Laws of Thermodynamics and Their Applications in Heat Engine

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Abstract:

Thermodynamics is a fundamental branch of physics that governs the behavior of energy and heat in various systems. This paper explores the key principles of thermodynamics and their applications in internal combustion engines and gas turbines. The first law of thermodynamics, which states that energy cannot be created or destroyed but can only change forms, is fundamental to understanding energy transfer in these machines. The second law of thermodynamics introduces the concept of entropy and explains the direction of heat flow. We have discussed the applications of the laws in design and operation, such as improving performance and efficiency. We look forward to the development of the applications in the future.

Keywords: Thermodynamics laws, Thermodynamics cycles, Internal combustion engines. Gas turbine

Introduction

Thermodynamics provides a framework for understanding and analyzing the behavior of various systems, including engines and turbines, that are crucial in the modern industrial and transportation sectors. In this paper, we aim to explore the fundamental thermodynamic laws and their practical applications in the field of internal combustion engines and gas turbines.

The first law of thermodynamics, often referred to as the law of energy conservation, is a fundamental principle that states that energy cannot be created or destroyed in an isolated system, but it can change forms. This means that the first kind of perpetual motion machine is impossible. For heat engines, which convert the chemical energy of a fuel into mechanical energy, which means that the ability to output depends on the input fuel.

The second law of thermodynamics introduces the concept of entropy, which defines the direction of heat flow in a system. The Clausius Expression is that it is impossible to transfer heat from a cold body to a hot body without causing other changes. The Kelvin Expression is that it is impossible to take heat from a single heat source and convert it completely into useful work without other effects. For heat engines, this law helps in understanding the limitations and constraints of these machines. According to this law, the Carnot cycle is the most efficient cycle in thermodynamic theory. The cycle and various thermal cycles will be described later.

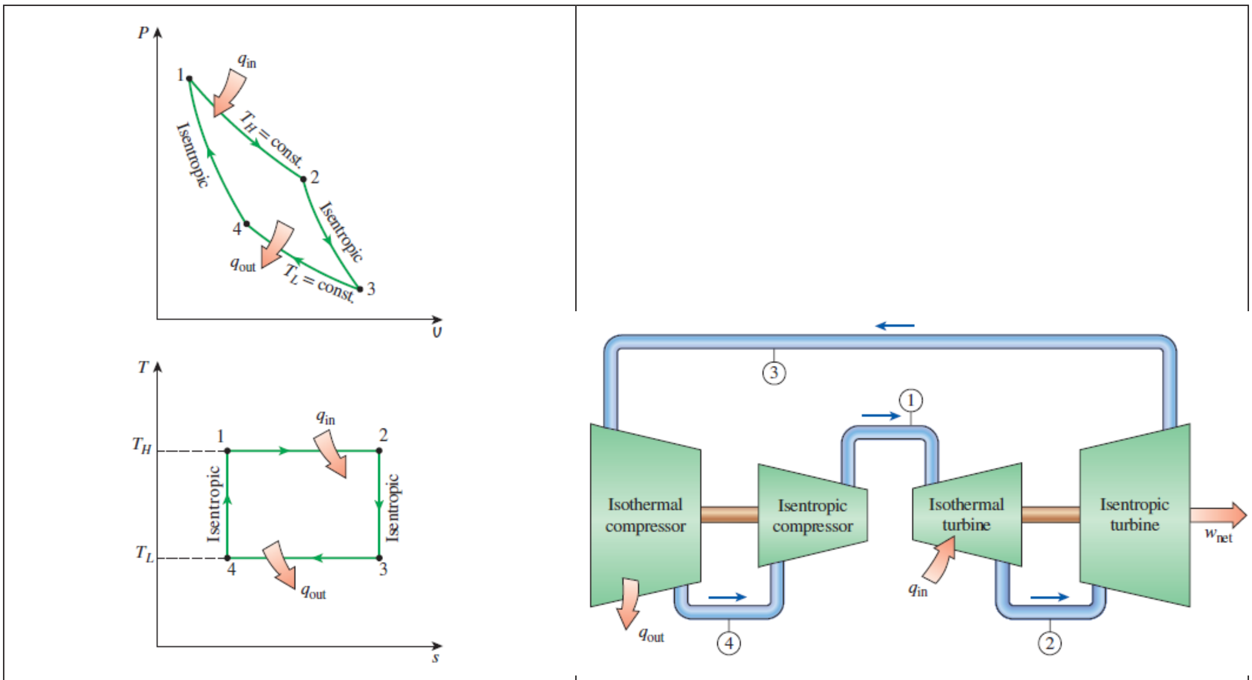
Admittedly, there are other laws of thermodynamics, such as the third law of thermodynamics and the zeroth law of thermodynamics, which state, respectively, that absolute zero is impossible to attain and that if each of two thermodynamic systems is in thermal equilibrium (the same temperature) with the third, they must also be in thermal equilibrium with each other. However, the other laws have little significance for the operation process of heat engines, and will not be discussed in detail here.

Thermodynamics cycle

A heat engine needs to undergo several continuous thermal processes to convert the chemical energy of fuel into mechanical energy. These thermal processes are that the working fluid undergoes a series of state changes from an initial state, and finally returns to the initial state. We call all the above processes the thermodynamic cycle, referred to as the cycle.

According to the fundamental laws of thermodynamics, the Carnot cycle is theoretically the most efficient cycle, which was proposed by the French engineer Sadi Carnot, who assumed that the cycle is reversible under quasi-static conditions, independent of the working medium. The Carnot cycle assumes a heat engine operating between two temperature reservoirs. The four processes are involved in the Carnot cycle: isothermal expansion, adiabatic expansion, isothermal compression, and adiabatic compression, shown in Figure 1.

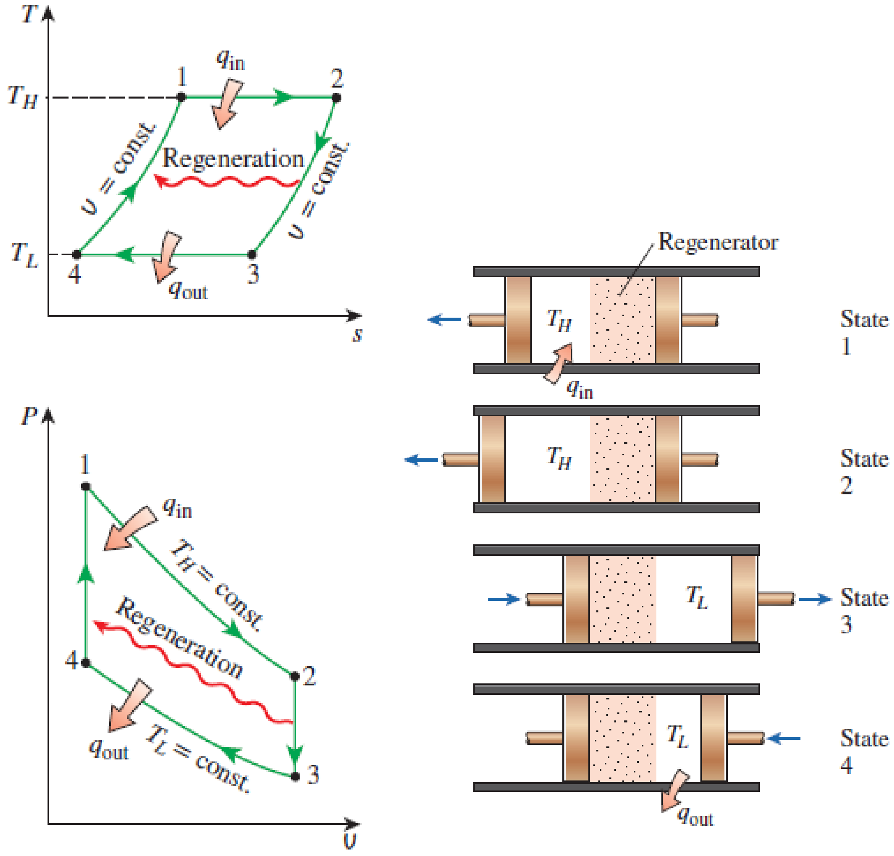
Obviously, the Carnot cycle is so ideal that it is impossible to achieve. In practical applications, the cycle of the heat engine is not an ideal thermal cycle, such as Stirling cycle, shown in Figure 2. The Stirling cycle is a closed-cycle engine that operates by cyclic compression and expansion of a working fluid, typically air or helium. This section explains the four processes of the Stirling cycle: isothermal compression, constant volume heat addition, isothermal expansion, and constant volume heat rejection. The Stirling cycle offers advantages such as high efficiency, low emissions, and the ability to use various heat sources, making it suitable for applications such as solar power generation and waste heat recovery.



a) P-V and T-s diagrams

b) A steady-flow Carnot engine

Figure 1 Carnot cycle[1]

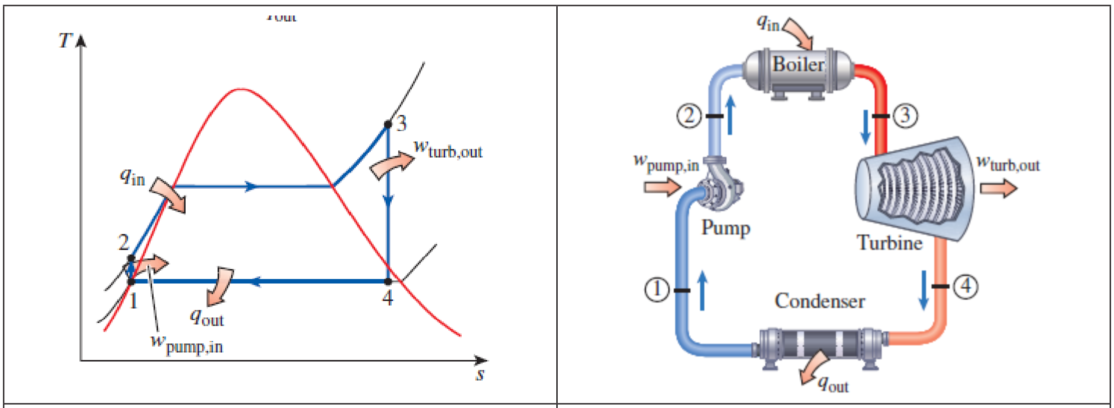


a) P-V and T-s diagrams

b) The execution of the Stirling cycle

Figure 2 Stirling cycle[1]

The Rankine cycle, shown in Figure 3, is widely used in steam power systems and involves the conversion of heat into mechanical work using a working fluid, typically water. This section discusses the four processes of the Rankine cycle: isentropic compression, constant pressure heat addition, isentropic expansion, and constant pressure heat rejection. The Rankine cycle is employed in thermal power plants and industrial processes due to its versatility, high efficiency, and ability to utilize various heat sources.

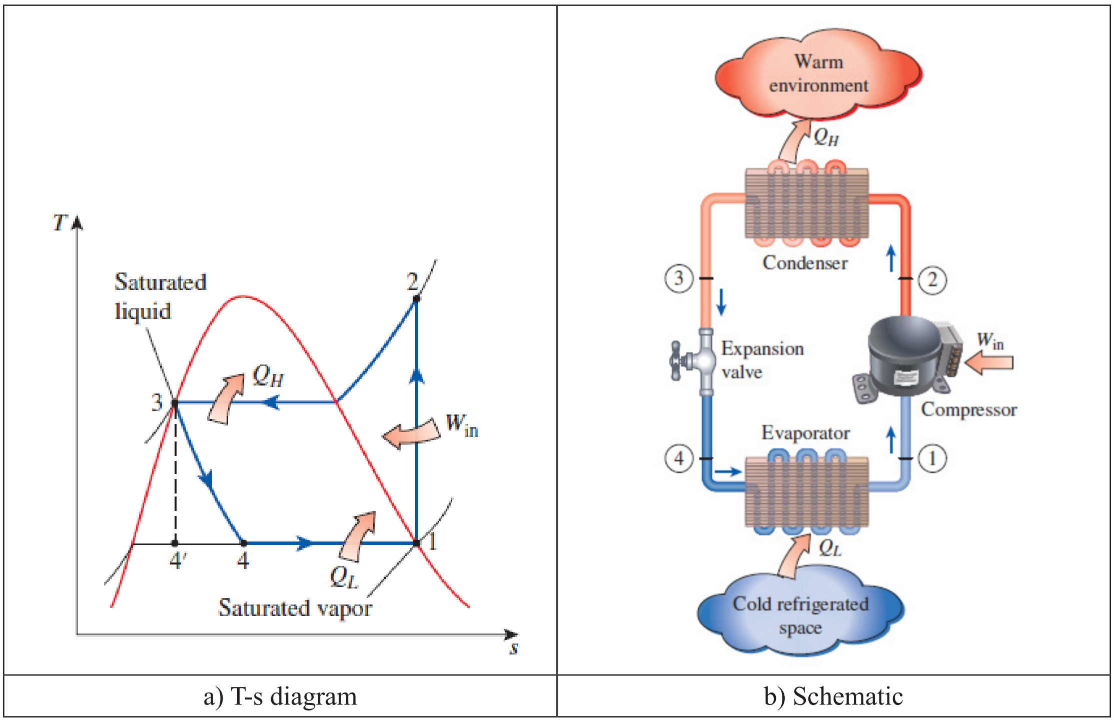


a) T-s diagram

b) Schematic

Figure 3 The simple ideal Rankine cycle[1]

In fact, the refrigeration cycle of air conditioning is also a kind of thermal cycle. Inverting the thermodynamic process of the Carnot cycle results in an inverse Carnot cycle. Like the Carnot cycle, the reverse Carnot cycle is practically impossible to achieve, so the common refrigeration cycle is vapor-compression refrigeration cycle. The cycle consists of four thermodynamic processes: isentropic compression, constant pressure heat release, throttling in expansion device, constant pressure heat absorption. The vapor-compression refrigeration cycle, as shown in Figure 4 can bring significant cooling, so common household air conditioners are run on this cycle.



a) T-s diagram

b) Schematic

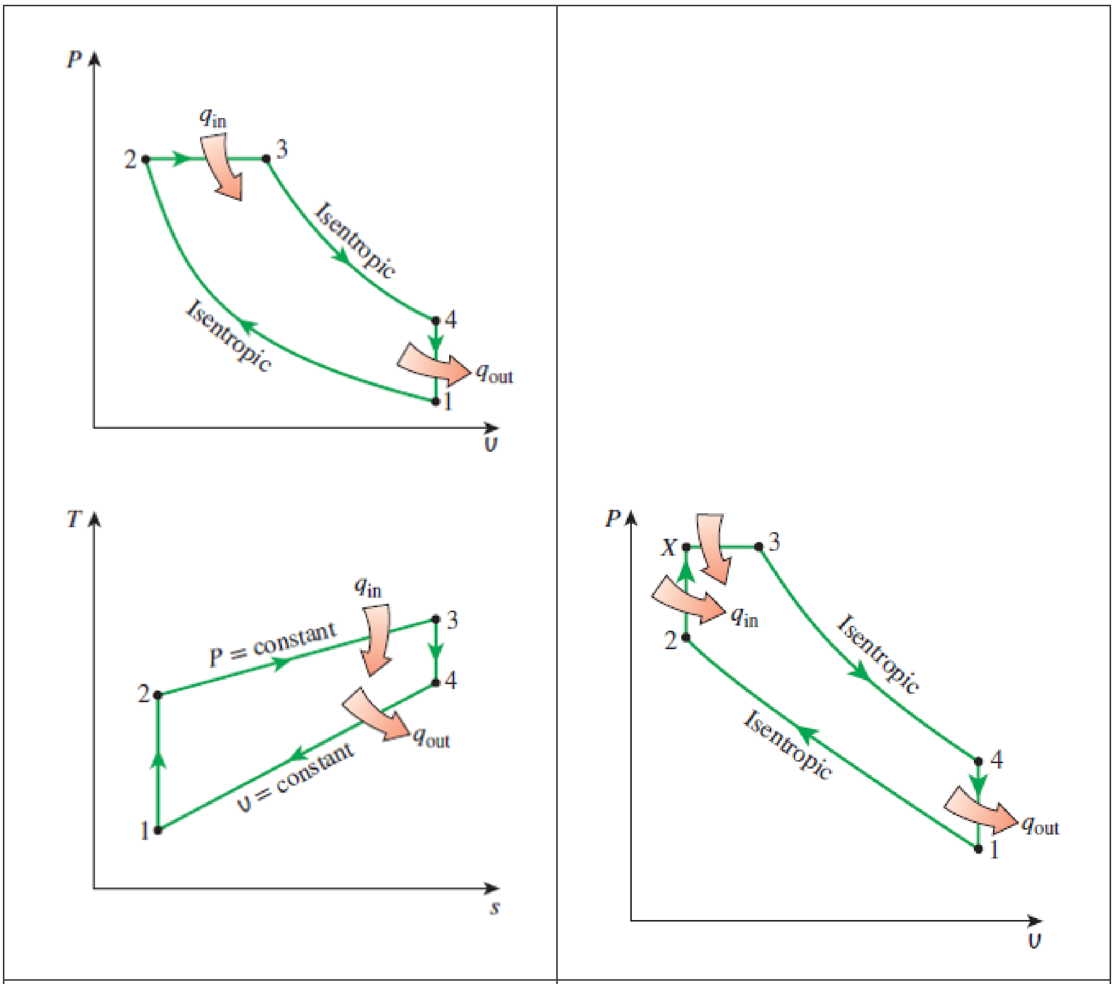
Figure 4 The ideal vapor-compression refrigeration cycle[1]

In general, according to the laws of thermodynamics, many thermal cycles can be extended, including the refrigeration cycle. All the above-mentioned thermodynamic cycles are ideal. Friction loss and heat loss still exist in the actual operation of thermal devices, and the actual cycle cannot be completely equivalent to the above cycle. For internal combustion engines and gas turbines and other power machinery also follow the same pattern, their thermodynamic cycle will be made in the following details.

Internal combustion engine and its thermal cycle

Internal combustion engines, as the name suggests, are power machines that burn fuel internally, converting chemical energy into mechanical energy. However, the narrow sense of the internal combustion engine generally refers to the piston engine or reciprocating engine, such as the gasoline engine used in family cars and the diesel engine used in large machinery, and of course, it is also widely used in small aircraft.

A general piston engine has four processes: air intake, compression, combustion and expansion, and exhaust. If the four processes operate independently, it is a four-stroke engine. If the process simplified into expansion stroke and compression stroke, it is called a two-stroke engine. Consider the process of a piston and a cylinder: isentropic compression, constant-pressure combustion, isentropic expansion, and constant-volume heat release. This is the Diesel cycle, shown in Figure 5a, which is commonly used in diesel engines.



a) P-V and T-s diagrams of Diesel cycle | b) P-V diagram of Sabathe cycle

Figure 5 Diagrams of Diesel cycle and Sabathe cycle[1]

In addition, there is another ideal cycle called Otto cycle, shown in Figure 6. The Otto cycle includes four processes: isentropic compression, constant volume heating, isentropic expansion, and constant volume heat release. The Otto cycle is commonly used in gasoline engines.

The basic properties of diesel and gasoline are different. Gasoline requires spark plug ignition for combustion, while diesel uses compression ignition. Therefore, the two engines use different cycle methods. Moreover, diesel engines have higher compression rates and more complete combustion, so they are generally more efficient. Of course, this is a rather simplified ideal cycle. In modern high speed compression spark ignition engines, fuel is injected into the cylinder more quickly and is ignited later in the compression stroke. Part of the combustion process is constant volume and the fuel is injected until the piston arrives. A constant pressure can be approximated during the expansion stroke. This is called dual cycle or Sabathe cycle, whose P-V diagram is shown inFigure 5b. Obviously, the Otto cycle and the Diesel cycle are special cases of the Sabathe cycle.

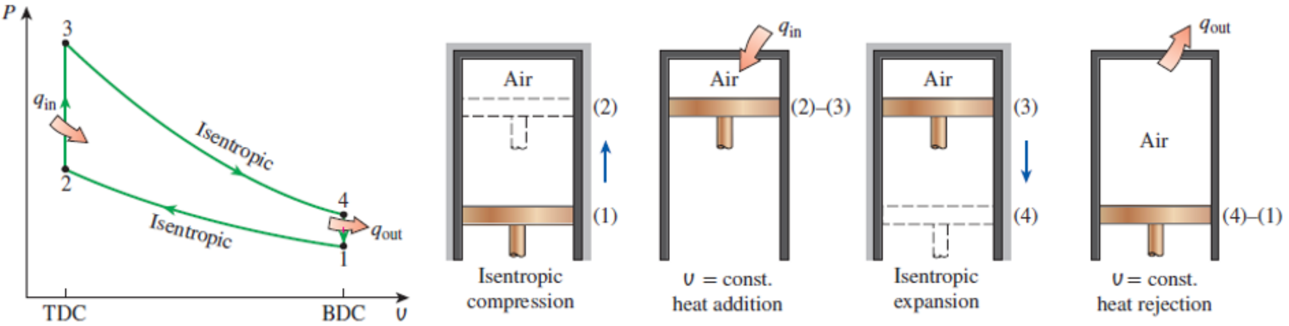


Figure 6 Ideal Otto cycles and P-V diagram[1]

In real practice, the actual cycle process of a four-stroke engine is more complicated, as an actual Otto cycle shown in Figure 7. The crank rotates twice, but many processes are performed. Compression stroke: Initially, the cylinder is filled with air-fuel mixture. At this time, the piston is at bottom dead center (BDC). During the compression stroke, the piston moves upward until it reaches top dead center (TDC). Expansion stroke (power/expansion stroke): After the piston reaches the top dead center, the spark plug ignites the fuel, and the piston begins to expand and move downward to perform work. This part is also the part that outputs external work. Exhaust stroke: The piston returns to bottom dead center, the exhaust port opens, the piston moves upward again, and the exhaust gas is discharged out of the cylinder. Intake stroke: The air inlet opens, fuel and air enter the cylinder, the piston moves from top dead center to bottom dead center, and starts the next compression stroke again after reaching bottom dead center.

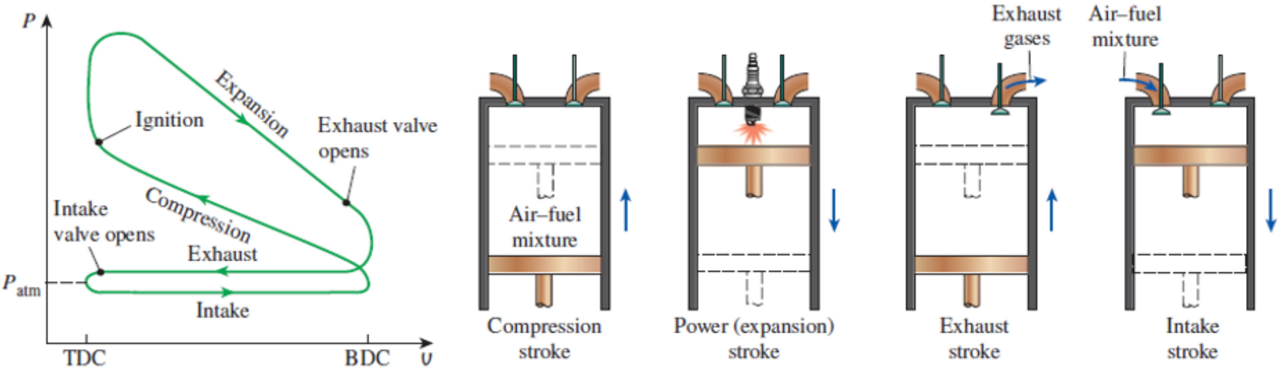
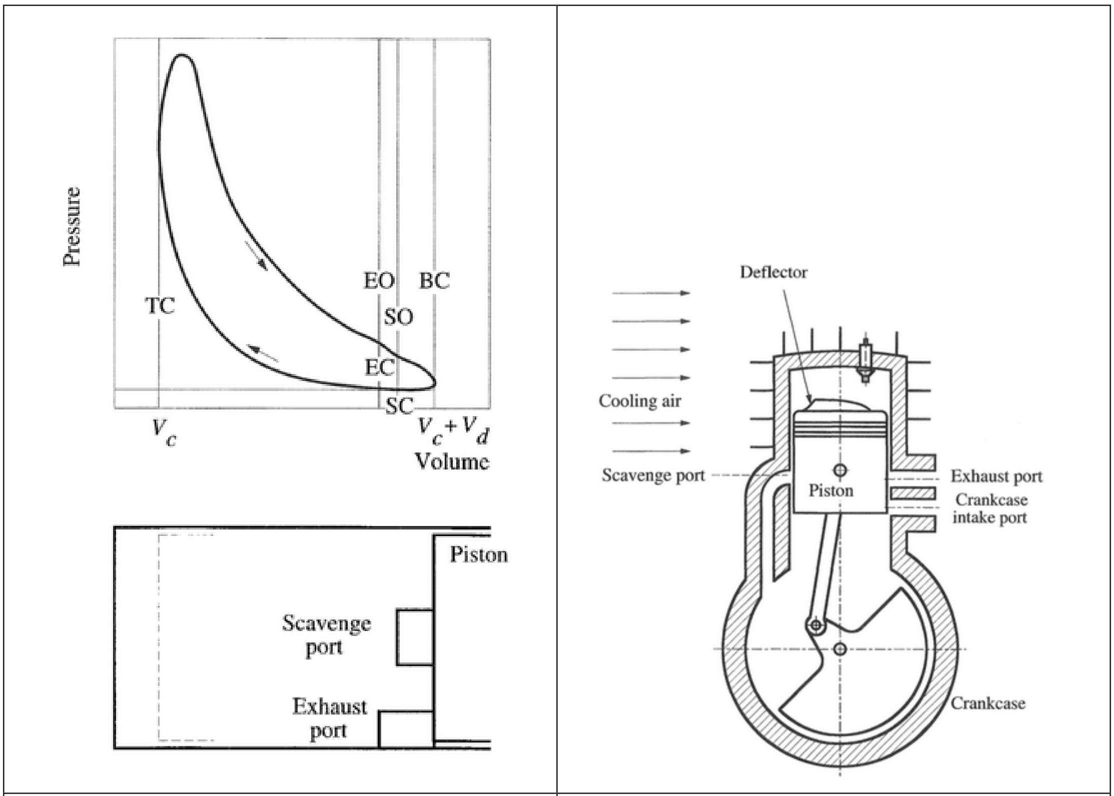


Figure 7 P-V diagram and schematic of an actual Otto cycle[1]

The actual cycle process for a two-stroke engine is simpler than for a four-stroke engine, shown in Figure 8. From the diagram, you can see the key moments of compression, combustion, maximum pressure, exhaust, air intake, etc.



a) P-V diagram

b) Schematic

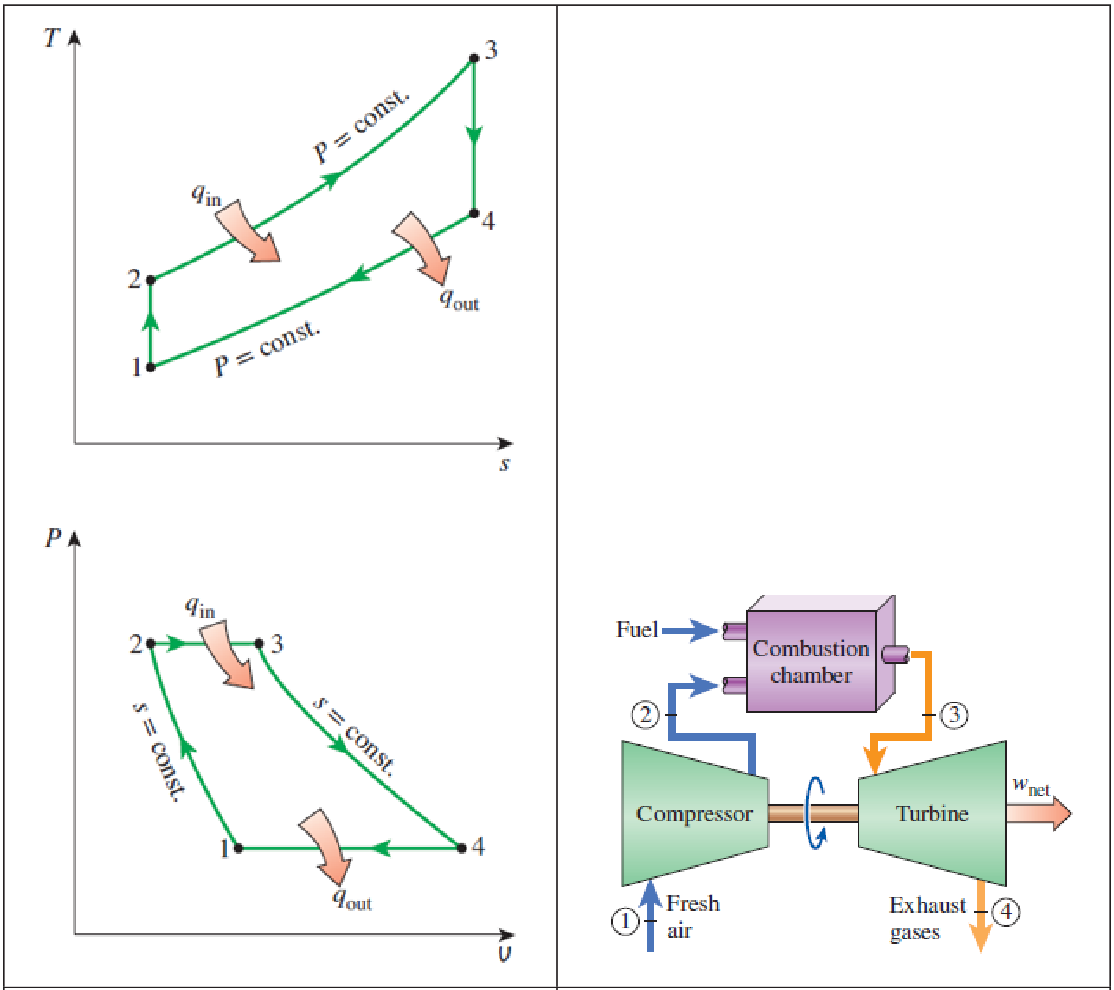
Figure 8 A two-stroke engine [2]

The first stroke is when the piston moves from bottom dead center (BC) to top dead center (TC). When the piston is at bottom dead center, the exhaust valve and air inlet hole have been opened. The compressed air in the air storage chamber enters the cylinder and rushes to the exhaust valve, which has the function of clearing the exhaust gas, that is, scavenging. When the piston moves upward, the air inlet is closed, and the scavenging valve (SC) and exhaust valve (EC) are also closed. The air is compressed inside the cylinder. Before the piston reaches top dead center, the fuel injection process is completed and combustion begins. The second stroke is when the piston moves from top dead center (TC) to bottom dead center (BC) to complete combustion and expansion. As can be seen from the diagram, after the combustion begins, there is a stage where the pressure increases sharply due to fuel combustion, and then the pressure decreases. EO is the moment when the exhaust valve begins to open. The combustion products are discharged from the cylinder into the atmosphere, and the pressure drops rapidly. When the piston continues to move downward, the scavenger valve (SO) will be opened. When both the scavenge and exhaust ports are open, the cylinder is subjected to a pressure gradient that simultaneously controls inflow and outflow through all valves. During this period (scavenging period), the compressed fresh charge flows into the cylinder through the delivery pipe. The pressure in the cylinder is approximately equal to the pressure in the storage chamber, and the combustion products are swept out of the cylinder through the exhaust port. This process continues until the piston moves to bottom dead center. These two strokes constitute the cycle of a two-stroke engine.

Two-stroke engines improve the engine's workability (the crank rotates once to power once, and the four-stroke engine cranks to rotate twice to power once), It also simplifies the engine structure, but its scavenge quality is poor and thermal efficiency is low, so it is widely used in large ships or small engines for go-karts and motorcycles.

Gas turbine and its thermal cycle

The Brayton cycle, also known as the gas turbine cycle, is commonly used in gas turbines and jet engines. This section explains the four processes of the Brayton cycle: isentropic compression, constant pressure heat addition, isentropic expansion, and constant pressure heat rejection. The Brayton cycle offers advantages such as high power-to-weight ratio, quick startup, and flexibility in fuel selection, making it suitable for aircraft propulsion, power generation, and industrial applications. The general Brayton cycle and gas turbine device are shown in Figure 9.



a) T-s and P-V diagrams

b) Schematic

Figure 9 Ideal Brayton cycle[1]

An open simple cycle gas turbine is a gas turbine that only consists of a thermodynamic cycle consisting of the process of compressing the working fluid, heating it once, expanding it and doing work before discharging it into the atmosphere. Part of the work done by the turbine is used to drive the compressor, and the other part is output to the outside world. Obviously, in the actual operation process, the fluid flow in the compression and expansion process is fast, so the friction loss cannot be ignored, which is an irreversible process. The actual thermodynamic cycle is as shown in the figure. The compression process and expansion process are both bent in the direction of entropy increase, shown in Figure 10.

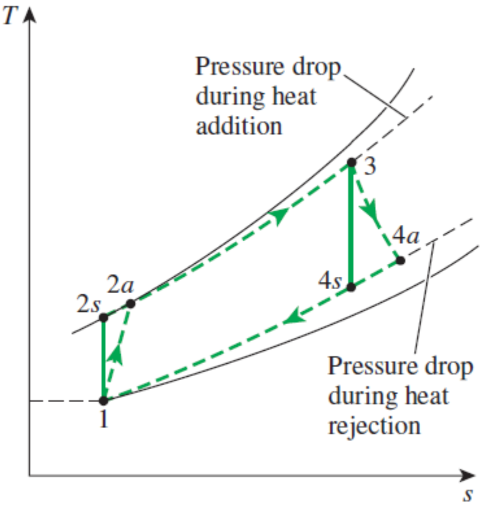
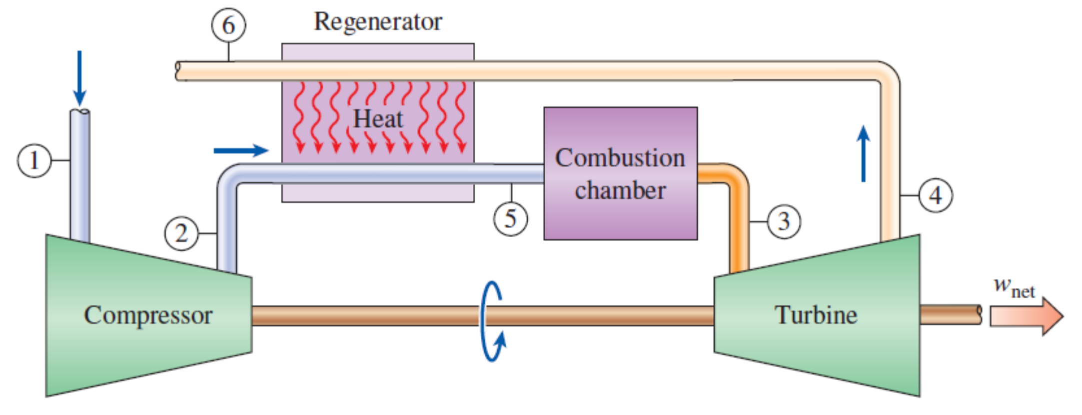
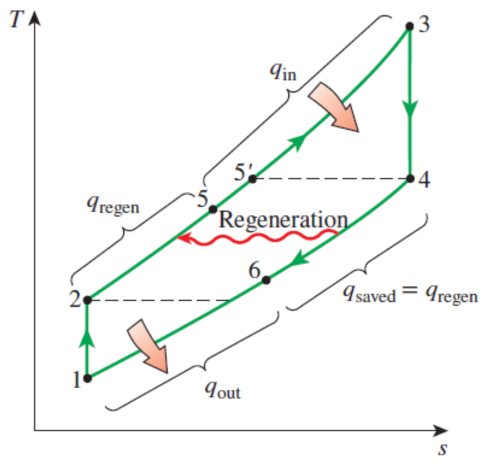


Figure 10 T-s diagram of an actual Brayton cycle[1]

Considering several processes of the Brayton cycle, generally speaking, there are the following methods to increase the power of gas turbines. First of all, according to the laws of thermodynamics, if the temperature before the combustion process is increased, fuel consumption can be reduced while maintaining the same gas temperature and economy can be improved. Therefore, a recuperator is generally added to the simple cycle gas turbine, as shown in Figure 2-2. The air enters the compressor from the intake duct for compression, and then enters the regenerator to absorb part of the exhaust heat. After increasing the temperature, it enters the combustion chamber and is mixed with fuel for combustion. The generated high-temperature gas enters the turbine to perform work. In addition to driving the compressor to work, the turbine output power also outputs power to the outside world. Finally, the low-temperature gas at the turbine outlet recovers part of the waste heat through the regenerator and then is discharged to the atmosphere. This is a Brayton cycle with regeneration, shown in Figure 11.



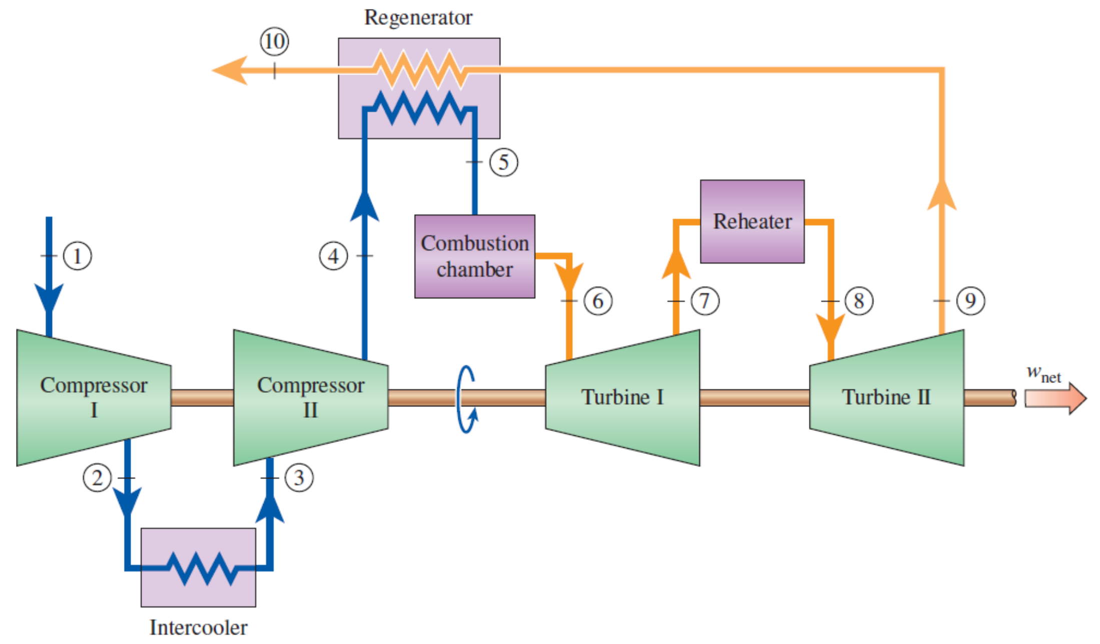
a) Schematic



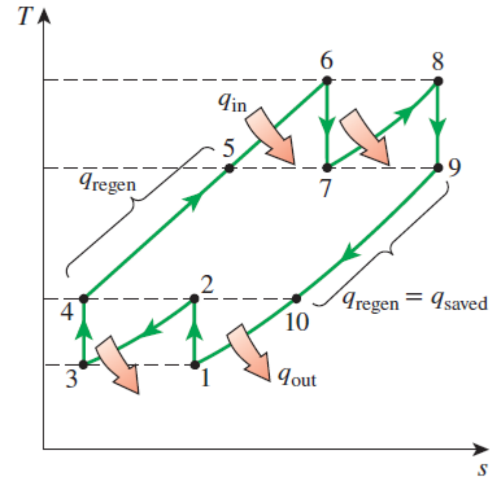
b) T-s diagram

Figure 11 Ideal Brayton cycle with regeneration[1]

In addition, Brayton cycle with intercooling , reheating and regeneration can also be used. The cycle with intercooling and regeneration engine is a new type of gas turbine engine consisting of an intercooler between the traditional high-pressure and low-pressure compressors and a regeneration in the exhaust gas. Its main structure includes a fan, reduction gearbox, low-pressure compressor, intercooler, high-pressure compressor, combustion chamber, high-pressure turbine, low-pressure turbine, regenerator, reheater and corresponding piping system, as shown in Figure 12.



a) Schematic



b) T-s diagram

Figure 12 Ideal Brayton cycle with intercooling, reheating and regeneration[1]

After being compressed by the low-pressure compressor, the air enters the intercooler for cooling, and then enters the high-pressure compressor for further compression; the air at the outlet of the high-pressure compressor is preheated by the regenerator, and then enters the combustion chamber. It is further heated by fuel combustion; the high-temperature and high-pressure gas coming out of the combustion chamber sequentially enters the high-pressure turbine, reheater for heat again, low-pressure turbine and power turbine to expand and do work, and is discharged into the atmosphere through the regenerator; The high-pressure turbine drives the high-pressure compressor, the low-pressure turbine drives the low-pressure compressor, and the power turbine drives the load; the intercooler is arranged between the high- and low-pressure compressors and uses external cooling medium to cool the outlet air of the low-pressure compressor to reduce the compression process power consumption of the high-pressure compressor and increase the output power of the gas turbine. The regenerator is arranged between the power turbine outlet and the combustion chamber inlet. It uses the waste heat of the power turbine exhaust to heat the combustion chamber inlet air to reduce fuel consumption and improve the gas turbine cycle efficiency. The reheater is generally arranged between the high pressure and low pressure turbines, similar to the combustion chamber. The gas is heated at the constant pressure in the middle of the reheater, which can improve the output power. It is not difficult to imagine that if there are an infinite number of intercoolers and reheaters, and the regeneration is used, the Brayton cycle will become similar to the Carnot cycle, as shown in Figure 13. If only an intercooler is used without a regenerator, it is called an intercooling cycle. It should be emphasized that although the intercooler can reduce the compression power consumption, the efficiency of the cycle is reduced if the regenerator is not used. Therefore, the intercooler and reheater must be used on the basis of reheating to improve the cycle efficiency.

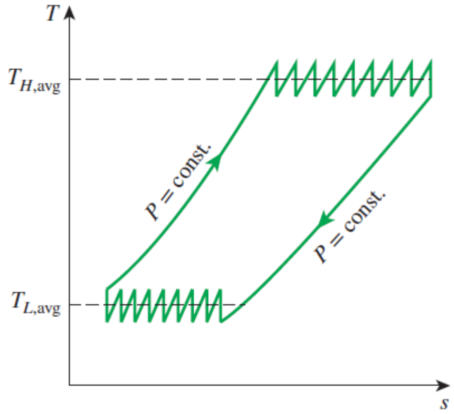


Figure 13 T-s diagram of a Brayton cycle with infinite intercooling, reheating and regeneration[1]

In fact, the potential of intercooling and regenerative technologies to improve gas turbine performance was discovered and studied as early as the 1940s. In 1943, Germany first proposed the concept of heat exchange aero engine, planning to design a low total pressure ratio with a conical drum regenerator regenerative cycle turboprop engine. In the same year, the UK proposed the Bristol Theseus regenerative turboprop engine concept and began to implement the development program, the first time the regenerator was installed in the aero engine, but the first operation was damaged at the end of 1945, and the program was terminated. In 1967, the United States developed the Allison T63 regenerative turboshaft engine, and installed it on the YOH-6A helicopter, and carried out manned flight tests with heat exchanger engines. In 1991, the intercooled regenerative gas turbine WR-21[3], as shown in Figure 14, developed by the navies of the United States, Britain and France, was the first high-power advanced cycle gas turbine to be developed and put into use. The turbine is based on Rolls-Royce's RB211 and TRENT aero engines. In the 2000s, the LMS100[4], as shown in Figure 15, an intercooled cycle gas turbine for power generation, was introduced by GE in the United States and entered commercial operation in 2006. This engine is still modified from an aero-engine and is a variant of LM6000. Based on the supercore, it has high efficiency by selecting a suitable low pressure system. It is widely used and uses advanced emission control technology, which is friendly to the environment.

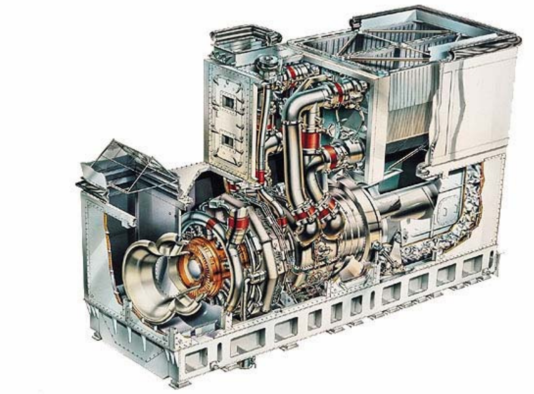


Figure 14 WR-21 intercooled and recuperated gas-turbine[3]

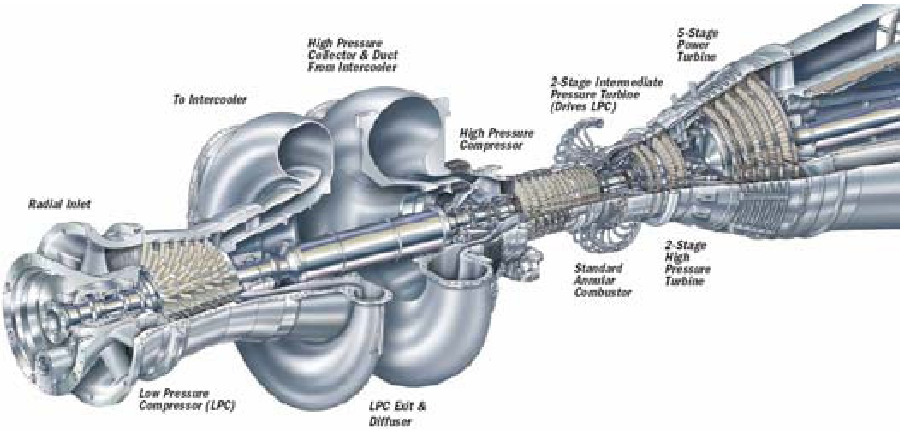


Figure 15 LMS100 intercooled gas-turbine[4]

Conclusions

Based on the laws of thermodynamics, this paper studies the development of the thermodynamic cycle and its application in real life. Through thermodynamic analysis, researchers have proposed advanced cycle theories for various internal combustion engines and gas turbines, and produced various advanced thermal machinery.

Obviously, the application of thermodynamics is not limited to internal combustion engines and gas turbines. For refrigeration cycle, heat pump cycle, boiler, nuclear power plant and other fields of thermal machinery, can also use the thermodynamic law to analyze and make improvements for the established goals.

There is no denying the fact that most of this article is based on the first law of thermodynamics basically from the perspective of cycle analysis of the engine, the analysis method has certain limitation. In recent years, there has been an analysis method that integrates the first law and the second law of thermodynamics. By introducing energy quality -- exergy, it analyzes the power cycle from the perspective of work capacity loss and exergy efficiency. This method can analyze the power cycle more comprehensively, which is worthy of in-depth study.

Reference

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