1 Overview of Gas Turbines for Propulsion and Power Generation

1.0 Introduction

This is the age of gas turbines with their ever-growing contributions to people's living standard and well-being. As a great technological marvel, perhaps next only to the inventions of electricity and light bulb, gas turbines have become indispensible in commercial aviation, shrinking the travel time around the globe in hours rather than days and weeks as was the case in the early 1990s by sea. Almost all modern military fighter jets with high maneuverability deploy gas turbine engines. Even in liquid rocket propulsion, gas turbines are used to pump liquid fuel and oxidizer to the combustion chamber at high pressure. Nonflying gas turbines, where weight considerations are important only to reduce material cost, have revolutionized the means of power generation both on land and sea. Their impressive applications portfolio includes utility and industrial power generation, combined heat and power (CHP), oil and gas, and mechanical drive. Gas turbines are a strong candidate of choice where fast power is needed in the distributed power generation for commercial buildings and facilities. Their fuel flexibility is leveraged in applications involving biogas, biomass, waste gas, and waste to energy to produce utility steam. In view of the growing demand for energy around the world, it is highly unlikely that wind turbines and other forms of turbomachinery using renewable will make gas turbines obsolete as they (gas turbines) did to piston-powered reciprocating machines in the early part of the last century. In fact, in the foreseeable future, the world demand for gas turbines for both propulsion and power generation is expected to grow monotonically.

Bathie (1996), Soares (2014), and Saravanamuttoo et al. (2017) present the history of gas turbines for aircraft propulsion and for various power-generation applications. Historically, the gas turbine technology has cascaded from military engines to commercial engines to large and small engines used for power generation. Aeroderivative gas turbines used for land and marine applications are directly derived from aircraft engines. For reasons of high reliability and safety, the development of the most of aviation gas turbines has been evolutionary rather than revolutionary, each engine being an upgrade of a previous successful engine or a conglomeration various technologies from other engines.

Olson (2017) touts the advanced technologies associated with the GE9X™ engine, shown in Figure 1.1. Designed specifically for the Boeing 777X airplane, the GE9X is the most fuel-efficient and quietest jet engine GE has ever produced. This engine is designed to deliver 10 percent improved aircraft fuel burn versus the GE90–115B-

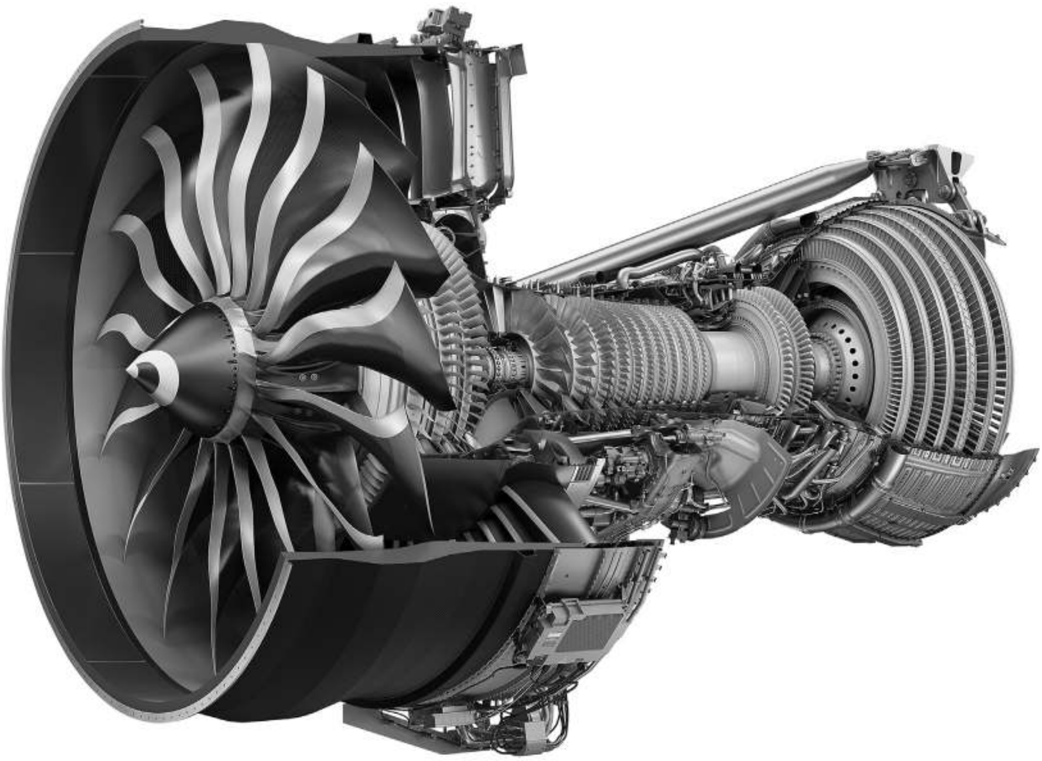

Figure 1.1 Cutaway view of the GE9X engine (with permission from GE Aviation).

powered 777–300ER and 5 percent improved specific fuel consumption versus any twin-aisle engine available. Additional design features include an approximate 10:1 bypass ratio, 60:1 overall pressure ratio, and 8 db margins to Stage 5 noise limits. As to the cooling technology, the GE9X engine features ceramic matrix composite (CMC) materials in the combustor and high-pressure turbine for twice the strength, a third of the weight, and greater thermal management capabilities than their metal counterparts. The low-pressure turbines of the GE9X use enhanced titanium aluminide (TiAl) airfoils, which are stronger, lighter, and more durable than their nickel-based counterparts. Achieving this milestone for gas turbines in the history of aviation would have been beyond any forecast fifty years ago!

GE is not the sole manufacturer of such large aircraft engines. Other original equipment manufacturers (OEMs) include Pratt & Whitney (P&W) and Rolls-Royce (R-R), which in their portfolio have similar class of engines, being marketed in a close global competition with GE. As a result of the enormous cost, which runs into hundreds of millions of dollars, associated with the development of a new large gas turbine for commercial aviation and a decade-long breakeven point, the entire market for such engines has remained divided among these three companies (GE, P&W, and R-R) with no new major OEM seen on the horizon.

Unlike aircraft engines, the gas turbines used to generate electricity can operate under a simple cycle (i.e., the Brayton cycle, discussed in Chapter 2) or jointly with a steam turbine using a heat recovery steam generator (HRSG), which yields significantly improved combined-cycle thermal efficiency ($\eta_{\mathrm{th_{CC}}} \approx \eta_{\mathrm{th_{GT}}} + \eta_{\mathrm{th_{ST}}} - \eta_{\mathrm{th_{GT}}}\eta_{\mathrm{th_{ST}}}$). Until the early 1990s, the simple-cycle thermal efficiency, which depends on the overall pressure ratio and turbine inlet temperature (TIT), was limited to 33–38 percent, and the combined-cycle efficiency was in the range of 51–58 percent. Around the turn of this century, OEMs including GE and Siemens embarked on the new line of high-efficiency gas turbines called H-class with a TIT of around 1427°C, which is around 100°C higher than the previous class of gas turbines. These new gas turbines for electricity generation were developed to break the perceived barrier of the combined-cycle efficiency of 60 percent. GE designated their H-class machines as 9H for 50 Hz (3000 rpm) and 7H for 60 Hz (3600 rpm) applications. To maintain the same turbine tip speed, 9H gas turbines are hence larger in size than their 7H counterpart. Siemens, by contrast, designated their machines as SGT5–8000H and SGT6–8000H for 50 Hz and 60 Hz electricity generation, respectively.

For the initial development of the H-class gas turbines, GE used a somewhat revolutionary design philosophy of introducing closed-loop steam cooling in the first stage turbine stator and rotor system, including internal cooling of vanes (nozzles) and blades (buckets). At this time, GE remains the only OEM that has successfully introduced steam cooling for a rotating gas turbine component. After an extensive validation process, GE installed their first 9H combined-cycle gas turbine at Baglan Bay in 2003. Since then, the plant has been reliably providing up to 530 MW to the UK national grid, operating at over 60 percent combined-cycle efficiency.

Siemens, by contrast, used an evolutionary approach to the design and development of their H-class gas turbines and tested their first SGT5–8000H at full load in Ingolstadt, Germany, in 2008. The gas turbine unit performed at 40 percent efficiency and as a part of a combined-cycle system reached a world efficiency-record of 60.75 percent. This plant has been providing power to the German grid since the end of the testing period.

While maturing their steam-cooled gas turbine technology, GE simultaneously launched the development of the traditional air-cooled H-class machines under the designation 9HA and 7HA. According to Vandervort, Wetzel, and Leach (2017), in April 2016, under the auspices of the Guinness Book of World Records, a 9HA.01 GTCC set a world record for the combined cycle efficiency of 62.22 percent while producing more than 605 MW of electricity. In June 2016, GE and Électricité de France (EDF, Electricity of France) officially inaugurated the first 9HA combined-cycle power plant in Bouchain, France, and achieved a combined cycle efficiency of over 62 percent. A cutaway view of GE's 9HA gas turbine is shown in Figure 1.2.

Key gas turbine technologies, their mutual interactions, and their influence on the core components (compressor, combustor, and turbine) are depicted in Figure 1.3. Aerodynamics influences the design and performance of gas turbine primary flow path, which participates directly in the energy conversion process. Modern gas turbine compressors and turbines feature 3-D airfoils, whose details are designed using computational fluid dynamics (CFD) for a nearly isentropic performance.

A device is as strong as its weakest link. All components of a gas turbine must perform in concert for its successful operation. To realize the desired aerodynamic performance, the structural integrity of both compressor and turbine are critically

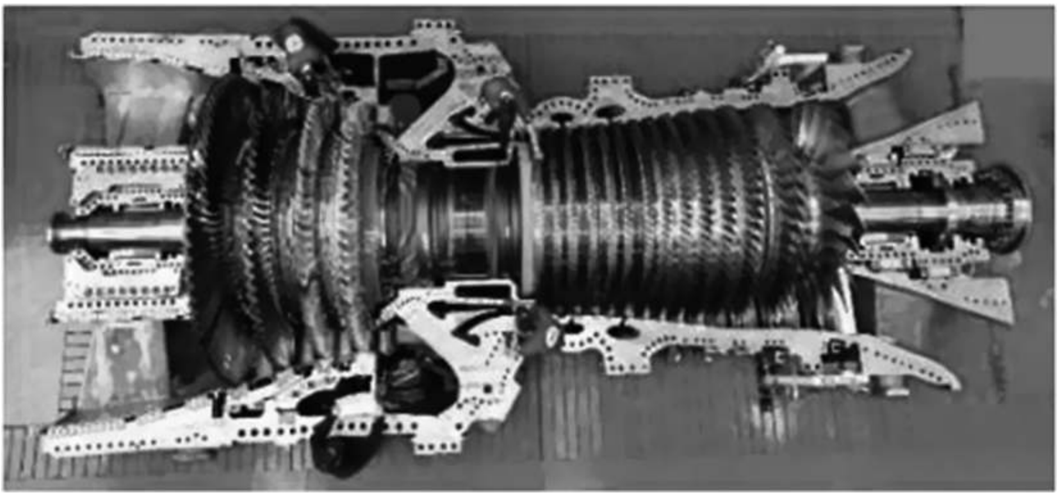

Figure 1.2 Cutaway view of GE's 9HA gas turbine (with permission from GE).

important, as they involve rotating components at very high temperature. A failure of either of them could be catastrophic. The key drivers of gas turbine technology are: (1) the fuel cost, which in turn drives the technology development for higher efficiency; (2) engine reliability, durability, and availability, which require active life management of each engine from cradle to grave, determining its maintenance intervals and the overall product cost; and (3) environmental regulations against pollution, which drives the combustor technology development.

As the compressor pressure ratio and TIT keeps rising for more efficient gas turbines, heat transfer (cooling), secondary air system (SAS), and materials and coatings constitute today's pacing technologies. SAS delivers gas turbine cooling and sealing flows, which could be around 20 percent of the compressor flow. Note in Figure 1.3 that SAS strongly influences gas turbine heat transfer, which in turn has a weak influence on SAS.

Any reduction in cooling and sealing flows directly translate into higher thermal efficiency for a gas turbine. Advances in materials and coatings technology, such as CMC, has led to increased cooling effectiveness with reduced cooling flow requirements. In addition, many aspects of gas turbine design are already benefitting from the fast-emerging additive manufacturing (also called 3D printing) technology. Earlier designs were almost always constrained by manufacturability. With the widespread use of additive manufacturing, the new paradigm is "if you can design it, we can manufacture it."

1.1 Primary Flow: Energy Conversion

The primary flow of the core engine consists of the flow through low-pressure and high-pressure compressors, combustor, and high-pressure and low-pressure turbines. As the air flows against an adverse gradient, the high-pressure ratio over the compressor is achieved in multiple stages to prevent boundary layer separation over the airfoils. For an

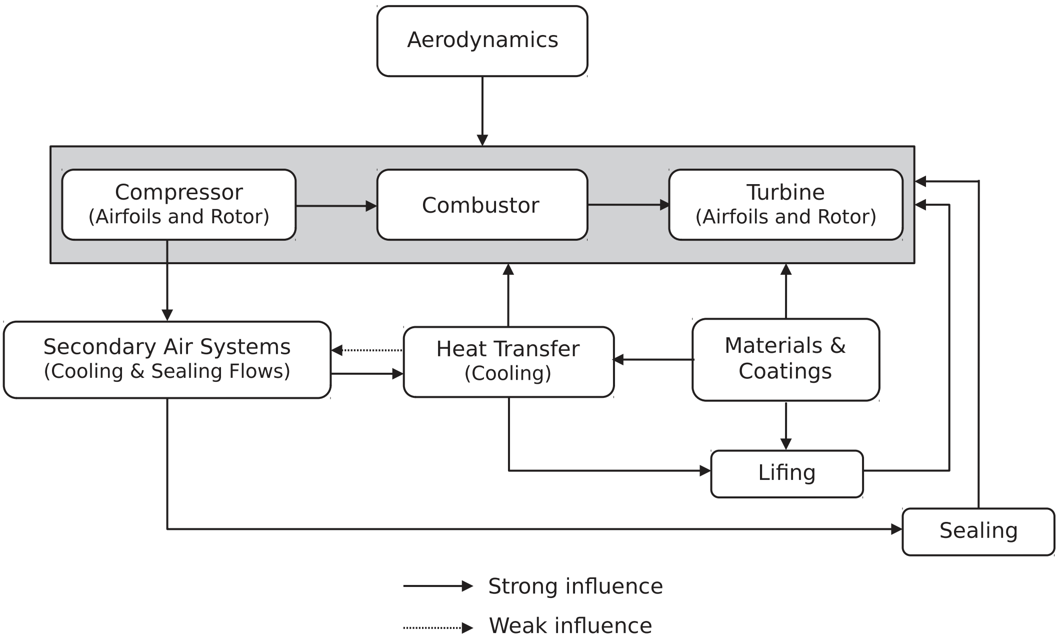

Figure 1.3 Interactions among gas turbine key technologies.

axial-flow compressor, which is found in most modern large gas turbines, the flowpath area continuously decreases downstream with the increase in air density, pressure, and temperature as the work transfer from the compressor blades (rotating airfoils) to airflow occurs continuously in each stage. This transfer of energy into the airflow from compressor is governed by the Euler's turbomachinery equation presented in Chapter 2. In essence, this equation states that for unit air mass flow rate through a blade passage, we obtain the amount of work transfer by subtracting the product of the air tangential velocity (absolute) and blade tangential velocity at the inlet from their product at the outlet. It is interesting to note that Euler's turbomachinery equation deals with velocities in the absolute (inertial) reference frame. Although turbines operate under the most adverse thermal environment, the compressor operating under stall-free and surge-free conditions is the heart of a gas turbine, playing a critical role in its overall operation and performance. The compressor flow is the source of all cooling and sealing flows in a gas turbine with the exception of a steam-cooled gas turbine, where some of the cooling needs are met by steam in a combined cycle operation, as in GE's 9H/7H machines.

The combustor is the place where the primary flow path air receives chemical energy from the fuel through an efficient combustion, significantly raising its temperature (TIT). But for a slight loss of pressure in the combustor, the turbine handles nearly the same overall pressure ratio as the compressor but in fewer stages. The turbine flow path predominantly operates under a favorable pressure gradient with negligible propensity for boundary-layer separation. For a gas turbine engine used in aircraft propulsion, the high-pressure turbine drives the compressor, and the exhaust gases from the turbine are expanded in a nozzle for generating the propulsive thrust. In a power generation application, by contrast, we may have separate turbines; one, which is called a gas generator turbine, drives the compressor; and the other, called a power turbine, rotates a generator to produce electricity. Euler's turbomachinery equation also holds good for computing energy transfer from hot gases to turbine blades and rotor. In this case, however, the product of flow tangential velocity and blade tangential velocity at the outlet is less than that at the inlet of a row of turbine blades. Vanes (nonrotating airfoils) have no direct role in the work transfer both in the compressor and turbine. Their main purpose is to receive the upstream flow with minimum pressure loss and to prepare the flow to enter the downstream blades, which are rotating, with minimum entrance loss.

Heat transfer (cooling) considerations take the center stage in the design of turbines, whose flow path contains hot gases at temperatures close to the melting point of structural material in contact. For an acceptable life and durability of the turbine components during their entire operational envelope, designers must ensure that these components are adequately cooled using compressor air at the required high pressure. A serious uncertainty, however, remains for the temperature distribution in the hot gases exiting the combustor, critically impacting the thermal design of the first stage vanes and possibly the downstream blades.

While the gas turbines for aircraft propulsion are fitted with a nozzle to expand the flow exiting the last stage turbine to ambient pressure with a high exit velocity to produce thrust, shaft-power gas turbines use an exhaust diffuser at the turbine exit. Using additional duct work with minimum pressure loss, the gases from the exhaust diffuser are either ducted to an HRSG in a combined-cycle operation or by-passed to ambient in a simple-cycle operation. The primary role of a diffuser is to render the turbine exit static pressure subambient through the static pressure recovery to the ambient pressure, while minimizing loss in pressure in the downstream duct. The exhaust diffuser thus helps create higher pressure ratio across the turbine, making it more efficient. For a detailed experimental and 3-D CFD investigation of scaled GE's 9E gas turbine exhaust diffuser, which exhausts sideways, see Sultanian, Nagao, and Sakamoto (1999).

Based on the Brayton cycle analysis presented in Chapter 2, we can easily deduce Equation 1.1 for the net specific work output (nondimensional), which when multiplied by the compressor mass flow rate (neglecting fuel mass flow rate into the combustor) yields the total cycle power output, and Equation 1.2 for the thermal efficiency:

$$\frac{w_{\text{net}}}{c_p T_{t_1}} = \left(\frac{T_{t_3}}{T_{t_1}}\right)\eta_{T_i}\left(1 - \frac{1}{\pi^{\frac{\kappa-1}{\kappa}}}\right) - \frac{1}{\eta_{C_i}}\left(\pi^{\frac{\kappa-1}{\kappa}} - 1\right) \tag{1.1}$$

$$\eta_{\text{th}} = \frac{\left(\frac{T_{t_3}}{T_{t_1}}\right)\eta_{T_i}\left(1 - \frac{1}{\pi^{\frac{\kappa-1}{\kappa}}}\right) - \frac{1}{\eta_{C_i}}\left(\pi^{\frac{\kappa-1}{\kappa}} - 1\right)}{\left(\frac{T_{t_3}}{T_{t_1}}\right) - \frac{1}{\eta_{C_i}}\left(\pi^{\frac{\kappa-1}{\kappa}} - 1\right) - 1} \tag{1.2}$$

Under the assumptions of equal pressure ratio across the compressor and turbine with an isentropic efficiency of 0.9 and $\kappa = 1.4$ for the fluid (assumed to be air) in their

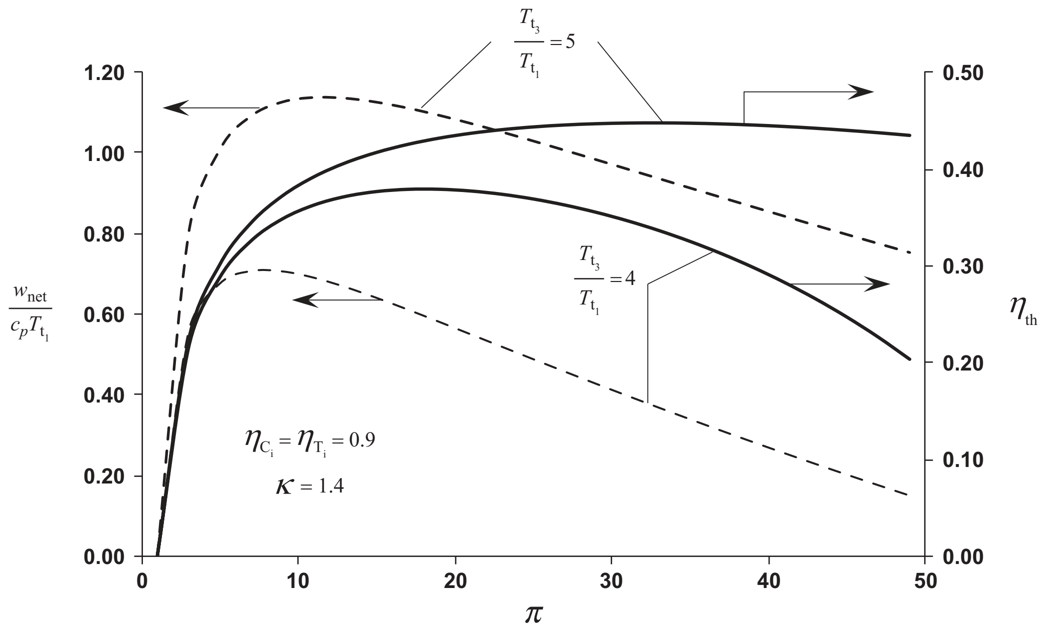

Figure 1.4 Variations of net specific work output and thermal efficiency with pressure ratio and turbine inlet temperature.

primary flow path, Equations 1.1 and 1.2 are plotted in Figure 1.4. We can make the following key observations from this figure:

(1) The net specific work output ($w_{net}/c_p T_{t_1}$) and the cycle thermal efficiency (η_{th}) depend upon the compressor pressure ratio (π) and the ratio of turbine inlet temperature to compressor inlet temperature (T_{t_3}/T_{t_1}).

(2) For a given compressor pressure ratio, both $w_{net}/c_p T_{t_1}$ and η_{th} increase with T_{t_3}/T_{t_1}.

(3) For a given value of T_{t_3}/T_{t_1}, the compressor pressure ratio needed to maximize $w_{net}/c_p T_{t_1}$ is lower than that needed to maximize η_{th}. This explains why the gas turbines used for military planes requiring higher $w_{net}/c_p T_{t_1}$ tend to operate at a lower pressure ratio, while the gas turbines for civil aviation, where higher thermal efficiency is preferred, operate at a higher pressure ratio.

(4) The curves for $w_{net}/c_p T_{t_1}$ feature sharper maxima than those for η_{th}. This means that a small variation of compressor pressure ratio around the optimal value will not significantly impact the engine thermal efficiency.

From Equation 1.1, we can easily show that, for a given value of T_{t_3}/T_{t_1}, the optimum pressure ratio that yields the maximum value of $w_{net}/c_p T_{t_1}$ is given by

$$\pi_{optimum} = \left(\eta_{T_i} \eta_{C_i} \frac{T_{t_3}}{T_{t_1}} \right)^{\frac{\kappa}{2(\kappa-1)}} \tag{1.3}$$

which tends to vary as $0.692(T_{t_3}/T_{t_1})^{1.75}$ for a gas turbine with compressor and turbine isentropic efficiency of 0.9.

1.2 Internal Flow System (IFS)

The air flows extracted from the compressor primary flow path for the purpose of cooling various hot components and providing effective sealing between rotor and stator parts is known among gas turbine engineers as secondary flows. The system of such air flows is called secondary air system (SAS). It is also alternatively known as internal air system (IAS). In this textbook, we have further generalized this system where coolant could be different from air, for example, steam in a steam-cooled gas turbine in a combined-cycle operation, calling it internal flow system (IFS). The use of secondary flows instead of internal flows may be confused with the secondary flows of the first and second kind found in duct flows, see Schlichting (1979). For all practical purposes, SAS, IAS, and IFS are used synonymously here. Further note that the primary flow paths of gas turbine compressor and turbine are essentially annuli through which internal flows of air and hot gases occur with interruptions from vanes and blades, the latter being responsible for work transfer into compressor air flow or out of the hot gases flowing through the turbine. In this textbook, we will avoid referring to the primary air flow as an internal flow.

A typical cooling and sealing arrangement of a hypothetical turbine (to avoid disclosing the proprietary design of any OEM) as a part of its internal flow systems is shown in Figure 1.5. The internal air system is also used to balance the pressure distribution on the rotating disk and drum structure in the engine to maintain acceptable bearing loads. Another function of the internal air flow is to ventilate the bearing compartments so as to prevent the buildup of combustible gas mixtures and to carry lubrication oil droplets to the oil separators. A distinguishing feature of gas turbine internal flows is the presence of rotation with its generally nonintuitive behavior. The energy transfer in such flows occurs both from heat transfer and work transfer, which requires interactions with rotating components.

Based on years of research in the flow and heat transfer of gas turbine rotating disk systems at the University of Sussex, largely funded by Rolls-Royce, Owen and Rogers (1989, 1995) were the first to publish a comprehensive monogram in two volumes. Unfortunately, both these volumes have been rendered out of print. More recently, Childs (2011) published a book on rotating flow covering the ones found in gas turbine internal air systems as well as earth's atmosphere. Among others, Kutz and Speer (1994) and Johnson (2010) describe industry-oriented approach to the simulation of secondary air systems involving elements such as restrictors, tappings, seals, vortices, and coverplates. They also briefly discuss the two-phase (oil and air) flow that occurs in bearing chamber vent systems.

1.2.1 Key Components

Gas turbine internal flows are generally driven between the compressor flow path as the source and the turbine flow path as the sink. In each system, the flow has to pass through a number of components such as stationary and rotating orifices, stator–rotor and rotor–rotor cavities, preswirler nozzles, labyrinth and other types of seals, turbine rim seals, and so on. Some of these components are depicted in Figure 1.6, and their brief

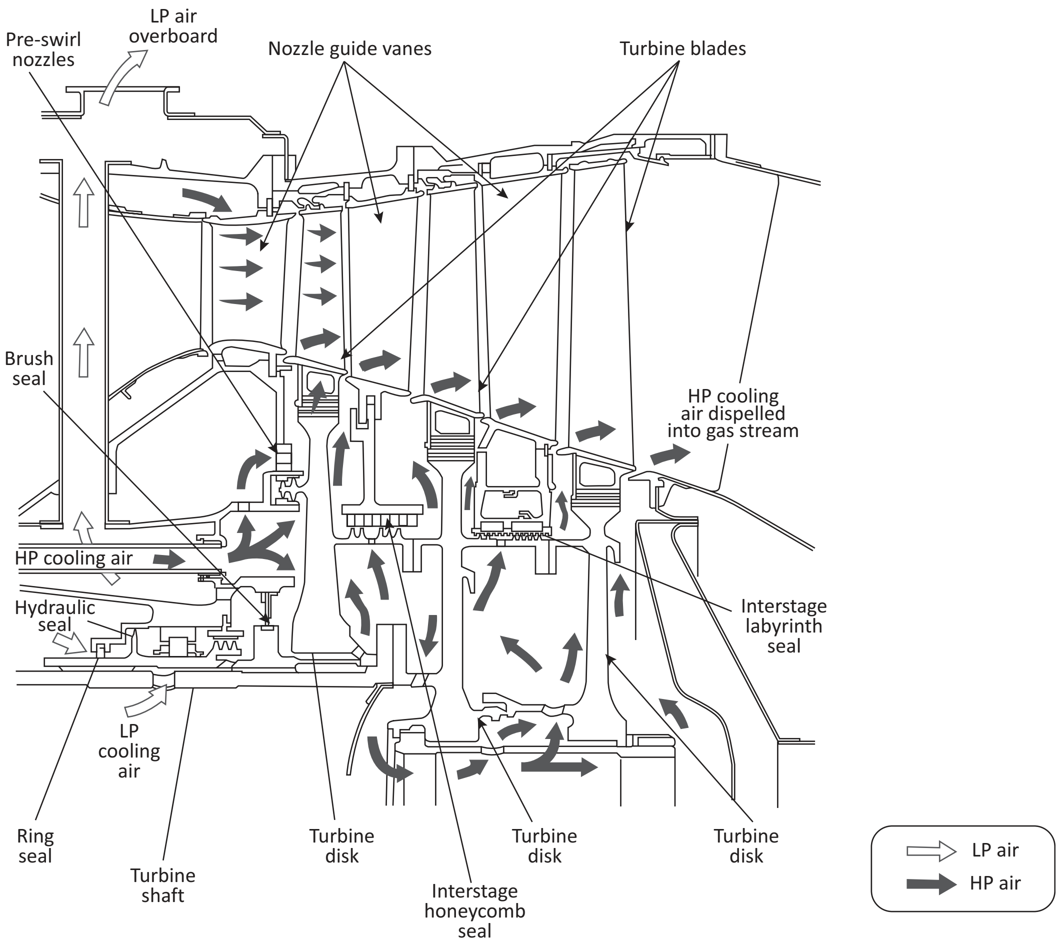

Figure 1.5 Cooling and sealing arrangement of a hypothetical turbine (with permission from Roll-Royce).

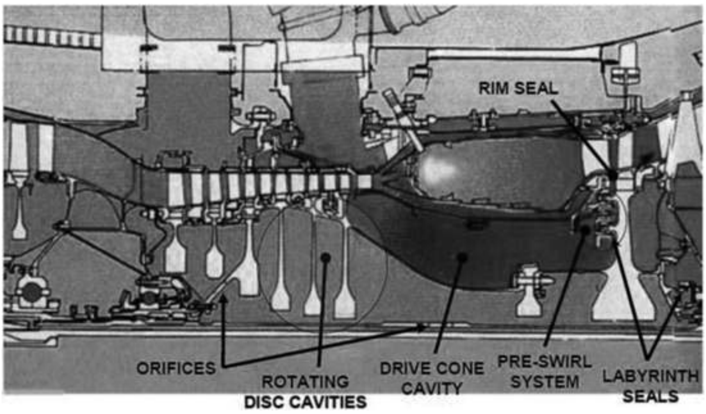

Figure 1.6 Key components of gas turbine internal flow systems (Source: Alexiou and Mathioudakis (2009) with permission from ASME).

description is provided here. We discuss modeling of these components in later chapters.

Ori ce. Orifice, like a resistor in an electrical network, is a basic component of the gas turbine internal flow system. It may belong to stationary part or a rotating part, in which case it is called a rotating orifice. Typically, an orifice is modeled as an adiabatic flow element. For given inlet total pressure and temperature, exit static pressure, and reference flow area, orifice mass flow rate depends upon the discharge coefficient, or loss coefficient, which mainly depends upon its length-to-diameter ratio, ratio of throughflow velocity to total velocity at orifice inlet, pressure ratio across the orifice, and its rotational velocity. Note that both the discharge coefficient and loss coefficient are determined using empirical correlations. In the flow network modeling using an orifice element, its exit dynamic pressure associated with flow velocity is considered lost for the downstream element.

Channel. A channel, also known as pipe, duct, or tube element, offers the most flexibility in internal flow modeling. Unlike an orifice element, the channel allows the simulation of heat transfer effects and conservation of flow linear momentum governed by the momentum equation. The most general formulation of 1-D compressible flow through a channel includes area change, friction, heat transfer, and rotation. Thus, we can possibly simulate an orifice using a channel but not the other way around. While the closed-from analytical solutions are available for individual effects in a channel flow (compressible), namely, isentropic flow with area change, Fanno flow (constant area with no heat transfer and rotation), and Rayleigh flow (constant area with no friction and rotation), when two and more effects are present, their linear superposition is ruled out. In that case, we resort to numerical solution of the resulting nonlinear system of governing equations. For the simulation of general channel flow, we need empirical equations to determine the wall friction factor and heat transfer coefficient.

Vortex. Vortex is a uniquely important component of gas turbine internal flow system and arises due to the presence of rotation. Like solid-body rotation, the forced vortex is characterized by a constant angular velocity. By contrast, a free vortex, which is free from any external torque, keeps its angular momentum constant. In internal flows, because of the presence of walls with friction, a pure free vortex is seldom found. When the flow enters a rotating channel, it immediately assumes the state of solid-body rotation with the channel and thus becomes a forced vortex. In gas turbine cavities, the internal flow features the most complex vortex structure. Such a vortex structure does not fit the definition of either the forced vortex or the free vortex. We call this a general vortex, which can be modeled using a stacked combination of forced vortices. For a radially inward flow in a rotor cavity, the flow shows the tendency of a free vortex with its swirl velocity increasing downstream. For a large radial span, the flow may rotate faster than the adjacent rotor surfaces. The radially outward flow features the opposite behavior, rotating slower than the rotor surface.

The primary effect in a free, or forced, vortex is to increase the static pressure in a radially outward flow and decrease it in a radially inward flow. It also influences the amount of work transfer with the rotor surface in contact. For example, if the fluid is rotating at the same angular velocity as the surface in contact, no rotational work transfer occurs. The pumping flow induced by a rotor disk also depends on the vortex