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PART I

# *Cycle Analysis*

GE90-94B
(courtesy of General Electric Aircraft Engines)

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CHAPTER 1

# Introduction

## 1.1. History of Propulsion Devices and Turbomachines

Manmade propulsion devices have existed for many centuries, and natural devices have developed through evolution. Most modern engines and gas turbines have one common denominator: compressors and turbines or “turbomachines.” Several of the early turbomachines and propulsive devices will be described in this brief introduction before modern engines are considered. Included are some familiar names not usually associated with turbomachines or propulsion. Many of the manmade devices were developed by trial and error and represent early attempts at design engineering, and yet some were quite sophisticated for their time. Wilson (1982), Billington (1996), ASME (1997), Engeda (1998), St. Peter (1999), and others all present very interesting introductions to some of this history supplemented by photographs.

One of the earliest manmade turbomachines was the aeolipile of Heron (often called “Hero” of Alexandria), as shown in Figure 1.1. This device was conceived around 100 B.C. It operated with a plenum chamber filled with water, which was heated to a boiling condition. The steam was fed through tubes to a sphere mounted on a hollow shaft. Two exhaust nozzles located on opposite sides of the sphere and pointing in opposite directions were used to direct the steam with high velocity and rotate the sphere with torque (from the moment of momentum) around an axis – a reaction machine. By attaching ropes to the axial shaft, Heron used the developed power to perform tasks such as opening temple doors.

In about A.D. 1232, Wan Hu developed and tested the Chinese rocket sled, which was driven by an early version of the solid propulsion rocket. Fuel was burned in a closed container, and the resulting hot gases were exhausted through a nozzle, which produced high exit velocities and thus the thrust. Tragically, this device resulted in one of the earliest reported deaths from propulsion devices, for Hu was killed during its testing.

Leonardo da Vinci also contributed to the field of turbomachines with his chimney jack in 1500. This device was a turbine within the chimney that used the free convection of hot rising gases to drive a set of vanes rotationally. The rotation was redirected, using a set of gears, to turn game in the chimney above the fire. Thus, the game was evenly cooked. At the same time, da Vinci also contributed to turbomachinery development with his conception of a helicopter producing lift with a large “screw.”

From the conceptions of Robert Hooke and others, windmills (Fig. 1.2) – actually large wind turbines – were extensively used in the Netherlands for both water pumping and milling from the 1600s to the 1800s. These huge wind turbines (more than 50 m in diameter) made use of the flat terrain and strong and steady winds and turned at low rotational speeds. Through a series of wooden “bevel” gears and couplings, the torsional power was turned and directed to ground level to provide usable power. Some of the early pumping applications of “windmills” in the Netherlands used an inverse of a water wheel – that is, the “buckets” on the wheel scooped water up at a low level and dropped it over a dyke to a higher level, thus, recovering land below sea level from flooding.



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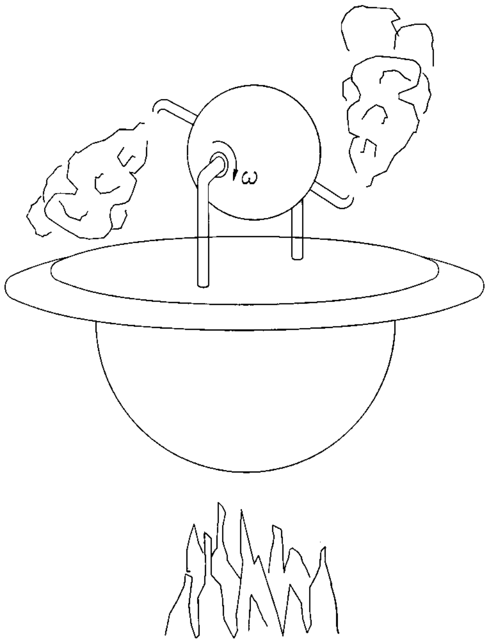


**Figure 1.1** Hero's aeolipile, 100 B.C.

Giovanni de Branca developed a gas turbine in 1629 that was an early version of an impulse turbine. Branca used a boiling, pressurized vessel of steam and a nozzle to drive a set of radial blades on a shaft with the high-velocity steam. The rotation was then redirected with a set of bevel gears for a mechanical drive.

In 1687, Sir Isaac Newton contributed the steam wagon, which may be viewed as an early automobile. He used a tank of boiling water constantly heated by a fire onboard the wagon and a small nozzle to direct the steam to develop thrust. By adjusting the fire intensity, the valve on the nozzle, and the nozzle direction, he was able to regulate the exhaust velocity and thus the thrust level as well as thrust direction. Although the concept was viable, the required power exceeded that available for reasonable vehicle speeds. Thus, the idea was abandoned.

Denis Papin developed the first scientific conceptions of the principles of a pump impeller in a volute in 1689, although remains of early wooden centrifugal pumps from as early as the fifth century A.D. have been found. In 1754, Leonhard Euler, a well-known figure in mathematics and fluids, further developed the science of pumps and today has the ideal pump performance named after him – "Euler head." Much later, in 1818, the first centrifugal pumps were produced commercially in the United States.

Garonne developed a water-driven mill in 1730. This mill was an early venture with a water (or hydraulic) turbine. Water at a high hydrostatic head from a dammed river was used to direct water onto a conoid (an impeller) with a set of conical vanes and turn them. The rotating shaft drove a grinding mill above the turbine for grain preparation. The same concept was applied in 1882 in Wisconsin, where a radial inflow hydraulic turbine was used to generate electricity.

Gifford was the first to use a controlled propulsion device successfully to drive an "aircraft." In 1851, he used a steam engine to power a propeller-driven dirigible. The total load

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**Figure 1.2** Dutch windmill (R. Flack).

required to generate power was obviously quite large because of the engine size, combustion fuel, and water used for boiling, making the idea impractical.

In 1883, Carl de Laval developed the so-called Hero-type *reaction* turbine shown in Figure 1.3 utilized for early water turbines. Water flowed through hollow spokes, formed high-velocity jets normal to, and at the end of, the spokes, and was used to turn a shaft. This is the basic type of rotating sprinkler head used to convert potential energy from a static body of water to a rotating shaft with torque.

As another example, in 1897 de Laval developed the *impulse* steam turbine (Fig. 1.4). This utilized jets of steam and turning vanes or blades mounted on a rotating shaft. The high-speed steam impinged on the blades and was turned, thus imparting momentum to the blades and therefore rotating the shaft and providing torque.

Over the next quarter century, rapid developments took place. Gas and steam turbines came into wide use for ships and power generation. For example, in 1891 the first steam turbine was developed by Charles Parsons. This device was a predecessor to the modern gas turbine. It had two separate components: the steam generator–combustor and the turbine.

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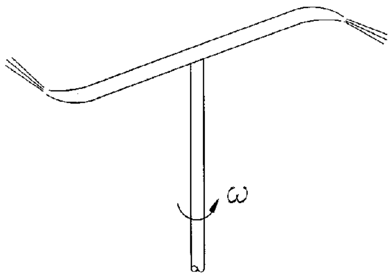


**Figure 1.3** DeLaval "Hero" reaction turbine, 1883.

The generator–combustor developed a high-pressure steam, which was directed as a high-velocity jet into the steam turbine. In the early 1800s, ship propellers or "screws," which are themselves a variety of turbomachines, were invented by Richard Trevithick and others. Parsons' steam turbine, rated at 2100 hp (1570 kW), was used to power such a propeller directly on the 100-ft (30.5-m)-long ocean vessel *Turbinia* in 1897 and drove it at 34 kt, which was a true feat if one considers that most seaworthy vehicles were slow-moving sail craft.

In 1912, a large (64-stage) steam turbine facility was installed in Chicago and ran at 750 rpm to deliver 25 MW of electrical power. In the 1920s, several General Electric 40-MW units were put in service. These ran at 1800 rpm and had 19 stages. Although many refinements and advancements have been made to steam-turbine technology since this installation, the same basic design is still in use in power plants throughout the world.

In the 1930s, simultaneous and strictly independent research and development were performed in Great Britain and Germany on gas turbines. In 1930, Sir Frank Whittle (Great Britain) patented the modern propulsion gas turbine (Fig. 1.5). The engine rotated at almost 18,000 rpm and developed a thrust of 1000 lbf (4450 N). It had a centrifugal flow compressor and a reverse-flow combustion chamber; that is, the flow in the burner was opposite in direction to the net flow of air in the engine – a concept still used for small engines to conserve space. This gas turbine was first installed on an aircraft in 1941 after several years of development. Meher-Homji (1997a) reviews this early effort in great detail. Dunham (2000) reviews the efforts of A. R. Howell, also of Great Britain, which complemented the work of Whittle.

In 1939, the first flight using a gas turbine took place in Germany. Hans von Ohain patented the engine for this aircraft in 1936 (Fig. 1.6), which developed 1100 lbf (4890 N) of thrust. This engine had a combination of axial flow and centrifugal compressor stages. In general, this gas turbine and further developmental engines were superior to the British counterparts in efficiency and durability. A few years later the German Junkers Jumo

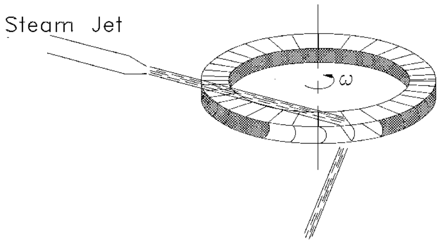


**Figure 1.4** DeLaval impulse turbine, 1897.

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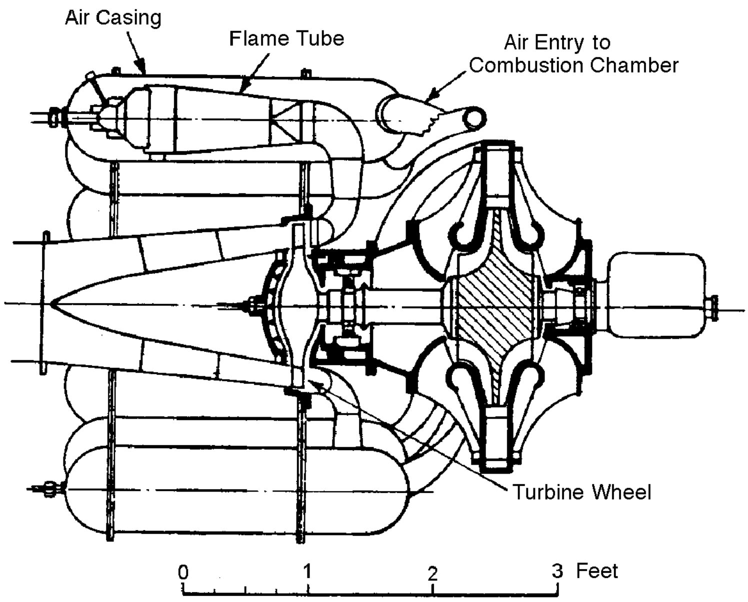


**Figure 1.5** Whittle's WU1 jet engine (from Fig. 105 Lloyd [1945] reproduced with permission of the Council of the Institution of Mechanical Engineers).

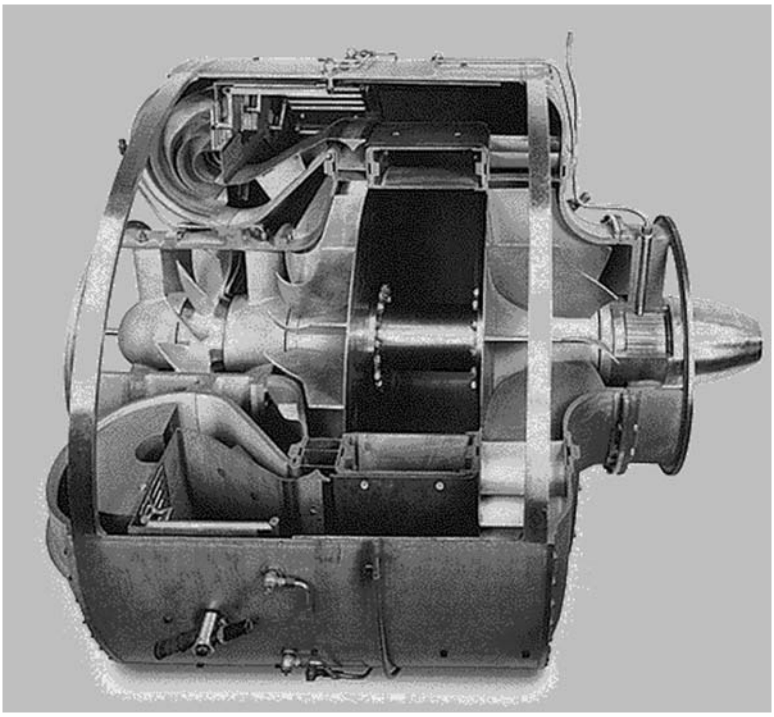

**Figure 1.6** Ohain's jet engine (© Deutsches Museum Bonn photographer: Hans-Jochum Becker).

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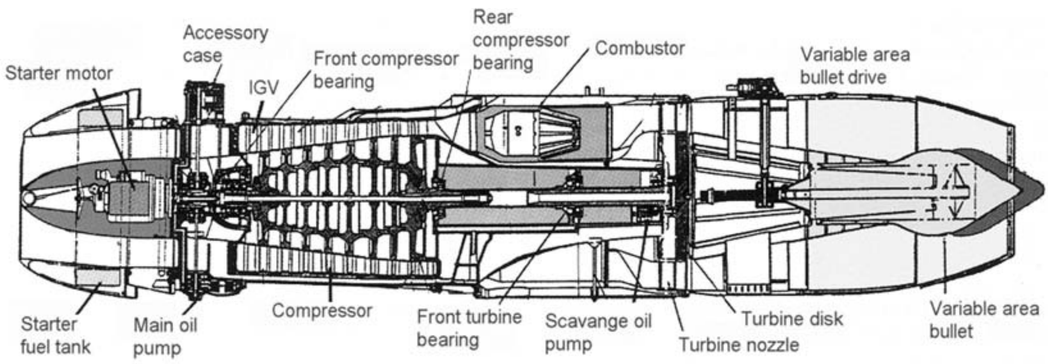


**Figure 1.7** Junkers' Jumo 004 (courtesy of Cyrus Meher-Homji).

004 (Fig. 1.7), designed by Anselm Franz, was the first engine to be mass produced. Meher-Homji (1996, 1997b, and 1999) also presents an interesting review of these early developments. Other historical perspectives on turbomachines and propulsion are offered by Heppenheimer (1993), St. Peter (1999), and Wilson (1982). Today both Whittle and von Ohain are credited equally with the invention of the jet engine.

Also during the 1930s, the first high-speed turbopumps for rocket propulsion were developed in Germany for the V2. Hot exhaust gases from a combustor were expanded by turbines and drove the high-speed oxygen and hydrogen cryopumps, which in turn pumped or compressed the cryofluids, readying them for the combustor. The maiden voyage of the V2 occurred in 1940, and its introduction allowed for previously unattainable long-range delivery of warheads. This type of propulsion inspired modern rocket technology and is still the basic operating principle for modern rocketry.

In 1942, General Electric (GE) developed what is considered the first American jet engine, the GE I-A. This was a small engine that generated 1300 lbf of thrust and was a copy of the early Whittle engine. The GE I-A was developed into the larger GE J-31 (or I-16), which

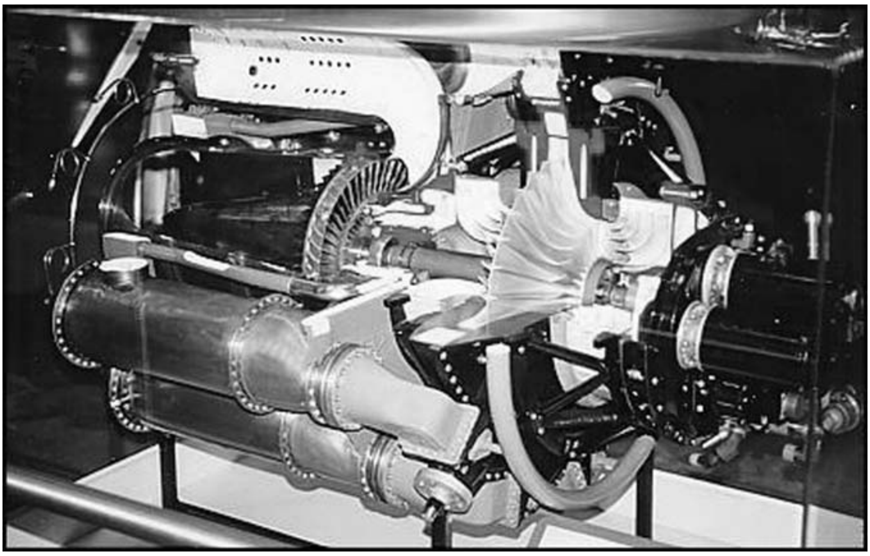

**Figure 1.8** General Electric J-31 (courtesy of Wright Patterson Air Force Base (WPAFB)).

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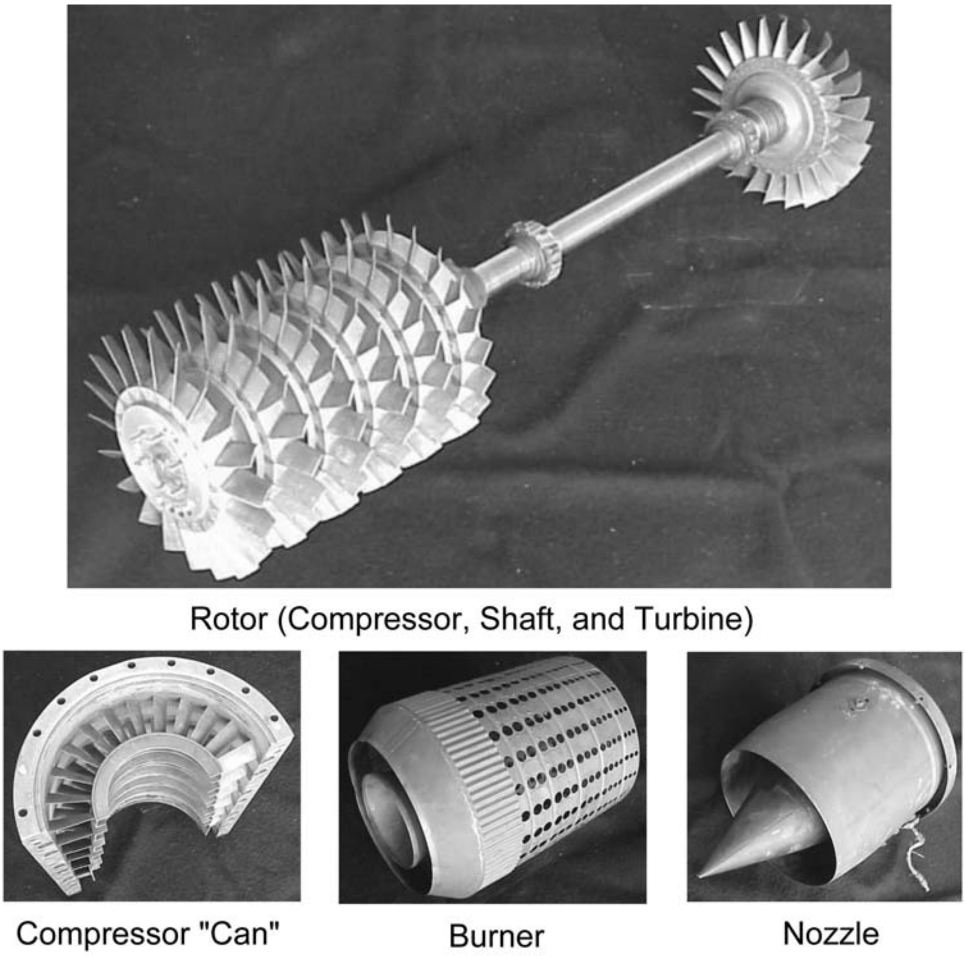


**Figure 1.9** Disassembled Westinghouse J30 (photos by R. Flack).

ran at 16,500 rpm, weighed 850 lb (385 kg), and developed 1650 lbf (7340 N) of thrust (Fig. 1.8). After this engine became commercially available, several standing manufacturers of other power-generation equipment rapidly began developing such jet engines: Pratt & Whitney, Allison, Honeywell, Garrett, Avco, Solar, Volvo, Westinghouse, and Rolls-Royce, among others. Another very early engine in the United States was the Westinghouse J30 (Fig. 1.9), which had a six-stage axial compressor and a single-stage turbine and developed 1560 lbf (6940 N) of thrust.

Today the largest engines are built by Pratt & Whitney (PW 4098), General Electric (GE 90), and Rolls-Royce (Trent), and all of these manufacturers produce engines that develop thrusts in excess of 100,000 lbf (445,000 N). The Rolls-Royce Trent turbofan series is one in such a series of engines (Fig. 1.10). Since the 1950s, gas turbines, which are derivatives of jet engines, have found their way into automobiles (Parnelli Jones almost won the 1967 Indianapolis 500 with an Andy Granatelli turbine), trains (the Union Pacific BoBoBoBo 4500-hp [3360-kW] oil-burning gas turbine and other trains in Europe and Japan), naval and commercial ships and boats, and many electric-power generation units.

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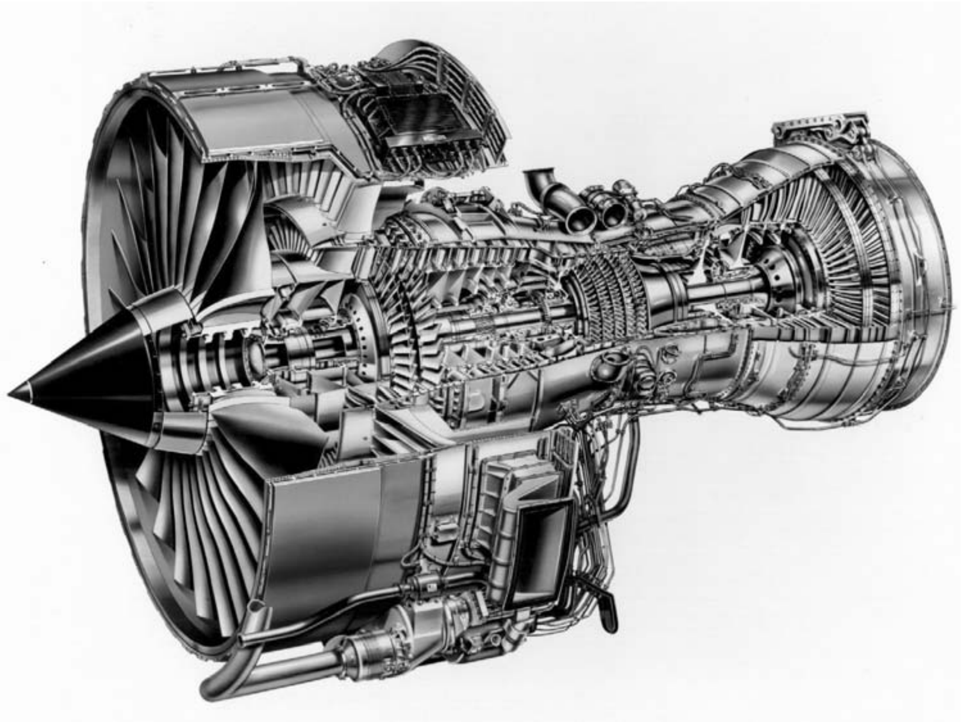

**Figure 1.10** Rolls-Royce Trent turbofan (courtesy of Rolls-Royce).

Before proceeding it is important to note that other very respectable books and references, provide complimentary material and sometimes different perspectives of analysis for both gas turbines and components thereof and have in fact provided inspiration for this book. These include Cumpsty (1997), Cohen et al (1996), Hesse and Mumford (1964), Hill and Peterson (1992), Kerrebrock (1992), Mattingly (1996), Oates (1985, 1997), Pratt & Whitney (1988), Rolls-Royce (1996), Treager (1979), and Whittle (1981).

## 1.2. Cycles

### 1.2.1. *Brayton Cycle*

A Brayton cycle is the basis for the operation of a gas turbine and can be used to approximate the cycle of all such units. A jet engine operates with an open cycle, which means fresh gas is drawn into the compressor and the products are exhausted from the turbine and not reused. A typical ideal system is illustrated in Figure 1.11a. Shown are the compressor, combustor, and turbine. It is important to remember that the compressor and turbine are on the same shaft, and thus power is extracted from the fluid by the turbine and used to drive the compressor. Also shown in Figures 1.11b and c are the h-s and p-v diagrams for the cycle. The compression process, in which work is performed on the fluid mechanically and the pressure and enthalpy ideally increase isentropically (at constant entropy), is from 2 to 3. The combustion process, in which a fuel burns with the air, increases the enthalpy significantly from 3 to 4, and the process (3 to 4) is ideally isobaric.

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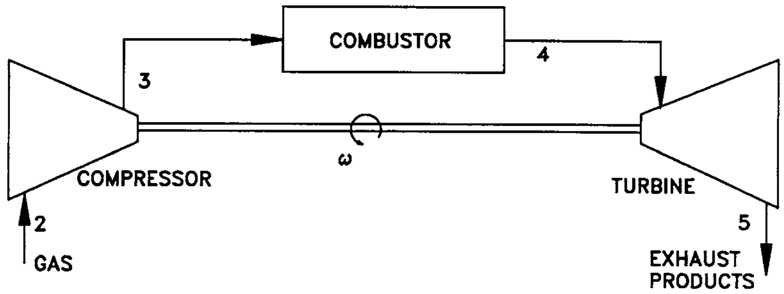


**Figure 1.11a** Geometry of open Brayton cycle.

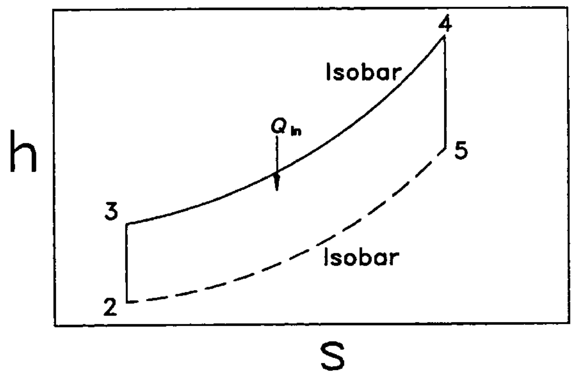


**Figure 1.11b** h–s diagram for Brayton cycle.

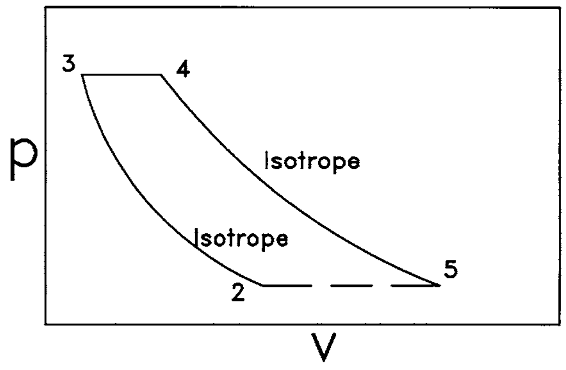


**Figure 1.11c** p–v diagram for Brayton cycle.

The expansion process, in which the pressure and enthalpy ideally decrease isentropically and energy is mechanically extracted from the fluid, is from 4 to 5.

Some ground or power-generation applications use closed Brayton cycles. In this process, the same gas is continually used in a recirculating process. Such a cycle is shown in Figure 1.12. The h-s and p-v diagrams are also shown in Figures 1.11b and c. For a closed cycle, the gas is heated with a heat exchanger from 3 to 4 (not a combustion process), and hot gas products from the turbine are cooled with a heat exchanger and fed back into the compressor for process 5 to 2. Typically, the heat exchanger is very heavy, which makes the closed cycle inappropriate for jet engines and results in an exhaust temperature that is too cool for propulsion purposes. For the closed cycle, the compression

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