purification and pumping stations, refrigeration equipment, and so on.

It is, hence, obvious that turbomachinery is of great importance to the global economy. On the one hand, any small increase in turbomachinery efficiency could have a great impact on the global economy. On the other hand, it is known that in some developing countries manufacture and design fail to keep pace with the advanced countries. Therefore, it is important to publicize ways of cost-effective development of aerothermodynamics studies in relation to turbomachinery.

Professor Aurel Boreslav Stodola (1859–1942) was a pioneer in the area of technical thermodynamics and its applications. He published his book “Die Dampfturbine” at the turn of the twentieth century. His book “Steam and Gas Turbines” was published in Berlin in 1924, an English translation was published in 1927 and was reprinted many times up to 1945. It was a basic reference for engineers working on steam and gas turbines world-wide and on the first generation of jet propulsion engines in the United States.

Professor Stodola was the founder of turbomachinery aerothermodynamics – theory and practice. He was also the prime author of books on aerothermodynamics in turbomachinery. He made great and outstanding contributions in research and development in this area.

After his famous books, many books on aerothermodynamics of turbomachinery have been written by others. Some are listed at the end of this chapter. The author would like to express sincere gratitude to these authors for their creative contributions to the subject of turbomachinery aerothermodynamics, which have educated several generations of researchers working on this subject.

1.2 Brief Description of the Development of the Numerical Study of the Aerothermodynamics of Turbomachinery

In recent decades much progress on the study of aerothermodynamics of turbomachinery has been achieved. Three major developments have led to this. First is the driving force from commercial and military aero-engine manufacture and large electricity power generation seeking improved performance and reduced fuel consumption, and also improved environmental impact. Second is the progress in measuring techniques and sophisticated experimental facilities, and third the rapid progress of computer technologies, and computational techniques.

In research centers and experimental establishments in different countries many large experimental facilities for testing different parts and devices, single rotor and multi-stage experimental turbomachines have been constructed and installed. At the same time a series of advanced measuring instruments and techniques have been implemented. They included two-focus laser and Doppler laser velocimeters, accurate hot wire probes, high frequency and sensitive pressure transducers, laser interferometers, schlieren apparatus, high speed photography and holography. The measuring techniques have enabled us to obtain the detailed information on different aerodynamic parameters of the flow field inside turbomachines. A large amount of useful experimental data has been accumulated. Laser, holography and other optical techniques have been applied to display the flow field in detail and have demonstrated a completely new way to get information which could not be realized before. The data collection, interpretation and processing procedures have completely removed manual work by the use of computers. All the achievements on the experimental side have made experimental studies leap forward: from low speed to high speed; from resting to rotational devices; from

steady to unsteady flows, and from global performance measurements to diagnoses of the detailed flow field.

The reliability and accuracy of computational fluid dynamics (CFD) have been improved dramatically in recent decades. The importance of investigation of aerothermodynamics in turbomachinery by applying CFD has been recognized in the turbomachinery community. In the last 20 years the computer speed has been increased several thousand times. Many problems that could not previously be solved have been numerically solved. People working on CFD have their own challenges in methodologies of numerically solving different physical and mathematical equations, computational grid generation methods, initial and boundary condition treatments, turbulence modeling and aerodynamic optimization design. The achievements obtained recently have shown that CFD can be used to illustrate fluid physics, conduct aerodynamic design, devise performance improvement and discover new concepts.

The study of the aerothermodynamics of turbomachinery has gone through several historical stages from the 1940s till now. The study in this period has moved from one-dimensional to two- and three-dimensional flows, from inviscid to viscous flows, and from steady to unsteady flows.

At the beginning of the 1950s, Professor Zhong Hua Wu (Chong-hua Wu) proposed a method that uses two kinds of S1 and S2 stream surfaces to solve three-dimensional inviscid flow problems in turbomachines. The mean S2 stream surface stream function solution method is an inverse (design) method. In that period the conformal mapping, singularity, velocity hodograph, potential- and stream-function methods and various approximate numerical approaches for solving two-dimensional or quasi-three-dimensional fluid flow were still being used. Papers concerning inverse (design) method were also published. From then on, the viscous effect on precise and approximate methods for solving laminar and turbulent boundary layer flows became more popular. For developing 2D and 3D transonic inviscid fluid flow solution methods, the focus was on accelerating the converged process to increase the time marching step and, as a result, a multi-grid algorithm was proposed, in the early 1980s. This was able to increase the converging speed for the solution of the Euler equation more than threefold.

From the 1970s, experimental and numerical studies on transonic and supersonic compressor blade cascades have been carried out. The research focused on designing supersonic inlet compressor blade cascades with the smallest loss coefficient by reducing the losses due to the shock and boundary layer interaction and managing the shock structure correctly. A total pressure ratio greater than 2.1 could be reached when the inlet Mach number was 1.6. At the same time, for these compressor blade cascades active and passive control techniques were used and evaluated.

It is well known that the Navier–Stokes (NS) equations are the governing equations describing the viscous flow in turbomachinery. Even though the equations were derived over a century ago, up to now only a few examples of the simpler forms have been solved properly. Due to the rapid progress in computer sciences and techniques, numerical computations for 2D viscous flows in different devices were conducted in the 1980s. The turbulence effect was also considered approximately.

In the 1990s different 3D viscous flow computation methods were proposed, such as various time-marching methods, pressure correction methods and some other methods using different schemes and algorithms. The NASA single rotor compressor blind test case examination,

which was initiated by Professor J. D. Denton and Dr T. Strazisar and organized by the Turbomachinery Committee of the ASME Gas Turbine Conference, was a challenging event in the turbomachinery community. The greatest challenge was how to sensibly resolve the NS equations to analyze the turbulence. Up to now there is no generalized turbulence model which can be used in different cases.

From the 1990s till now, studies of unsteady flow phenomena in turbomachinery and aerodynamic design optimization have become more popular in the field of aerothermodynamics in turbomachinery. The following aspects are worth investigating: unsteady NS solution method, stall and choke in compressor, stability enhancement technique, aerodynamic flutter of blades, unsteady aerodynamic interference between blade rows, aero-acoustics and multi-phase flow, and so on.

Figure 1.1 is a brief qualitative illustration of the history of the development of the numerical methods. There are two arrows in the figure showing two trends. The upper arrow shows the computer speed and capacity requirements for the computational methods. The lower one shows that the use of these computational methods requires the qualification and experimental validation that the designers have to have. For decades, the requirements of computer speed and capacities for the method used have increased and the requirements of designers' experience and experimental validation have decreased.

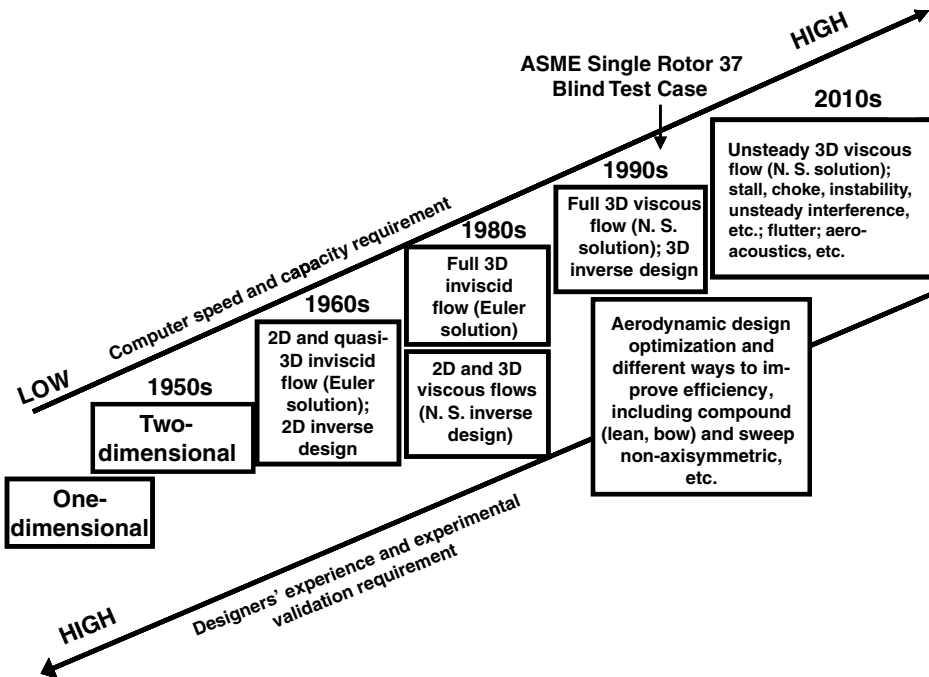


Figure 1.1 Development of numerical computational method

The achievements in aerodynamics design methodologies of turbomachinery due to the development of experimental, theoretical and numerical studies have resulted in improved turbomachine performance. From the published materials of different research institutes, companies, societies and exhibitions working on gas turbines it can be summarized as shown in Figure 1.2. Compared with the 1950s the averaged polytropic efficiency and averaged overall pressure ratio for gas turbine compressors have shown very rapid increase. At the same time the design parameters such as averaged solidity and aspect ratio have also improved. In particular, the development of the axial compressor achieved by the General Electric Company should be noted. There are 10 stages in the compressor of the E³ engine. It achieves a total pressure ratio of 23 with an efficiency of almost 86% of the design condition.

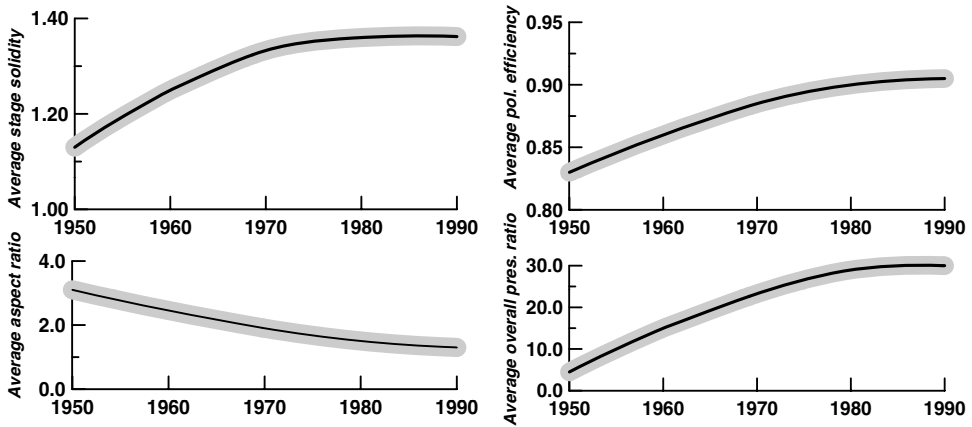


Figure 1.2 The trend in performance (polytropic efficiency and overall pressure ratio) and in compressor geometry (solidity and aspect ratio) for a gas turbine compressor) with time (Adapted from Rohlik, H.E., “Current and Future Technology Trends in Radial and Axial Gas Turbines,” NASA IM 83414, 1983; Freeman, C. and Dawson, R.E., “Core Compressor Developments for Large Civil Jet Engines,” Paper 83-Tokyo-IGTC-46, International Gas Turbine Congress, Tokyo, 1983; Wisler, D., “Advanced Compressor and Fan System,” GE Aircraft Engines, Cincinnati, Ohio, U.S.A. (or Lecture to ASME Turbochinery Institute, Ames Iowa), 1986; Cumpsty, N.A., *Compressor Aerodynamics*, Longman Group, New York, 1989; and Lakshminarayana, B., *Fluid Dynamics and Heat Transfer of Turbomachinery*, Wiley-Interscience Publication, John Wiley & Sons, Inc., New York, 1996.)

Figure 1.2 and Figure 1.3 show the trend and level of aerodynamic design. On this problem many authors have contributed very valuable information, such as Rohlik, 1983, Freeman and Dawson, 1983, Wisler, 1988, Cumpsty, 1989, and Lakshminarayana, 1996, and so on.

Solidity and aspect ratio, stage loading and compressor total pressure ratio are important geometrical and performance parameters in compressor blade design. In Figure 1.2 the trend of compressor aerodynamic design is clearly shown. The average aspect ratio is inversely proportional to the stage average solidity. This is due to the chord length. The increase in solidity and decrease in aspect ratio with decade can result in a pressure rise per

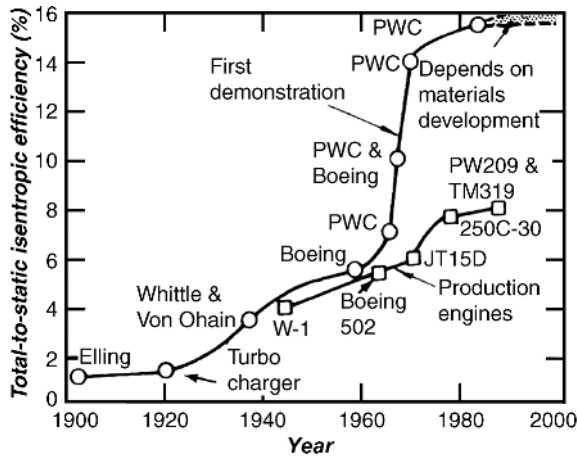


Figure 1.3 The trend in the total pressure ratio of a centrifugal compressor (Reprinted from Kenny, D.P., “The history and future of the centrifugal compressor in aviation gas turbines,” 1st Cliff Garrett Turbomachinery Award Lecture, Society of Automotive Engineers Paper SAE/SP-804/602, 1984, with permission from SAE paper 841635 © 1984 SAE International.)

stage and also increase in the global total pressure ratio. Over 30 years the stage average loading and the spool pressure ratio have increased by approximately 1.3 and 2.1 times, respectively.

Centrifugal compressors are widely used in different industries. Due to the production of a very high pressure ratio in one stage gas turbine engines with centrifugal compressors are often used in small aircraft. Figure 1.3 (Kenny, 1984) illustrates the trend in the pressure ratio over time. One can see that the pressure ratio of the centrifugal compressor has risen significantly.

1.3 Summary

Turbomachinery plays an important role in different industries relating to national economy and defense.

Great progress in the study of the aerothermodynamics of turbomachinery has been achieved in recent decades. This is due to: (i) the requirements of suppliers of commercial, and military aero-engines, and large electricity power plants for improved performance and reduced fuel consumption, and also for improvements to the global environment; (ii) the progress in measurement techniques and experimental facilities; (iii) the rapid progress of computer science, technology and computational techniques.

Professor Stodola was the author of the first book on aerothermodynamics in turbomachinery. Since then a number of books on aerothermodynamics of turbomachinery have been published. Some are listed at the end of this chapter.

I have realized that the contents of the first one or two chapters in these published books are similar: the first and second laws of thermodynamics, the properties of liquids and gases, design parameters of turbomachinery, classification of turbomachines, some basic concepts in fluid mechanics, and the working principles of turbines, compressors and fans. In some, the

elementary or applied mathematics, vector and tensor analyses are given. In the present book, therefore, these are not included. Readers can find these basic concepts in the books listed under Further Reading.

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