Turbines Compressors and Fans

(SI UNITS)

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Foreword

It is gratifying to note that in this book unified treatment and dimensional analysis have been duly emphasized in the initial chapters of the book, although its title projects specific types of turbo-machinery. Such a unified treatment generally broadens the horizon and facilitates horizontal transfer of knowledge and experience. Another significant aspect is the use of SI units throughout the book. This should form a pace-setter for having all other technical books with SI units.

After covering the essential aero-thermodynamic principles of turbomachinery, the author deals separately with a chapter on cascades which have formed the basis for the optimum selection of aerodynamic geometry of blades. This is a very welcome feature of the book. A subject of topical interest dealing with "High Temperature Turbines" has been covered by devoting to it a full chapter.

Although classical turbomachines continue to play a major role in the energy sector, a class of machines called wind turbines are gaining importance due to the renewable nature of wind energy. It is but appropriate that the book closes with a chapter on wind energy and turbines giving it a measure of completeness commensurate with the title.

The value of the book is enhanced by the numerous illustrations and a balanced emphasis on various topics covered in the book. Principal technical data of modern aviation gas turbines such as that for the supersonic aircraft Concorde and RB-199, specifications of the turbine and compressor blade profiles and some wind turbines form other distinguishing features of the work. This book will be a valuable addition to the existing books in turbomachinery which are primarily directed towards the course work of students. Moreover, the book introduces the reader to the current research areas in turbomachinery. The author's extensive experience in teaching and research has been truly reflected in this book. A detailed topic-wise bibliography containing over 800 references will be a valuable source of information for the researchers. This book would be equally helpful to practising engineers who desire to initiate themselves professionally in the field of turbomachinery.

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Preface

Recent emphasis on energy problems has generated renewed interest in turbines, compressors and fans. Steam and gas turbines develop the bulk of power required for land and air applications. Similarly, fans, blowers and compressors are some of the major power-absorbing machines in industry. The wind turbine or windmill has reappeared on the power-generation scene. Therefore, at this time a book wholly in SI units dealing with this class of machines is badly needed by students, teachers and practising engineers.

The basic principle of working of these machines is the same—the energy level of a continuously flowing fluid is changed by the action of a rotating element, the rotor. The theoretical treatment of such machines requires the knowledge of both fluid dynamics and thermodynamics. Therefore, some fundamental problems in thermodynamics and fluid dynamics common to these machines have been covered in separate chapters in the beginning. They provide the important link between the engineering sciences and an important class of machines (turbomachines) used in a variety of industrial, power generation and aircraft propulsion fields.

The overall performance and the importance of a given machine is better appreciated when its role in relation to other components in the plant is understood. Therefore, chapters on gas and steam turbine plants which employ these machines have also been included and placed in the earlier part of the book.

A short chapter on dimensional analysis prepares the reader to proceed to the analysis of particular types of machines. In this the various quantities that affect the design and performance of turbomachines are identified and discussed. A brief discussion on various dimensionless parameters is also given.

Chapters 1 to 6 deal with the various kinds of turbines, compressors and fans in a general way. The later chapters deal with the aero-thermodynamic aspects of particular kinds of thermal turbomachines in greater depth. Therefore, theoretical details and physical explanation of individual machines are given in separate chapters on turbines, compressors and fans which constitute the main body of this volume. Velocity triangles and enthalpy-entropy diagrams have been frequently used in these chapters to explain the various kinematic and thermodynamic aspects of these machines.

Chapter 7 on cascades acquaints the reader with the geometries of blades and blade rows in different types of turbomachine stages. This also focuses attention on the practical aspects of turbomachines. Various types of wind tunnels employed for cascade testing are described here.

Chapter 8 deals with the conventional axial-flow turbine stages. Some unconventional turbines usedin aerospace applications like partial admission and cooled turbines are also covered in Chapters 8 and 9 respectively.

The treatment of axial compressor stages in Chapter 10 is on the same lines as discussed in the earlier chapters for axial turbine stages.

Both centrifugal compressors and radial turbines form a separate group of turbomachines employing a different technology. These machines have been discussed in Chapters 11 and 12. Here the tangential direction is taken as the reference direction in velocity triangles for the stages. This is in marked contrast to the treatment for axial stages where the axial direction has been taken as the reference direction.

Fans and blowers on account of their low pressures (expressed in millimetres of water gauge instead of bar) are also a separate class of turbomachines. Therefore, instead of combining them with the compressor stages they are separately discussed in Chapters 13 and 14.

Chapter 15 deals briefly with the salient features of wind turbines. Some general aspects of wind energy have also been included here.

Only SI units have been used in this book. Generally bar and millibar have been used as units for pressure; their relationship to N/m^2, kN/m^2 and MN/m^2 is given in an appendix.

Useful references for further reading are given in the Select Bibliography at the end of the book.

The material covered in this volume will be useful in the study of subjects on steam and gas turbines, aircraft propulsion, thermal power plants, thermal turbomachines, fluid machinery and energy studies. Therefore, besides students and teachers, design engineers in the areas of power plants, aerospace, supercharged IC engines, industrial fans, blowers and compressors should also find this book useful.

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Acknowledgements

It is gratefully acknowledged that the material throughout the book is based on the ideas and concepts already developed over the years by numerous authors and researchers, some of whose publications are reported at the end of the book. Formal reference of many laws and theories that are now of a classical nature has not been given. I regret if any acknowledgement that is due has been missed out or found inadequate. The needful will be done if attention to this is drawn.

I am grateful to The Rolls-Royce Ltd, Turbounion Ltd, United Technologies, and Pratt and Whitney Aircraft Company for supplying useful information material for inclusion in this book. Institution of Mechanical Engineers, American Society of Mechanical Engineers and the Pergamon Press gave permission for using some material from their publications which is gratefully acknowledged.

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Introduction

Turbines and compressors are now being used in electric power generation, aircraft propulsion and a wide variety of medium and heavy industries. Small- and heavy-duty fans and blowers cover a wide range of industrial applications. Axial fans (propellers) are used for propelling small low-speed aircrafts, while large jet-airliners employ axial-ducted fans in their comparatively new turbo-fan concept.

Though the steam turbine was perfected much earlier than the gas turbine engine, the last two decades have seen almost parallel developments in aeroengines and steam turbine power plants. As a result today on the one hand we have the jumbo-jets and their high thrust engines in the aeronautical field, while on the other there are giant steam turbine plants operating in the "super-thermal power stations". These developments suggest that the 2000 MW steam turbine plants will be operating in many countries by the turn of the century; along with this the "super jumbo-jet" airliners will also be flying between the major cities of the world.

1.1 TURBOMACHINES

Turbines, compressors and fans are all members of the same family of machines called turbomachines. A turbomachine [1,3,5,11] is a power or head generating machine which employs the dynamic action of a rotating element, the rotor; the action of the rotor changes the energy level of the continuously flowing fluid through the turbomachine. Before discussing other aspects of turbomachines, they are compared here with the positive displacement machines. This will help in understanding the special features of turbines, compressors and fans.

Positive displacement machines (both engines and compressors as shown in Figs. 1.1 and 1.2), especially of the reciprocating type are inherently low-speed machines on account of mechanical and volumetric efficiency considerations. In contrast to this the majority of turbomachines run at comparatively higher speeds without any mechanical problems. The volumetric efficiency of turbomachines is close to hundred per cent.

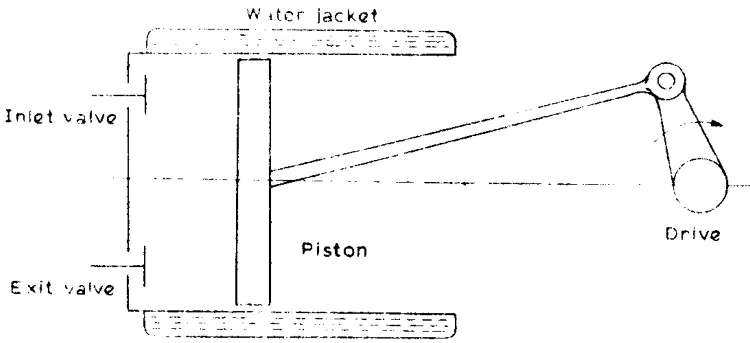

Fig. 1.1 Reciprocating compressor

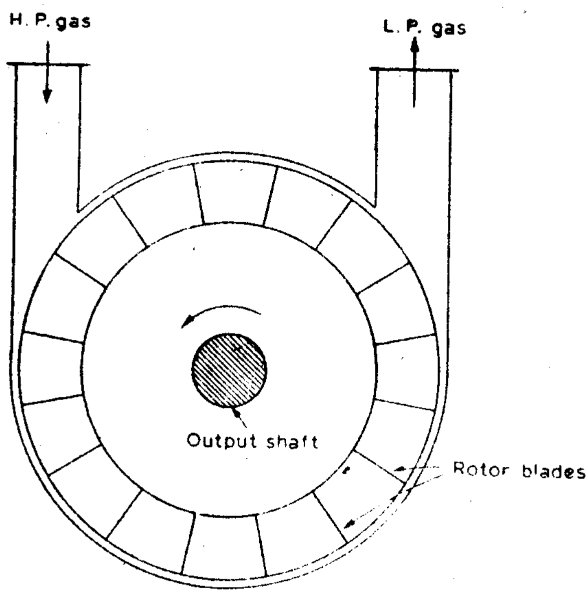

Fig. 1.2 Drag turbine (positive displacement machine)

If a reciprocating engine is stopped, the working gas trapped inside the cylinder stays there in the same state in which it was at the time of stoppage of the engine piston. This is possible if the cylinder is perfectly insulated from the surroundings and there is no leakage.

Now consider the state of the gas in a turbine whose motion is stopped.

The gas will experience changes in its state dictated by the surroundings. This is an important feature which distinguishes turbomachines from positive displacement machines.

On account of much lower speeds, a reciprocating compressor can theoretically be made to work isothermally. Cylinder jacket cooling and intercooling with multistage compression help in achieving isothermal compression. On the other hand, the high speed turbocompressor is an adiabatic machine; the same is true for other turbomachines.

A reciprocating or positive displacement machine, due to its low speed and limited displacement can only handle smaller flow rates of fluids through it. While on account of much higher rotor and fluid velocities the flow rates in turbomachines are much larger compared to positive displacement machines.

1.2 TURBINES

The power generating turbomachines decrease the head or energy level of the working fluids passing through them. These machines are called turbines, e.g. steam, gas, hydro and wind turbines. They are coupled to power absorbing machines, such as electric generators, pumps, compressors, etc.

1.3 PUMPS AND COMPRESSORS

The head or pressure producing machines increase the energy level (pressure or head) of the fluids passing through them. These machines are known as pumps, compressors (or turbocompressors), fans, blowers and propellers. They are driven by prime movers such as turbines and electric motors for supplying the power required to increase the energy level of the fluid.

1.4 FANS AND BLOWERS

A fan continuously moves a mass of air, gas or vapour at the desired velocity by the action of its rotor. For achieving this objective there is a slight increase in the gas pressure across the fan rotor. However the main aim of a fan is to move a gas without an appreciable increase in its pressure. The total pressure developed by fans is of the order of a few millimetres of water gauge (W.G.).

A blower which is also sometimes referred to as a fan develops an appreciable rise in pressure of the gas flowing through it. This pressure rise is required to overcome pressure losses of the gas during its flow through various passages. In some applications such as power plant boilers and mine ventilation system the pressures developed by the blowers are more than 1000 mm W.G. Some low-pressure turbocompressors are also called blowers or turboblowers.

In contrast to fans and blowers, the pressures developed by the compressors are from moderate to high. Therefore the pressure rise through the compressors is expressed in terms of pressure ratio.

1.5 COMPRESSIBLE FLOW MACHINES

The pressure, temperature and density changes occurring in fluids passing through steam and gas turbines, and compressors are appreciable. A finite change in the temperature of the working fluid is a typical characteristic of this class of machines which distinguishes them from other turbomachines. This class of machines with predominantly compressible flows are referred to as compressible flow or thermal turbomachines.[14] They are characterized by higher temperatures and peripheral speeds of the rotor. Therefore their design and operation are influenced by compressible flows, high temperature and speed problems.

1.6 INCOMPRESSIBLE FLOW MACHINES

Hydraulic pumps and turbines are examples of turbomachines working with a liquid. The fluid or water is incompressible giving a constant volume flow rate for a given mass flow rate in steady operation. Water and air are considered here as typical working fluids in turbomachines handling liquids and gases. The density of water is about 800 times that of atmospheric air. Therefore the force required to accelerate a given mass of water is much larger compared to that required for air. This factor largely accounts for much lower fluid and rotor velocities in hydro-turbomachines.

Turbomachines dealing with gases over a small pressure difference also behave as incompressible flow machines. This is because of negligible changes in the temperature and density of the fluid across the machine. Fans, low pressure blowers, airscrews and windmills are examples of such machines.

Thus a majority of incompressible flow machines work near ambient conditions and are comparatively low speed and low temperature machines. This makes their running and maintenance much easier compared to thermal turbomachines.

1.7 TURBINE, COMPRESSOR AND FAN STAGES

A stage of a turbomachine generally consists of a ring of moving blades along with a ring of fixed blades.

A turbine stage as shown in Fig. 1.3 is made up of a ring of fixed nozzle blades followed by the rotor blade ring. However a nozzleless stage with only the rotor is also possible and is often employed in an inward flow radial turbine.