Introduction to Engineering Thermodynamics

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Volume

1. BASIC CONCEPTS AND DEFINITIONS

1.0 Chapter introduction and learning objectives

Classical thermodynamics is a macroscopic approach to the study of thermodynamics. This chapter introduces basic concepts and definitions used in classical thermodynamics. It lays the foundation for a comprehensive analysis of different thermodynamic processes and cycles to be presented in this book.

Learning Objectives

After completing the chapter, you should be able to

1. Explain the basic scope of engineering thermodynamics and its common areas of application
2. Demonstrate an understanding of fundamental concepts, such as system and its surroundings, closed and open systems, extensive and intensive properties, equilibrium state, quasi-equilibrium process, and cycle

1.1 What is thermodynamics about?

You probably have this experience; when you rub your hands quickly for a few minutes, your hands will start to feel warmer. How is this common phenomenon related to thermodynamics? Well, when you rub your hands quickly, your muscles do **work**. This work is then converted to **heat**; therefore, you feel warmer. Heat and work are two forms of energy. Work can be converted to heat, as seen in this daily example. However, can heat be converted to work? Can we use heat to produce work?

Heat engine is a device that produces work continuously by absorbing heat from a high-temperature heat source and rejecting the waste heat to a low-temperature heat sink. Since the 17th century, various heat engines were invented in an attempt to harness work from heat. Figure 1.1.1 illustrates Watt's engine invented by Scottish engineer James Watt in the late 18th century. Watt's engine is one of the most successful early heat engines. Its main components are a boiler (not shown in the figure) and a condenser, each connecting to a piston-cylinder device. The two valves, *V* and *V'*, control the flow of steam into and out of the cylinder. When valve *V* opens, valve *V'* remains closed. Steam from the boiler enters the cylinder, pushing the piston up until it reaches the top of the cylinder. Then valve *V'* opens, and valve *V* closes. The steam in the cylinder escapes to the condenser and is condensed, creating a vacuum in the cylinder. Consequently, the piston moves downward under atmospheric pressure. The reciprocating motion of the piston drives the pivoting beam *DEF*, which then powers the pump chained to the beam. Watt's engine demonstrates how heat is converted to work. This conversion relies on the phase change of a working fluid, e.g., water, in the Watt's engine. The boiler in the Watt's engine is the heat source, where the hot steam is generated; and the condenser is the heat sink, where the hot steam is cooled and condensed to liquid water. All heat engines need a working fluid circulating in a specially-arranged set of equipment, which operates between a high-temperature heat source and a low-temperature heat sink. Figure 1.1.2

is a schematic drawing of a heat engine. The yellow circle represents the heat engine consisting of a set of equipment.

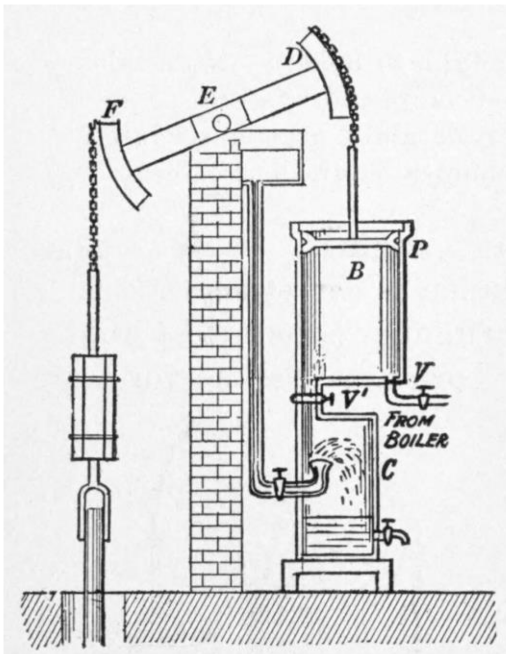

Figure 1.1.1 *Watt's heat engine*

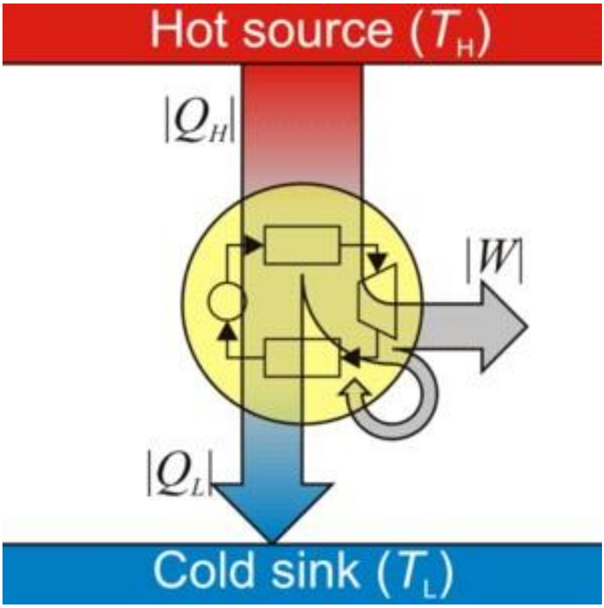

Figure 1.1.2 *Schematic drawing of a heat engine*

By examining Figure 1.1.2, you might notice that a certain amount of heat is not converted to work. It is true that ***not all of the heat from a heat source can be converted to useful work!*** Heat engines and their underlying principles are governed by the two fundamental laws of thermodynamics, the first and second laws of thermodynamics. We will briefly introduce the two laws here and will provide detailed explanations in Chapters 4-6.

- **The first law of thermodynamics** is about energy conservation. Energy can neither be created nor destroyed. It can only be converted between different forms.
- **The second law of thermodynamics** explains why all real processes are irreversible, and how the irreversibility of a process is quantified with the concept of entropy generation. In reality, all processes always occur in the direction of producing positive entropy generation due to the existence of irreversibilities. From the second law of thermodynamics, we can

estimate the theoretical limit of efficiency that a real thermodynamic process or system can possibly achieve.

Thermodynamics emerged in the early 19th century with the inventions of heat engines. It originally focused on the scientific theories of heat-work conversion, and the operations and efficiency improvement of heat engines. Nowadays, the applications of thermodynamics have extended to all fields related to energy conversion and conservation. In engineering fields, the principles of thermodynamics are widely used in the design of thermal systems, such as power plants using different energy sources (e.g., steam, gas, nuclear, hydro, wind, and solar), air conditioning and refrigeration systems, jet engines, biomedical devices, and chemical processes, to name but a few. Figure 1.1.3 is a schematic drawing of a nuclear power plant, whose performance and efficiency are governed by the fundamental principles of thermodynamics.

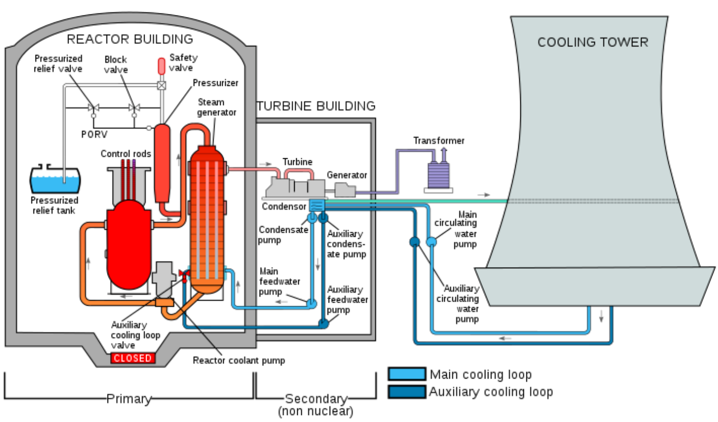

Figure 1.1.3 *Nuclear Power Plant*

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1.2 System and surroundings

In thermodynamics, a **system** refers to a selected quantity of matter in the case of closed systems or a selected region in space in the case of open systems, see Figure 1.2.1. The rest of the universe outside the system is called **surroundings**, and the surface that separates the system and its surroundings is called **boundary.** A boundary may be fixed or movable, real or imaginary, rigid or flexible.

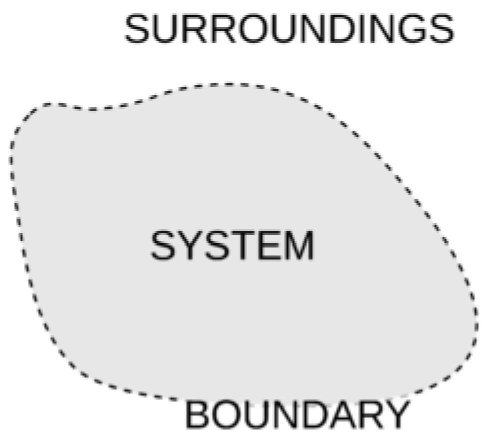

Figure 1.2.1 *System and surroundings*

A system interacts with its surroundings through two mechanisms:

1. **Mass transfer**
2. **Energy transfer** (i.e., in the form of heat and work)

A system of a fixed mass is a **closed system**, which can only interact with its surroundings through energy transfer. Mass cannot cross the boundary of a closed system. For example, a sealed bottle of soft drink, Figure 1.2.2, can be modelled as a closed system because there is a fixed amount of liquid in the bottle. When you take the bottle out of your cooler, the liquid will warm up slowly due to the temperature difference between the bottle and the ambient air (surroundings). In other words, the system (the liquid in the bottle) interacts with its surroundings (the ambient air) through energy transfer (in the form of heat transfer). Figure 1.2.3 illustrates a piston-cylinder device, which can also be modelled as a closed system. The amount of the fluid in the cylinder (the system) remains constant as the piston moves. Only the transfer of energy, in the form of heat and work, may happen across the system boundary consisting of the cylinder walls and the lower surface of the piston.

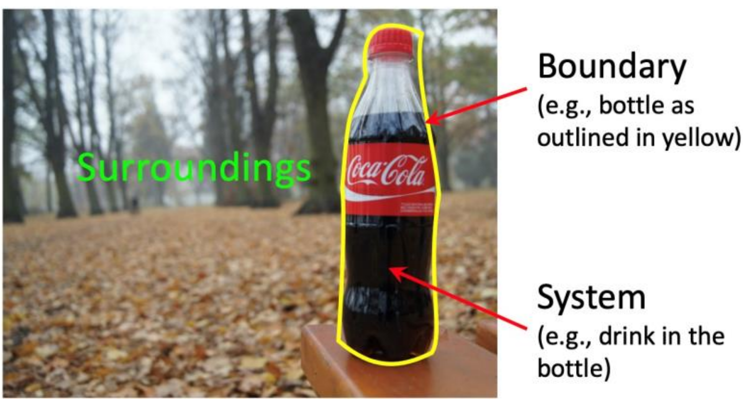

Figure 1.2.2 *A sealed bottle of soft drink as an example of closed systems*

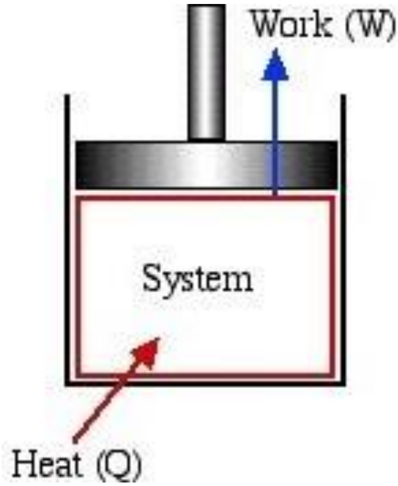

Figure 1.2.3 *Piston cylinder device as an example of closed systems*

An **open system**, also called **control volume**, is a selected region in space. An open system always exchanges mass with its surroundings. It may exchange energy with its surroundings in the form of heat and work, but energy transfer is not a necessary condition for a system to be an open system. In other words, an open system doesn't have to exchange heat or work with its surroundings at all. Figure 1.2.4 illustrates an open system, which typically encloses a device that involves mass flow through its inlet and outlet. Figure 1.2.5 illustrates the outdoor condensing unit of an air conditioner. It may be treated as an open system because the coolant can enter and leave the condensing unit (the system) via its connecting coolant lines.

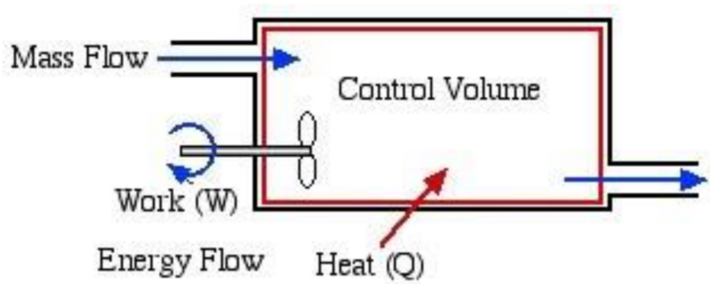

Figure 1.2.4 *Open system (also called control volume)*

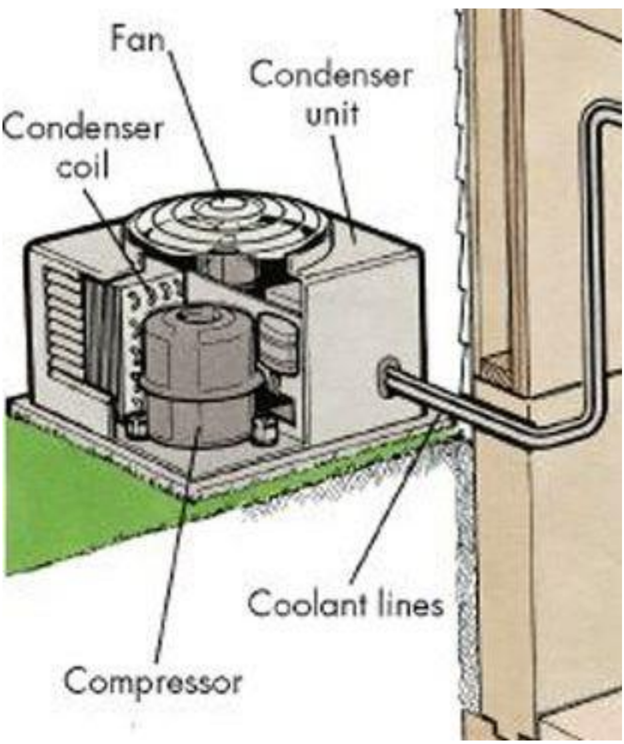

Figure 1.2.5 *Outdoor condensing unit of an air conditioner as an example of open systems*

If a system doesn't allow the exchange of mass and energy with its surroundings, it is called an **isolated system**. An isolated system is an idealized, hypothetical system. In reality, no device is absolutely isolated.

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1.3 Extensive and intensive properties

From the macroscopic perspective, a system is viewed as a continuous, homogeneous matter called **continuum**, which consists of a huge number of interacting molecules distributed throughout the system. The interactions between the molecules are so frequent that the physical or bulk properties of the system do NOT depend on the behaviour of individual molecules. This hypothesis is valid in a wide range of engineering applications. It allows the physical properties of a system, such as pressure, density, and temperature, to be defined as a continuous function at any point of the system.

The following thermodynamic properties are typically used to describe the interactions between a system and its surroundings:

- mass m
- pressure P
- temperature T
- volume $\mathbb{V}$ and specific volume v
- internal energy U and specific internal energy u
- enthalpy H and specific enthalpy h
- entropy S and specific entropy s

These properties can be classified into two categories based on their dependence on the mass of a system. More detailed explanations of their physical meanings can be found in Chapter 2.

- **Extensive properties** depend on the mass of a system.
  Properties, such as mass m, volume $\mathbb{V}$, internal energy U, enthalpy H, and entropy S are extensive properties. Their values change accordingly as the mass of a system changes.

- **Intensive properties** are independent of the mass of a system. Pressure P, temperature T, specific volume v, specific internal energy u, specific enthalpy h, and specific entropy s are intensive properties.

Let us consider a container of air at 101 kPa and 20°C. If the container is divided into two compartments and all other conditions remain unchanged, see Figure 1.3.1, the air in each compartment is still at 101 kPa and 20°C. The pressure and temperature of the air are not affected by the changing mass in each compartment; therefore, pressure P and temperature T are intensive properties. On the other hand, the mass and volume of the air in each of the compartments are different from the original values in the container. Both of them depend on the mass of the system; therefore, mass and volume are extensive properties.

All **specific properties** are intensive properties, as they refer to the corresponding extensive properties per unit mass, e.g., specific volume $v = \mathbb{V}/m$ and specific internal energy $u = U/m$.

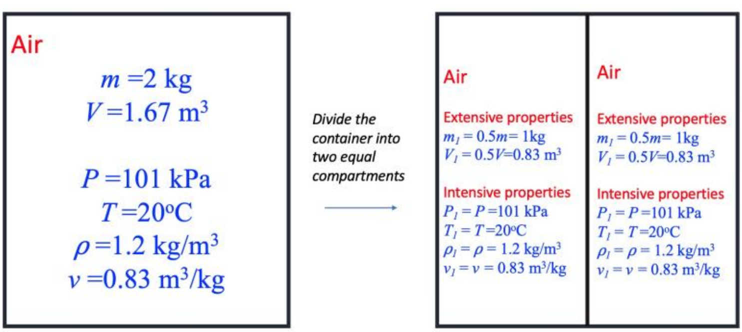

Figure 1.3.1 *Intensive and extensive properties*

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1.3 Extensive and intensive properties

1.4 State, process, and cycle

If a system is isolated from its surroundings or is free from any unbalanced potentials, such as forced flows of mass or energy, the system will eventually reach a uniform condition called **equilibrium**. A system in equilibrium has uniform properties throughout the system. The following equilibrium conditions are commonly considered in thermodynamics.

- A system that features spatially-uniform temperature is in **thermal equilibrium**.
- A system free from chemical reactions is in **chemical equilibrium**.
- If there is no tendency for a system to change its pressure over time, the system is in **mechanical equilibrium**.
- For a system consisting of a mixture of multiple phases, such as liquid water and water vapour, if the composition of the mixture remains constant over time, the system is in **phase equilibrium**.

State refers to the condition of a system, which may be described by a unique set of properties, such as pressure, temperature, and specific volume. The state of a system in equilibrium is called **equilibrium state**. A system may change from one state to another state through a **process**. Let us consider a container of water initially at 10°C and 101 kPa, as an example. We set the water in the container as the system. The water is heated until its temperature reaches 50°C, while its pressure is kept constant 101 kPa. We may say that the water undergoes a constant-pressure, heating process with an initial state of 10°C and 101 kPa and a final state of 50°C and

101 kPa.

Typically, there are many possible paths that a system may take between two states; therefore, ***the exact path of a process is extremely important and must***

be clearly specified in order to describe a process! Here are the definitions of some common processes.

- **Isobaric process**: the pressure remains constant in a process.
- **Isochoric process**: the specific volume remains constant in a process.
- **Isothermal process**: the temperature remains constant in a process.
- **Adiabatic process**: no heat transfer occurs between a system and its surroundings in a process.
- **Isentropic process**: the entropy remains constant in a process.

Figure 1.4.1 shows a compression process as the piston moves from the right to the left. States 1 and 2 represent the initial and final states. Each point along the process path represents an equilibrium state. If all states in a process are equilibrium states, the process is called **quasi-equilibrium process**. In this book, we will deal with systems in equilibrium; therefore, all states thereafter refer to equilibrium states, and all processes refer to quasi-equilibrium processes.

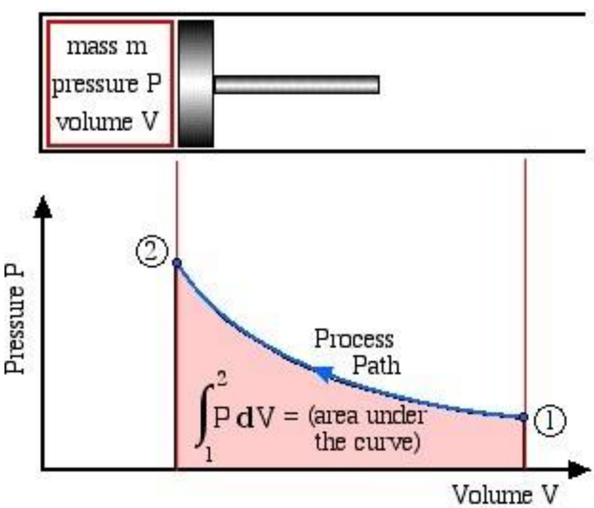

Figure 1.4.1 *Schematic of a process. States 1 and 2 represent the initial and final states; each point along the process path represents an equilibrium state.*

If a system undergoes a series of processes and finally returns to its initial state, we say that the system completes a **cycle**. Thermodynamic cycles are the basis for the operation of thermal equipment. For example, the vapour-compression refrigeration cycle is often used in conventional refrigerators and air conditioners, as shown in Figure 1.4.2. The cycle consists of four main devices: compressor, condenser, expansion valve, and evaporator. A working fluid called refrigerant circulates through these devices connected by tubes. The refrigerant in the cycle experiences phase changes between vapour and liquid, as shown in Figure 1.4.3. Phase diagrams (see details in Chapter 2) are commonly used to analyze a process or a cycle. Figure 1.4.4 illustrates the temperature-specific entropy, $T - s$, diagram for the vapourcompression refrigeration cycle, where the numbered dots represent different states and the lines with arrows represent different processes in this cycle. For example, the number “1” in Figure 1.4.3 and Figure 1.4.4 refers to the state of the refrigerant at the inlet of the compressor or the exit of the evaporator. The line 1-2 in Figure 1.4.4 refers to the compression process in the compressor.

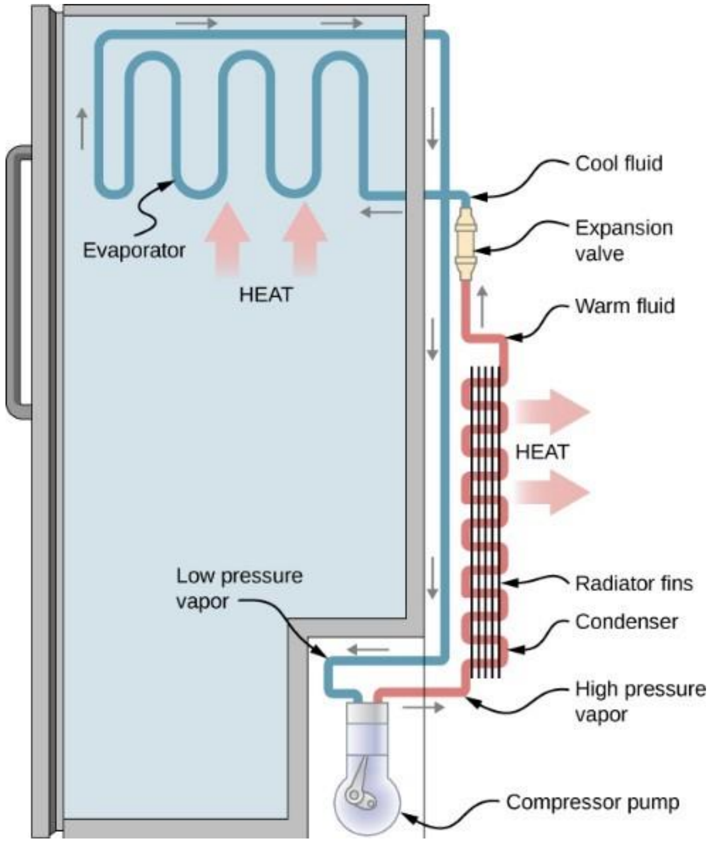

Figure 1.4.2 *Refrigerator working on the vapour compression cycle*

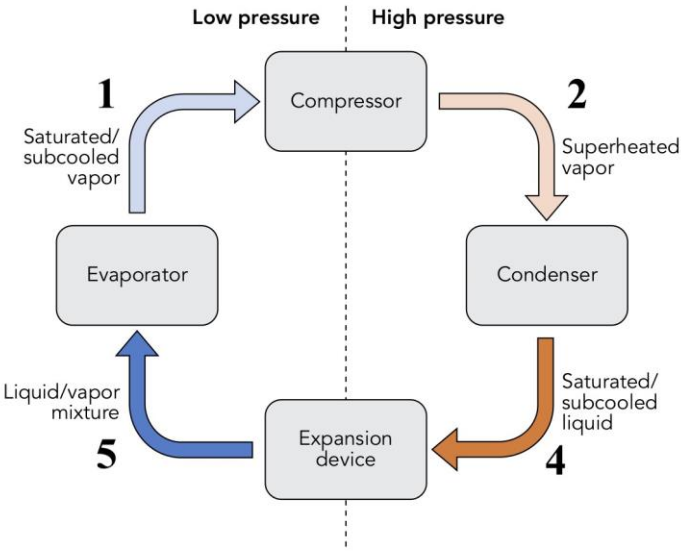

Figure 1.4.3 *Vapour compression cycle*

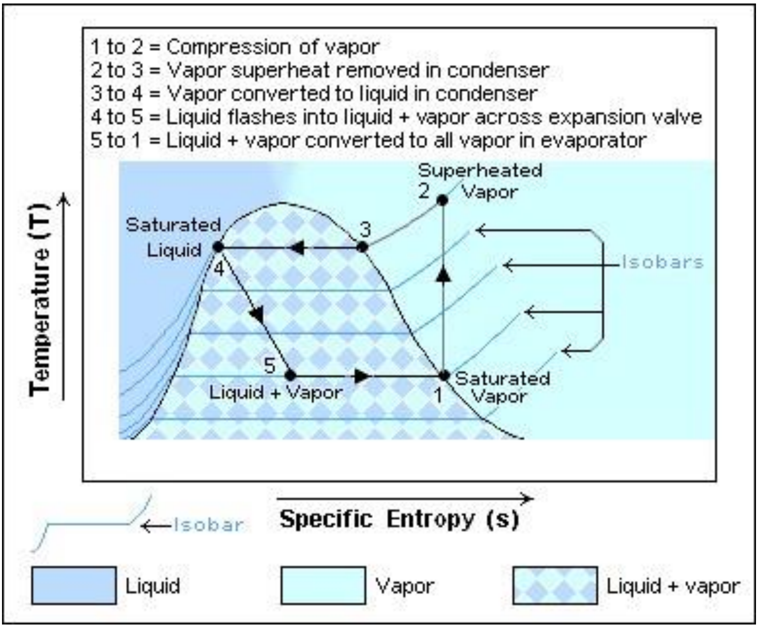

Figure 1.4.4 *Temperature-specific entropy (T-s) diagram of a vapour compression cycle*

Otto cycle is another thermodynamic cycle. It is an ideal cycle that modells the operation of internal combustion engines. Figure 1.4.5 shows the cycle consisting of four strokes. The pressure-volume diagram, Figure 1.4.6, illustrates different processes in this cycle.

1. Intake stroke, line 0-1 in Figure 1.4.6. During the intake stroke, the inlet valve opens and the outlet valve remains closed. Air is drawn into the cylinder as the piston moves to the bottom dead center (BDC).

2. Compression stroke, line 1-2 in Figure 1.4.6. During the compression stroke, both valves remain closed. The air is compressed as the piston moves from BDC to the top dead center (TDC).

3. Ignition and power stroke, line 2-3-4 in Figure 1.4.6. During this stroke, both valves remain closed. The piston is at TDC momentarily while the fuel-air mixture is ignited by the spark. The burning of the fuel-air mixture generates a large force, pushing the piston from TDC to BDC.

4. Exhaust stroke, line 4-1-0 in Figure 1.4.6. During the exhaust stroke, the outlet valve opens and the inlet valve remains closed. The piston remains at BDC momentarily, allowing a certain amount of heat to release to the surroundings. Then the piston moves from BDC towards TDC to reject the exhaust and more heat to the surroundings.

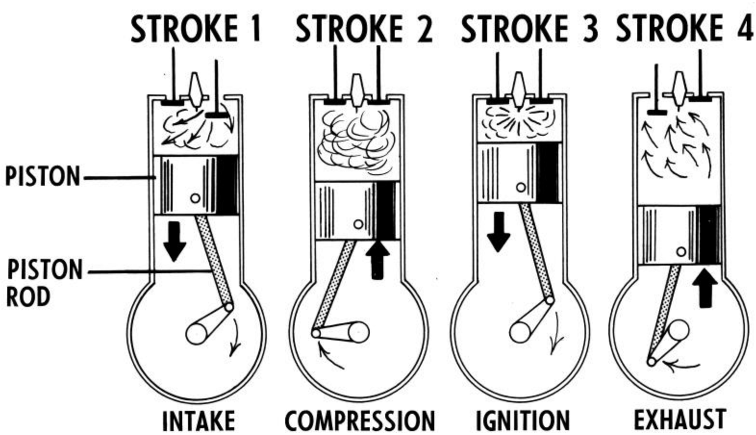

Figure 1.4.5 *Four-stroke combustion engine*

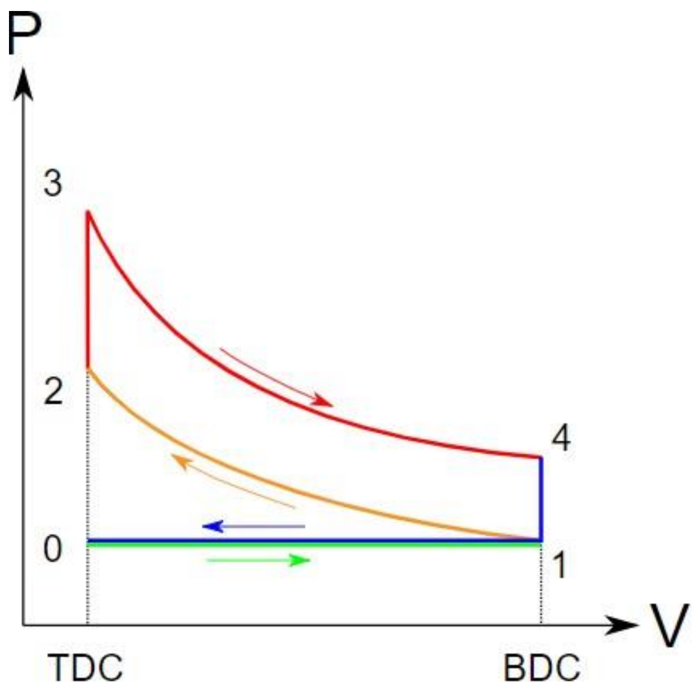

Figure 1.4.6 *Pressure-volume diagram of an Otto cycle*

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1.5 Chapter review

Thermodynamics has a wide range of applications in many engineering fields, in particular, the fields related to energy conversion and conservation. In this chapter, we have introduced some fundamental concepts and definitions used in the study of engineering thermodynamics.

An important skill that students need to develop, when performing thermodynamic analysis on devices, is to identify the system, its surroundings, and their interactions. There are three types of systems: closed system, open system, and isolated system, defined in terms of their ability to transfer mass and energy with the surroundings.

In this book, we consider systems in equilibrium. Each equilibrium state possesses a unique set of thermodynamic properties, which can be classified as extensive and intensive properties. When a system undergoes a process from one equilibrium state to another equilibrium state, its thermodynamic properties will change accordingly. The process path must be clearly specified when describing a process. Students need to understand the definitions of the common processes, including isobaric, isothermal, isochoric, adiabatic, and isentropic processes.