1

Fundamentals

1.1 Introduction

Energy has always been, historically, one of the most critical issues for humankind, which first started using wood (e.g. $C/H = 9.2$ for oak bark) as the source of energy; this was followed by coal (e.g. $C/H = 2.7$ for anthracite), oil (e.g. $C/H = 0.9$ for Alberta oil), and natural gas (e.g. $C/H = 0.26$ for Canadian natural gas). We are now moving into a low- and/or no-carbon era where hydrogen and other carbon free fuels (such as ammonia) become very critical solutions for implementation in our daily life. This is nicely illustrated in Figure 1.1 by providing a graph of carbon/hydrogen ratio versus types of fuels. It is also important to mention that humankind needs cleaner solutions, with carbon-free fuels (such as hydrogen and ammonia. These will result in significantly reduced environmental impact, particularly much lesser air, water and soil pollution which will apparently help improve human health and human welfare. Recently we have found ourselves in the Covid-19 coronavirus pandemic that has impacted every human being directly or indirectly. Of course, it has most harshly affected the elderly and people with weak immune system and those inflicted with various respiratory and cardiovascular illnesses. It has been evident that pollution, particularly air pollution, is recognized as a major risk to such illnesses and health problems. Here, the bottom line is that improving environmental quality will help improve human health and that people can better cope with such virus pandemics.

Another example of the importance of energy in humankind history is that energy sources have always been, are being, and will be the source of the main issues, ranging from conflicts to wars and peace. The competition around energy matters has been even more critical since the industrial revolution, when industry and other aspects of human life shifted its main driving fuel from human and animal power to fuel-based power and industrial activities.

Since we have begun facing many challenges, in particular ranging from the economy to the environment and technology to sustainability, it has even become more apparent that humankind needs more efficient, more cost effective, more environmentally benign, and more sustainable energy options and solutions. Figure 1.2 shows the key targets of sustainable development with respect to better design, analysis, and assessment, better management, better efficiency, better resources use, better environment, and better energy security, which are critical for any place/country to achieve better sustainability. The requirements for attaining such tasks come down to the thermodynamic fundamentals,

Thermodynamics: A Smart Approach, First Edition. Ibrahim Dincer.

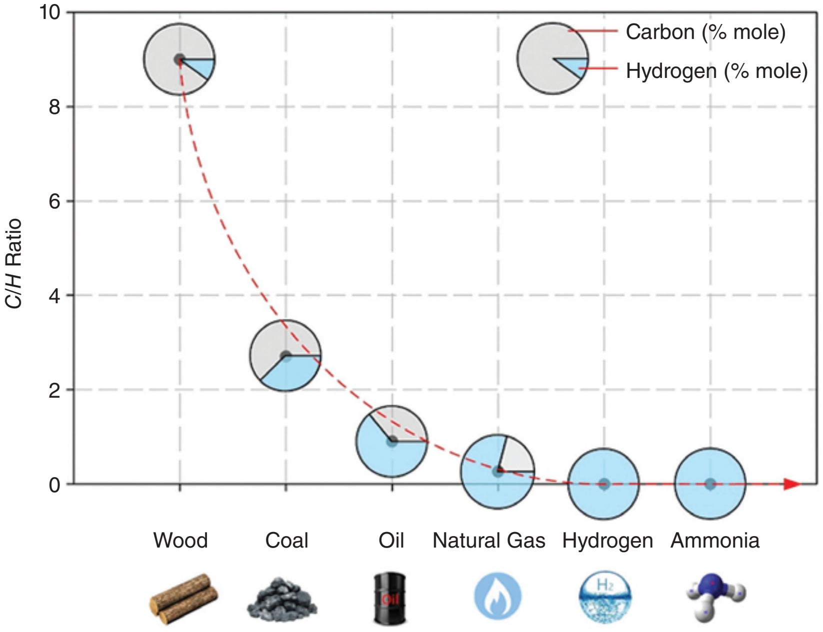


Figure 1.1 Illustration of historical carbon-hydrogen ratios of various fuels used by humankind.

concepts, and laws. That is why we need to understand, learn, and teach thermodynamics in a better way – to better tackle the issues and provide better solutions.

If we look at the environmental dimensions of the challenges through for example global warming, the phenomena can only be better understood with thermodynamics and analyzed and assessed by thermodynamic tools. This is another clear example of the power of thermodynamics.

Since, in this book, thermodynamics is defined as the science of energy, which comes from the first law of thermodynamics (FLT), and exergy, which comes from the second law of thermodynamics (SLT), it clearly shows that the subject sits on these two laws, namely two pillars, just like the way in which a person has two legs.

Going back to the earlier discussion, the requirements of more adequate energy, better environment, and better sustainability have been the main motivation behind going beyond traditional analysis methods and techniques. Traditionally, the FLT, which is recognized as the conservation law, has been the only tool comprehensively used in design, analysis, and assessment of thermodynamic systems. However, it became more apparent in the 1970s and 1980s that the FLT does not achieve much and has limited ability to help achieve things due to the fact that it is insufficient and incapable of addressing practical systems with irreversibilities (or losses, inefficiencies, etc.) and unable to quantify these for assessment and improvement. This is the key reason to have the SLT brought into the picture to account for irreversibilities or destruction through entropy and exergy.

Exergy is distinguished to be a primary tool under the SLT. Thermodynamics is defined as the science of energy and exergy. There are various definitions for energy; however, the definition chosen here is that energy is what causes changes or has the ability to cause changes.

Figure 1.2 Key targets for sustainable development.

Comparing the definition of thermodynamics in this book with the literature, this book follows a more correct approach and more consistent approach, as it considers both energy (coming from the first law of thermodynamics) and exergy (from the second law of thermodynamics) concepts with the same units consistently, and highlights two key efficiencies for performance assessment as the energy concept brings energy efficiency and exergy brings exergy efficiency. This way the concept of efficiencies dwell on two correct pillars of the FLT and the SLT for practical applications and complement each other. The exergy efficiency becomes more important for practical systems and applications since it is a true measure of system performance and indicates how much the actual performance deviates from the ideal performance.

In order to understand thermodynamics, it is essential to understand the four laws of thermodynamics: the zeroth law, first law, second law, and third law of thermodynamics. Each of these four laws is described later with details.

In closing, this chapter aims to provide the introductory aspects of thermodynamics, the basic principles, the main concepts, and the key points to better illustrate thermodynamics along with numerous examples.

1.2 The Spectrum of Energy

In the introduction it is mentioned that energy is critical for humanity. There have been many individuals and organizations ranking the world's key challenges where energy has always been among the top three issues – the first in many –followed by environment,

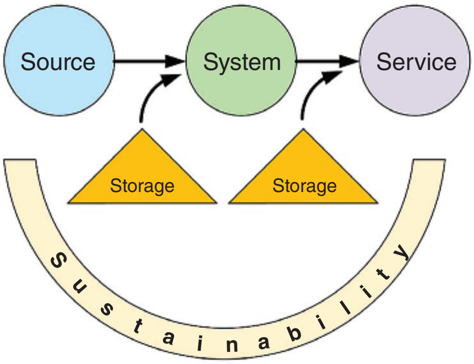


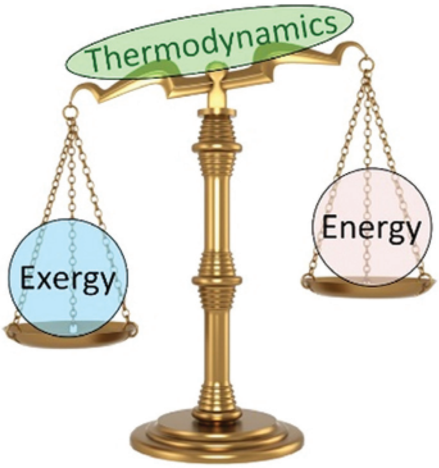
Figure 1.3 Illustration of the 3S + 2S ≅ **S** approach.

economy, water, food, poverty, etc. Of course, energy challenges require energy solutions in a smartly diversified portfolio, although many just propose the renewable energy sources, such as renewable energy technologies, clean fuels (e.g. hydrogen, ammonia), cleaner technologies for fossil fuels, efficient energy use and energy conservation, nuclear energy, and waste to energy technologies. Such smart energy solutions require a holistic approach to see the complete spectrum and understand the key dimensions. As presented in many events, there is a 3S + 2S ≅ **S** approach as illustrated in Figure 1.3 which clearly shows that everything related to energy comes down to 3S, source, system, and service. For any system we need a source, which could be a fossil fuel source or a renewable source or a nuclear source. Based on the services needed in terms of useful outputs (commodities), such as electricity, heat, hot water, cooling, air conditioning, fresh water, drying air, fuel, etc., we need to design the system that will be fed by a source. This system may be a single-, co- or tri-generation system or a multigeneration system with more than three useful outputs. The next 2S is illustrated in the form of storage as needed in this energy spectrum. For example, one may have solar energy not available all the time; what is needed is storage to offset the mismatch. For the second part after the system, one may have more useful output produced that needed. What is required is storage. Therefore, the energy sustainability **S** requires 3S and 2S provided accordingly.

1.3 Two Pillars of Thermodynamics

Thermodynamics, as described in the previous section, can be defined as the subject of both energy and exergy which illustrated in Figure 1.4, based on the previously mentioned two pillars. Of course, it shows that the weight of exergy is more due to its role. The first column of scale is energy, which is brought in by the FLT and concerned with energy as a quantity that is conserved throughout in any system. However, energy alone cannot support thermodynamics, and energy should not be treated as a quantity as it has a quality, which is defined by exergy. Exergy is derived or is based on the SLT as it defines the quality of energy and provides a more meaningful rational for the flow of energy from one reservoir to another. There is another significant thermodynamic property coming from the SLT, namely

Figure 1.4 Thermodynamic pillars of energy and exergy.



entropy, which is defined as the degree of disorder. This is also be discussed later. We can easily connect entropy as a literal approach to our daily life and call some situations where things are messy as entropic. Figure 1.5 illustrates two cases where we have low-entropy and high-entropy cases. Of course, the high-entropy case is the more messy.

As defined earlier, the FLT essentially brings the concept of energy, with the fact that energy is neither created nor destroyed but is always conserved; this is recognized as the conservation of energy principle. However, the SLT provides something more meaningful and more important with the concept of exergy: the fact that exergy is always destroyed/consumed; this is recognized as the principle of the nonconservation of exergy.

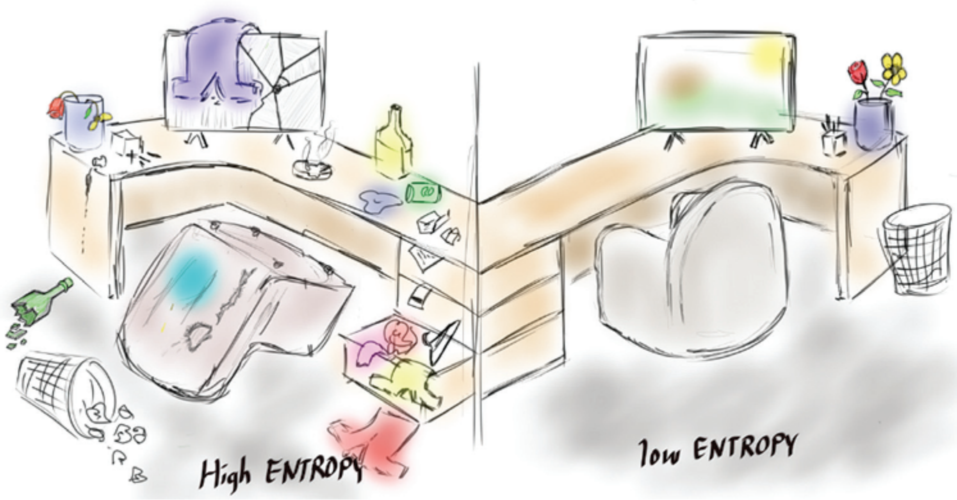


Figure 1.5 Graphical illustration of entropy for a daily situation as low-entropy (less-entropic) and high-entropy (more entropic) cases.

One should keep in mind that thermodynamics governs many aspects of our daily life, and to better explain the importance of thermodynamics and energy engineering various aspects of energy and thermodynamics in the world are presented next.

1.4 Units and Dimensions

In thermodynamics, the basics are important. In this regard, we need to look at units and dimensions and understand them for use. **Dimensions** are defined as physical quantities and the dimensions and the magnitudes assigned to these dimensions are referred to as **units**. There are many quantities used in our daily life where some are measurable, such as temperature and temperature, and some that are not measurable, such as enthalpy and entropy. Figure 1.6 shows a daily example where we have a glass of soda at 20 $^\circ C$ and can directly measure this by using a simple thermometer.

The unmeasurable quantities are normally calculated from measurable quantities. The quantities are often presented in terms of one or more of the basic dimensions, which are presented in Table 1.1. The dimensions shown in Table 1.1 are often referred to as the primary or fundamental dimensions; other quantities where the dimensions are a combination of two or more of primary dimensions are referred to as secondary or derived dimensions.

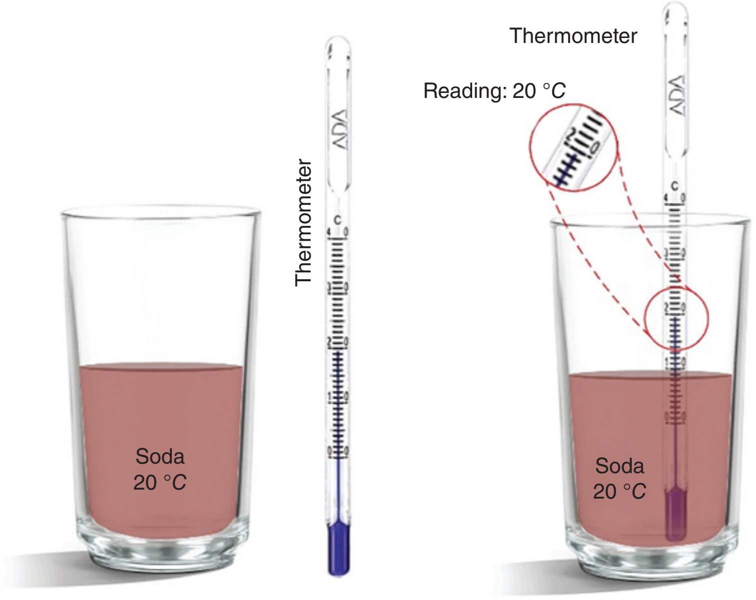


Figure 1.6 A thermometer can be used to measure the temperature of a drink by having both in direct contact.

Table 1.1 Some basic dimensions in SI units.

Dimension	Unit
Length	meter (m)
Time	second (s)
Mass	kilogram (kg)
Temperature	Celcius ($^\circ C$), Kelvin (K)
Electric current	ampere (A)
Amount of matter	mole (mol)
Amount of light	candela (cd)

⇒ Reminder

It is a common practice that one needs to write thermodynamic equations as well as balance equations in a dimensionally correct and consistent manner to have the final result correct; only in this way can we achieve **dimensional homogeneity**. For example, only an elephant can make a baby elephant or, in other words, having an elephant on one side of the equation means that there should be another elephant on the other side of the equation to be able to consistently balance. What we can make of this as a principle for engineers is the "3C rule": make things **C**orrect, **C**omplete and **C**onsistent.

An example of a secondary dimension is velocity, which has the dimension of length over time. Everyone knows the fact that we cannot add apples to potatoes to find the total amount of what? This is illustrated in Figure 1.7 which must be kept in mind. Note that the dimensional homogeneity can be used to solve engineering problems just based on the dimensions and the units given in Example 1.1.

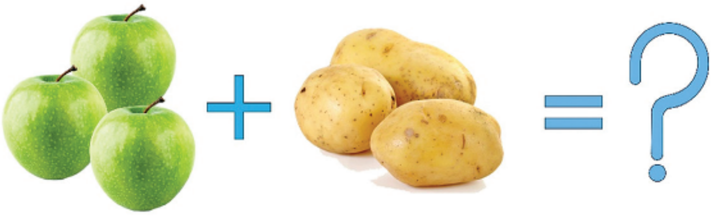


Figure 1.7 Illustration to highlight the importance of dimensional homogeneity.

Example 1.1 Calculate the mass of an object with a density of 1 kg/m^3 and a volume of 1 m^3

Solution

$$Mass = (Density) \times (Volume)$$

$$m = \rho V$$

$$m = 1\frac{kg}{m^3} \times 1\,m^3 = \mathbf{1\,kg}$$

1.5 The Zeroth Law of Thermodynamics

In thermodynamics, there are four laws:

- Zeroth law of thermodynamics
- First Law of Thermodynamics (FLT)
- Second Law of Thermodynamics (SLT)
- Third law of thermodynamics

The first and second laws of thermodynamics are recognized as **governing laws** like the constitutional laws for a state or country or institution which are known as the primary rules for regulating the functioning of a state or country or institution. When we look at the zeroth and third laws of thermodynamics, these are seen more as **guiding policies** for any state or country or institution. After this linkage, one may clearly understand that the first and second laws of thermodynamics are governing laws and the zeroth and third laws of thermodynamics are guiding laws depending on special/specific situations.

After these introductory points, we introduce the zeroth law of thermodynamics in this section with a supporting example. The zeroth law of thermodynamics states that when there are two bodies/objects (such as A and B) in contact in thermal equilibrium and another body/object (such as C) that is in thermal equilibrium with the body/object A, it will be in thermal equilibrium with the body/object B if brought into a contact. In brief, it states that if two bodies are each in thermal equilibrium with a third one, they will then be in thermal equilibrium with each other. This is illustrated in Figure 1.8. One may think that such a definition seems trivial and raises question of why such an obvious conclusion is considered one of the main laws of thermodynamics. The answer to this question is that the conclusion resulting from the zeroth law cannot be concluded from the other thermodynamics laws; another reason is that this zeroth law can be used to validate the concept of measuring the temperature.

The zeroth law of thermodynamics was originally formulated and stated by R.H. Fowler in 1931. Although it was formulated around more than half a century after the first and the second laws of thermodynamics were introduced, scientists felt that the law was a fundamental one and should come before the first and second laws of thermodynamics, so naming it the zeroth law.

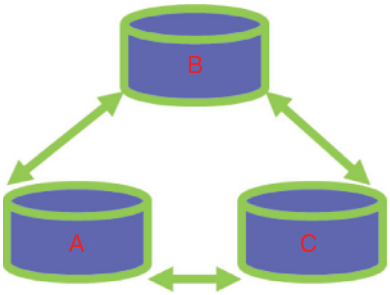


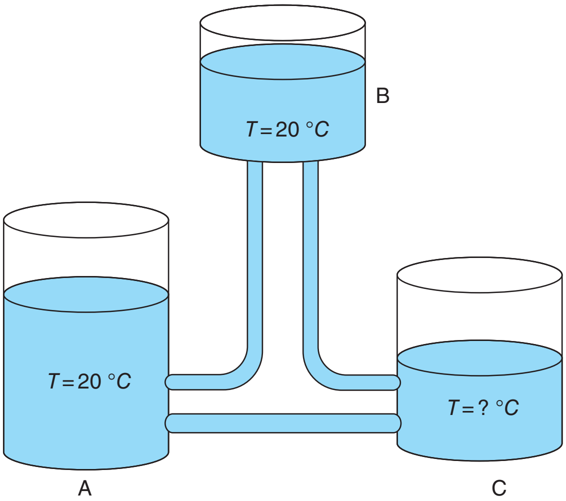
Figure 1.8 An illustration of the zeroth law of thermodynamics.

Example 1.2 Three fluid tanks in different sizes with different fluids are shown in Figure 1.9. The fluids in tanks A and B have the same temperature. If tank C, which is in thermal equilibrium with tank B is connected to tank A, find the temperature of tank C?

Solution

Since both of tanks A and B are in thermal equilibrium, both are expected to have the same temperature of 20 $^\circ C$ based on the zeroth law of thermodynamics. Once tank C, which is in thermal equilibrium with tank B, is connected to tank A, all three tanks will be in thermal equilibrium based on the zeroth law. So, the final temperature of tank C will be 20 $^\circ C$ accordingly.

Figure 1.9 Illustration of Example 1.2.



1.6 The First Law of Thermodynamics

The FLT defines one of the fundamental governing laws of life, which is recognized as the principle of conservation of energy. This principle states that no matter what happens energy cannot be created nor destroyed, but it can change from one form to another. For example, energy is converted from the thermal form of energy (so called: heat) to the mechanical form of energy (so-called: work) in a thermal power plant. We have another example where we have a refrigeration system. In this case, the electricity in the form of work is given to the system to operate it in order to produce a cooling effect in the evaporator which is in the form of heat.

It should be kept in mind energy is always conserved throughout any process, system, or application, and hence the total amount of energy will always remain constant. Figure 1.10 shows an example that graphically illustrates the conservation of energy of a soccer ball rolling down the hill where values are given for both kinetic energy (KE) as the function

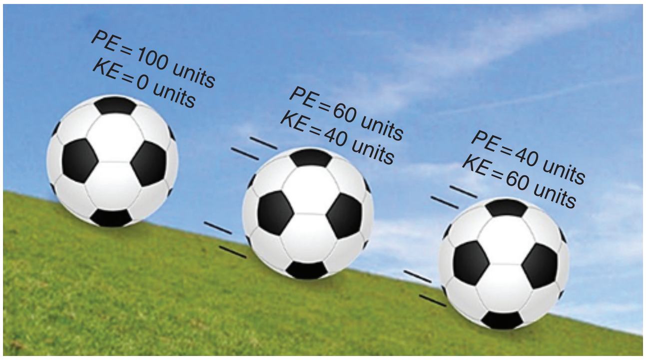


Figure 1.10 Illustration of the first law of thermodynamics concept through a soccer ball rolling down a hill with a constant total energy of 100 energy units.

of velocity and potential energy (PE) as the function of height (elevation). One can easily notice that the total energy remains constant as 100 units from the beginning to the end at every position.

The FLT is a presentation of the conservation of energy principle, where it defines energy as one of the properties of thermodynamics. From the definition of the FLT it enables us to analyze the energy exchange and interactions of power plants and energy devices since the FLT accounts for these interactions and makes sure that all these interactions are within the balance as nothing is created nor destroyed. It can, however, change the form of energy from one form to another. Quantifying the performance of such an energy system can also be done with the help of the FLT through the energy efficiency under the conservation principle, which measures the performance of an energy system through evaluating the amount of energy that is converted to the desired form and comparing it to the amount of energy that is supplied to the energy system or energy device. For example, consider a diesel power generator. The amount of energy fed into the system (power generator) is in the form of chemical energy after burning the diesel fuel. The amount of energy that is converted to a useful form is the amount of electricity produced by this generator. However, with all the advantages and the benefits we gain with the FLT, there is a clear disadvantage and insufficiency of not considering the irreversibilities, losses, inefficiencies, and quality destructions.

Example 1.3 The rock shown in Figure 1.11 freely falls down to the ground. The *PE* and *KE* of the rock are shown on the rock at different positions in time. Find what the total energy of the rock will be when it eventually hits the ground.

Solution

It is clearly seen that at any point the total energy (*PE* + *KE*) is **10 units**. The rock will hit the ground with a total energy of **10 units**, which fully comes from the *KE*. The rock will eventually stop on the ground and one may question what will happen to the 10 units of energy. It will be transferred to the ground, causing some damage.

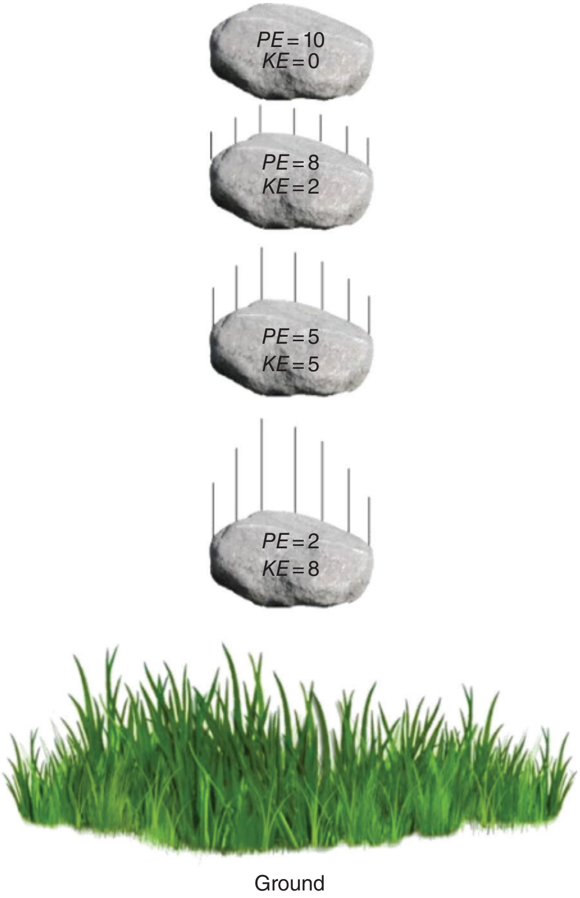


Figure 1.11 A rock falling with the same total energy content.

1.7 The Second Law of Thermodynamics

The deficiencies of the FLT in not taking into account the irreversibilities, losses, inefficiencies, and destructions are compensated by the SLT. This can easily be done through entropy and exergy approaches under the SLT. In this book, the primary focus becomes on exergy rather than entropy due to the fact that exergy units are consistent with energy units and that exergy takes us to exergy efficiency while energy leads to energy efficiency. This way we have the opportunity to compare both FLT and SLT results. The SLT is about both quantity and quality while the FLT is about quantity only.

For example: consider 1 *kJ* of superheated vapor, 1 *kJ* of liquid water, 1 *kJ* of heat, 1 *kJ* of electrical work, and 1 *kJ* of mechanical work and comment on if these will have the energy qualities and hence exergy contents. They are energetically the same under the FLT. However, they will not be the same under the ST as each type of energy has different energy quality which refers to the exergy content. Thus, their energy qualities become different

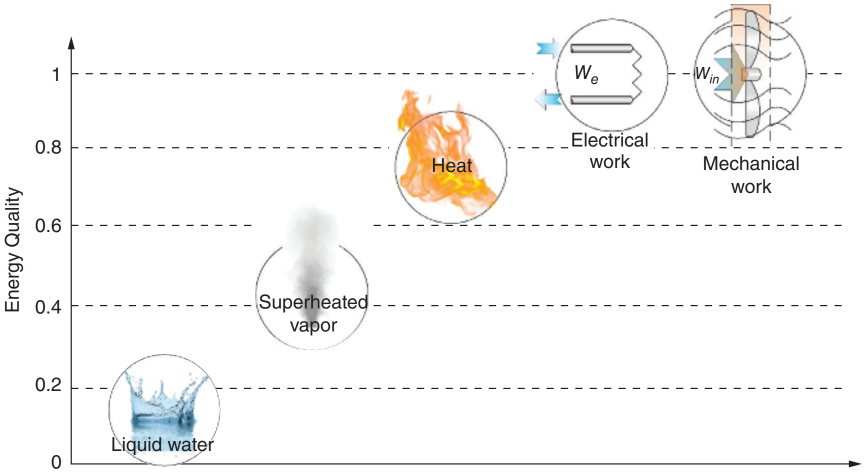


Figure 1.12 Energy quality diagram of various forms of heat and work.

as shown in Figure 1.12. Liquid water has the lowest and both electrical and mechanical works have the highest due to the fact that their actual energy contents become the same as the exergy contents.

Another example is the upper part of the water in the ocean since it is at ambient temperature and pressure, its quality is quantified as zero since it is already at ambient conditions, which are considered dead state (or reference state). Since the heat transfer naturally takes place in the direction of decreasing quality, an example is that thermal energy will naturally transfer from a high quality source (higher temperature source) to low quality thermal energy source (lower temperature source). This can be seen with the illustration in Figure 1.13 where a snowman is made out of snow at $-10\,^{\circ}C$ and the next day the

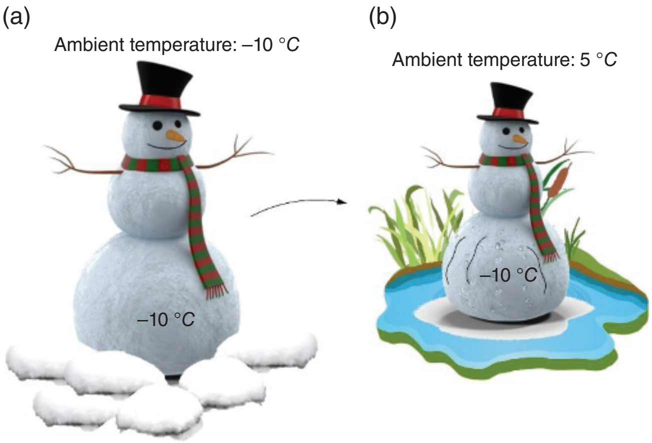


Figure 1.13 Illustration of the SLT with a snowman example where that heat transfer takes place in the direction of decreasing quality: (a) where there is no temperature difference between the snowman and the ambient to cause any heat transfer and hence melting; (b) where there is a temperature difference to cause heat transfer and help melt the snowman.

ambient temperature becomes 5 °C. Guess what will happen! The snowman will start melting, and the melted snow will become liquid water and eventually reach an ambient temperature of 5 °C. There are two key points to make here: (i) heat is transferred from a higher temperature to a lower temperature and (ii) the thermal equilibrium is achieved eventually where both have the same temperature and no more heat transfer takes place.

Example 1.4 From each of the following two pairs select which energy reservoir or source has higher quality.

a) Ice cube and warm water
b) Hot tea and cold water

Solution

a) The energy in the **warm water** is at higher quality (at a higher temperature) than that of the ice cube (at a lower temperature), since if both are brought into contact, thermal energy (so-called: heat) will transfer from the warm water to the ice cube, which eventually will melt it. Based on the SLT, heat will transfer from a high quality source to a lower quality source, the warm water will then have a higher quality energy.
b) The energy in the **hot tea** has higher quality (at a higher temperature) than that of the cold water (at a lower temperature) for the same reason mentioned in the above point. If both are brought into contact in a similar way heat will transfer from the hot tea to the cold water, which eventually will melt it. Based on the SLT, heat will transfer from a high quality source to a lower quality source, the hot tea will then have a higher quality energy.

1.8 Thermodynamic System

A thermodynamic *system* is defined as a mass of matter or a region in space or a device, which is separated from its surroundings, selected specifically for analysis and assessment. The system selected may be fixed in a stationary form or moving in a nonstationary form. The interaction of system with its surroundings is important in studies where one needs to define an imaginary boundary to start showing all inputs and outputs. *Surroundings* is anything surrounding the system and becoming external to it. It may be a region or mass depending on the application selected. A *boundary* is treated as a real or imaginary closed surface separating the system from its surroundings where mass and energy may enter in and go out of the system. Figure 1.14 shows a soda can as closed system and a pump as an open system with the boundaries and surroundings. Of course, the following chapters will dwell on such open and closed systems in detail with many examples.

For the thermodynamic system that involves mass entering and leaving its boundary then such systems are referred to as *open systems*, while the systems that have a constant, fixed amount of mass, where mass cannot enter or leave its boundary, are referred to as *closed systems*.

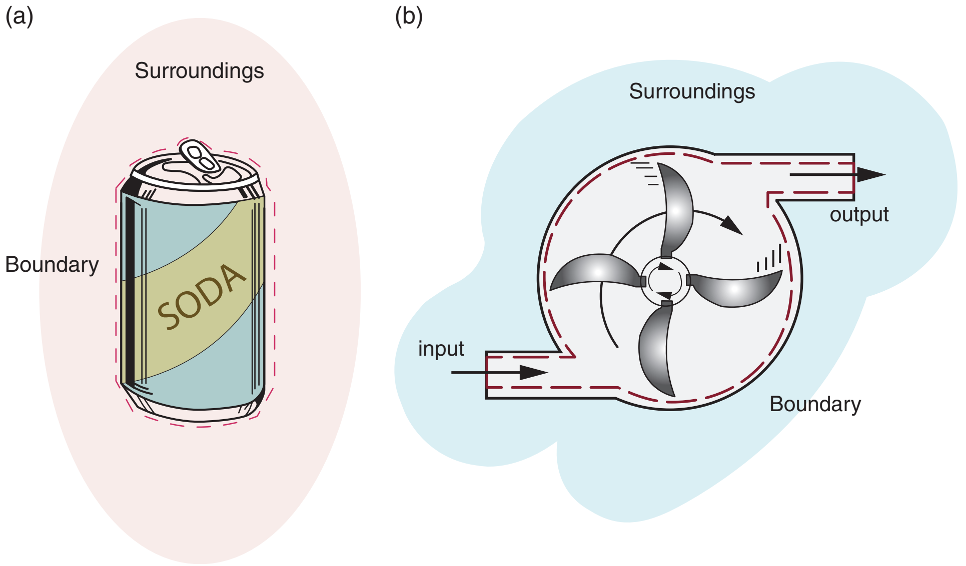


Figure 1.14 Two examples of (a) a soda can to illustrate a closed system and (b) a pump to illustrate an open system.

1.9 Seven-step Approach

This section introduces a seven-step approach to better understand the scope of thermodynamics in the book and clearly shows how thermodynamic concepts are orchestrated in a logical order. In thermodynamics everything starts with property, which is defined as any characteristic of a system (such as temperature, pressure). The next step is state, which is defined as any condition of a system (such as inlet and exit conditions) where there is a need to define at least two properties for each state. The third step is process, which is defined as a change from one state to another (such as isothermal [constant temperature], isobaric [constant pressure] processes) where there is a need to define at least two state points. It is really a beauty of "2," which means there is a need for a pair (couple) in almost everything. The fourth step is cycle, which is defined as the series of processes where the final state is expected to finally reach the initial state, which will make it complete a cycle. There is a need for at least two cycles to achieve this. One should keep in mind that the common power generating and refrigerating cycles have four processes to achieve the final desired outputs (for example, power and cooling effect). The next step is FLT, which was defined earlier as one of the main laws of thermodynamics (conservation of energy law) and which is followed by the SLT (nonconservation of exergy law). These are two critical laws that are the main pillars of thermodynamics. The seventh step is performance assessment, which is essential for all thermodynamic systems and their assessments. This can only be done through a pair of energy and exergy efficiencies or a pair of energetic and exergetic coefficients of performance. The seven step approach is summarized graphically in Figure 1.15; each step in the approach is defined in more details in the coming subsections.

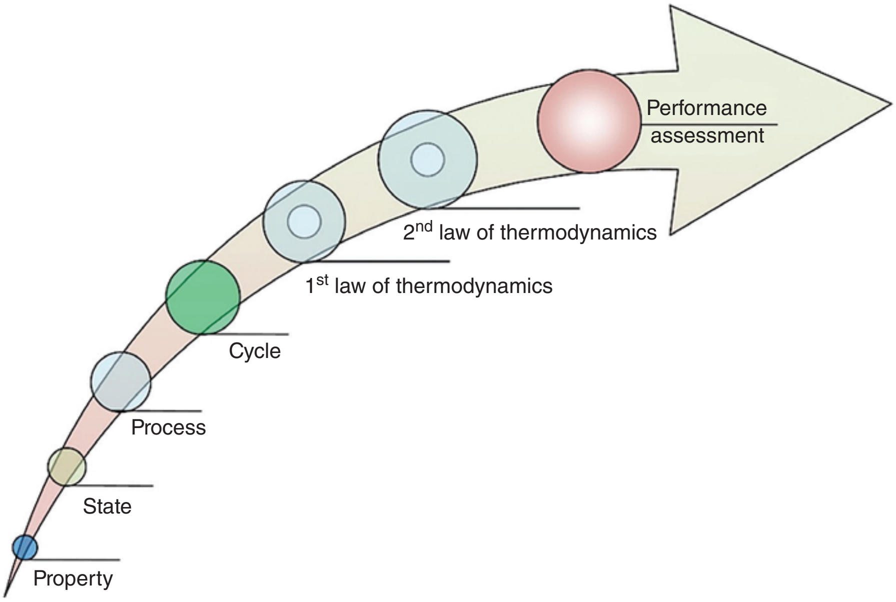


Figure 1.15 A schematic illustration of the seven-step approach.

1.9.1 Property

Property, as defined earlier, is recognized as any characteristic of a system and can be distinguished based on the relation to the mass and volume of the system. The properties that are independent of the mass and volume of a system are recognized as intensive properties, for example: temperature and pressure as well as specific properties. The properties that are dependent on the mass (m) and volume of the system are referred to extensive properties, for example: mass and volume. This is illustrated in Figure 1.16. Figure 1.16a shows a single apple, which is then cut into two halves as shown in Figure 1.16b. The questions are: Which properties will change? Which ones will not change? The replies: the properties, such as m and V, will change and are to be called “extensive properties.” The properties, such as P and T, will not change from full apple to half apple which are to be called “intensive properties.”

Furthermore, one should note that all lower case letters, such as specific volume (v), specific internal energy (u), specific energy (e), specific enthalpy (h), specific work (w), specific entropy (s) and specific exergy (ex) become intensive properties, except for temperature (T) and pressure (P).

The upper case letters, such as volume (V), internal energy (U), energy (U), enthalpy (H), work (W), entropy (S) and exergy (Ex), are extensive properties, except for m.

a) Specific Volume

Let us look at an example where we obtain an intensive property, specific volume (v), from an extensive property, Volume (V), by dividing it by mass (m) as follows:

$$v = V/m \tag{1.1}$$

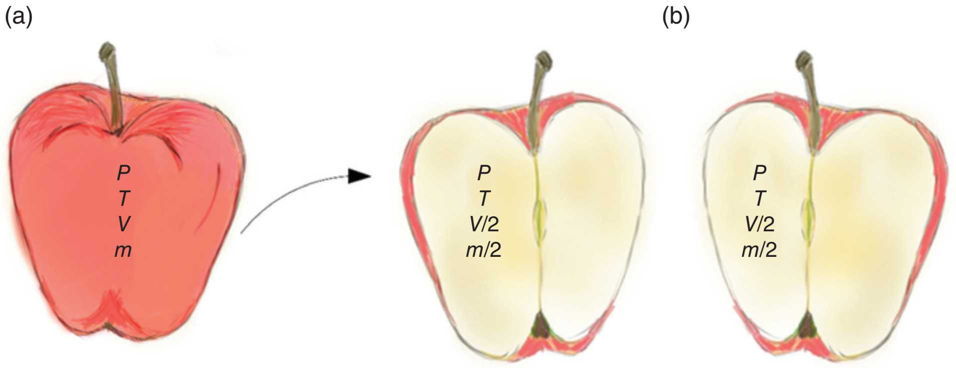


Figure 1.16 A comparison of intensive vs. extensive properties: (a) a full apple and (b) two half apples with intensive and extensive properties.

Note that the specific volume as well as other properties depends normally on the temperature and pressure of the system. For most gases (which are commonly treated as *compressible substances*), the specific volume is proportional to temperature and inversely proportional to pressure due to the ideal gas equation: $Pv = RT$. On the other hand, the specific volumes of liquids and solids tend to remain constant with a variation in pressure; these are referred to *incompressible substances*. Table 1.2 presents a comparison between the specific volumes of water and air with a variation of pressure at a temperature of 25 °*C*. Furthermore, one can see in this table that increasing the pressure from 100 to 200 *kPa* decreases the specific volume by more than 50% while the specific volume of water

Table 1.2 Variation of the specific volumes of incompressible liquid water and ambient air with the variation of pressure at a constant temperature of 25 °*C*.[a]

Pressure (*kPa*)	Specific volume of water (m^3/kg)	Specific volume of air (m^3/kg)
100	0.001 003	0.8558
110	0.001 003	0.778
120	0.001 003	0.7132
130	0.001 003	0.6583
140	0.001 003	0.6113
150	0.001 003	0.5706
160	0.001 003	0.5349
170	0.001 003	0.5034
180	0.001 003	0.4755
190	0.001 003	0.4504
200	0.001 003	0.4279

[a] Data are generated using the Engineering Equation solver (EES).

Table 1.3 Variation of the specific volumes of incompressible liquid water and ambient air with the variation of temperature at a constant pressure of 100 *kPa*.[a]

Temperature (°*C*)	Specific volume of water (m^3/kg)	Specific volume of air (m^3/kg)
10	0.001	0.8128
20	0.001 002	0.8415
30	0.001 004	0.8702
40	0.001 008	0.8989
50	0.001 012	0.9276
60	0.001 017	0.9563
70	0.001 023	0.985

[a] Data are generated using the Engineering Equation solver (EES).

remains constant. This is absolutely a clear indication that water is incompressible substance whereas air is compressible substance.

In addition, Table 1.3 tabulates the specific volume values of both water and air this time with varying temperatures from 10 to 70 °*C* at a constant pressure of 100 *kPa*. It can be seen from the table that the specific volume of water increases about 2.3% while the specific volume of air it increases about 21% with increasing temperature from 10 to 70 °*C*. This clearly shows that compressible substances experience larger differences in both pressure and temperature changes.

b) Density

Density is defined as the reciprocal (inverse form) of specific volume, which is considered another useful thermodynamic property as it is more commonly used in daily applications. It can also be used to determine whether an object will sink or float in addition to many other benefits that arise from knowing the density. As shown in Figure 1.17, if the density of an object is greater than the density of water then the object or body will sink; however, if the density of a body is less than the density of water, then the object will then float.

When the density of an object is measured relative to the density of water, it is referred to the *specific gravity*. The water that is usually used as the reference point to the specific gravity is the at a temperature of 4 °*C* and atmospheric pressure, which will result in a specific volume of 0.001 m^3/kg and a density of 1000 kg/m^3. The specific gravity is denoted in this book as SG and is calculated as follows:

$$SG = \rho_i/\rho_{ref} \tag{1.2}$$

Here, ρ_i denotes the density of any fluid and ρ_{ref} denotes the density of a reference substance or material, where, for example, water at a temperature of 4 °*C* with a density of 1000 kg/m^3 is often used.

Note that the temperature and the pressure are intensive properties as introduced earlier, and they are further discussed in upcoming sections.

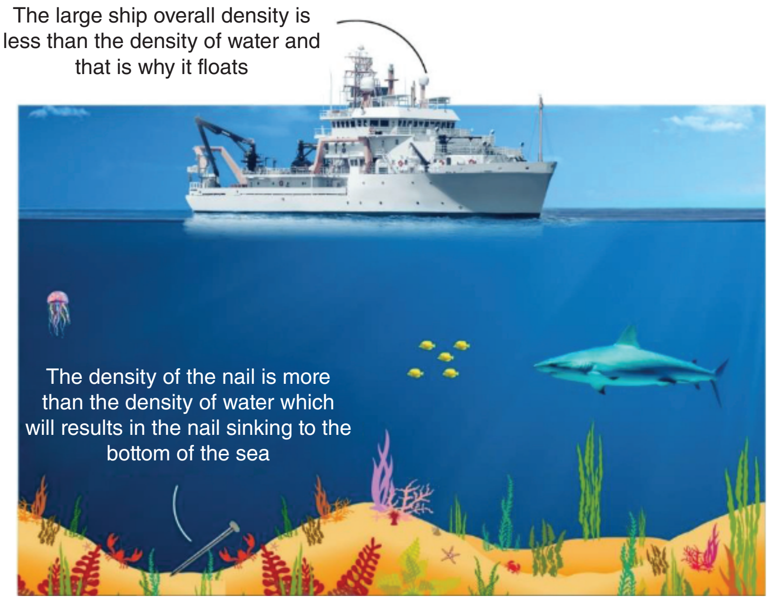


Figure 1.17 If the object density is greater than the sea's density the object will sink and if the object density is less then the object will float, depending on the contact surface area.

Example 1.5 Consider the following objects and find out which one of these will float or sink in a water bath:

a) a metallic bolt with a density of 7800 kg/m^3
b) mercury with a density of 13 600 kg/m^3
c) wood with a density of 750 kg/m^3

Solution

There is a need to check the specific gravity with the following equation to see what will happen.

$$SG = \frac{\rho_i}{\rho_{ref}}$$

a) Calculate the specific gravity of metallic bolt:

$$SG = \frac{\rho_i}{1000\ kg/m^3} = \frac{7800\ kg/m^3}{1000\ kg/m^3} = 7.8 > 1 \text{ which will then sink.}$$

b) Calculate the specific gravity of mercury:

$$SG = \frac{\rho_i}{1000\ kg/m^3} = \frac{13600\ kg/m^3}{1000\ kg/m^3} = 13.6 > 1 \text{ which will then sink.}$$

c) Calculate the specific gravity of wood:

$$SG = \frac{\rho_i}{1000\ kg/m^3} = \frac{750\ kg/m^3}{1000\ kg/m^3} = 0.75 < 1 \text{ which will then float.}$$

Example 1.6

Consider this time that the specific gravity value is given as 13.6. Find the density of this substance.

Solution

We need to use specific gravity equation as given below to extract the density of the unknown substance.

$$SG = \frac{\rho_i}{\rho_{ref}}$$

$$13.6 = \frac{\rho_i}{1000\ kg/m^3} \rightarrow \rho_i = 13\,600\ kg/m^3 \text{ which appears to be mercury.}$$

c) Temperature

In our daily life, the term "property" is mostly used for temperature to determine out how cold or hot a thing is. Although there is no a commonly accepted exact definition of temperature, it is generally defined as a measure of hotness and coldness. Some examples are then: the weather is colder today; the water is warmer this time; I feel colder; and many more. In addition, we usually understand or comprehend temperature based on our own experience and sensation. An example of the sensation part of determining the temperature of an object at room temperature – a metallic chair makes us feel colder than a wooden one, although both are in the same room at the same temperature. The scientific reasoning behind the metallic chair making someone feeling colder is due to the thermal conductivity, which is a property of materials that measures the effectiveness of the material to conduct heat. Sensation is not the only factor affecting our qualitative judgment on the degree of hotness or coldness is our own experience. For example, let us consider two people living in two distinctly different locations, such as one experiencing cold weather in Canada and the other one experiencing hot weather in the Middle East. Of course, they will adapt themselves to their living environments and their senses will be quite different for cold and hot. This clearly indicates that living species easily adapt themselves to the conditions in their living environments.

The key question here is that how accurately one can measure temperatures. This will definitely depend on various criteria, namely the materials being use to quantify it and their sensitivities to the temperature variations as well as their sizes, shapes, and phases. It is also important to consider repeatability and predictability in measuring the temperatures which will lead to accuracy. This will then bring us to the zeroth law of thermodynamics, which plays a critical role in temperature measurement devices. For example, a basic thermometer is recognized as a temperature measuring device, as illustrated in Figure 1.18. Note that the thermometer measures the temperature through the zeroth law of thermodynamics, as when it reaches thermal equilibrium with the object that it is in contact it will have the same temperature. One of the interesting facts of temperature is shown in Figure 1.19, where it shows the variation of the atmospheric temperature for the condition when the starting temperature from the earth surface is $25\,^{\circ}C$.

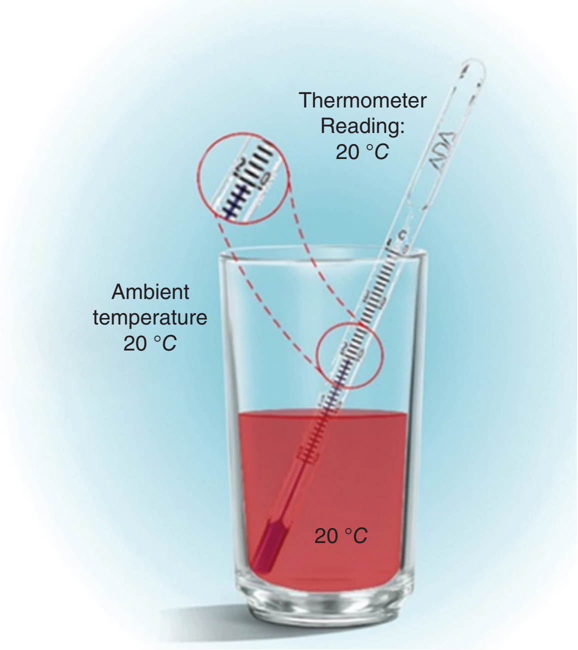


Figure 1.18 Illustration of how thermal equilibrium exists between a glass of liquid and its surroundings at the same temperature.

Note that the temperature reduces through the troposphere which extends from the Earth's surface to nearly 11 *km*. Following the froposphere, the temperature is well below zero, nearly around $-56\,^{\circ}C$. The temperature remains constant as the elevation increases from 11 to 20 *km* above Earth's surface (Figure 1.19. Moving further away from the Earth's surface also causes variations in the temperature, where it increases in some sphere bands while it decreases in others. Note the maximum temperature the atmosphere has in the Earth's surface to an elevation of 105 *km* is illustrated in Figure 1.19.

- ***Temperature Scales***

The most common temperature scales may be divided into two categories. In the first category are those that are relative to two points, namely boiling point and triple point, while the second category is based on the scientific fact that the lowest possible temperature point (so-called: absolute zero) is when the molecules stops moving (zero *KE*). The two temperatures that the first category of temperature scales are based on (the triple point of water and boiling of water) are the Celsius and Fahrenheit scales. The triple point temperature is the temperature where all of the three phases of a substance exists at the same time. The triple point of water can be found at a temperature of $0.01\,^{\circ}C$, $273.16\,K$, $32.02\,^{\circ}F$, and $491.69\,R$. The second temperature that the Celsius and the Fahrenheit scales is based on is the boiling temperature of water, which was experimentally determined to be $100\,^{\circ}C$ and $212\,^{\circ}F$.

The second category is based on the scientific fact that the lowest possible temperature point is when the molecules stops moving, since the temperature is a quantification of

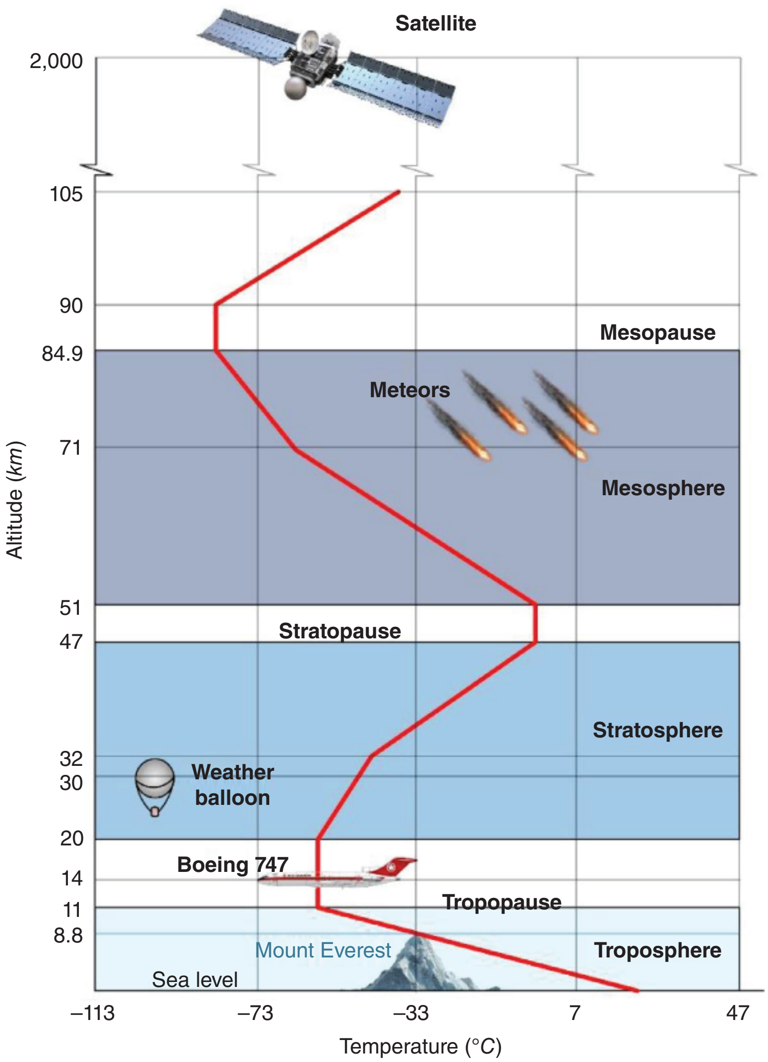


Figure 1.19 The variation of atmospheric temperature with elevation from the Earth's surface.

the molecules *KE*. It means that the lowest temperature would be at the lowest molecules *KE* and the lowest *KE* is zero. Kelvin and Rankine are absolute temperature scales, indicating that they depend on the zero temperature corresponding to a zero molecule *KE*. In this regard, Figure 1.20 shows the groups of temperature scales with the Celsius and Kelvin scales under the "*le Système International d'unités* (SI), referring to the International System of Units. The SI system is a simple and logical unit system that is based on the decimal relationship between the various units of the same dimensions. The second group of temperature scales with the Fahrenheit and Rankine scales is known as the English System of Units, which is also known as the *United State Customary System* (USCS). Although one

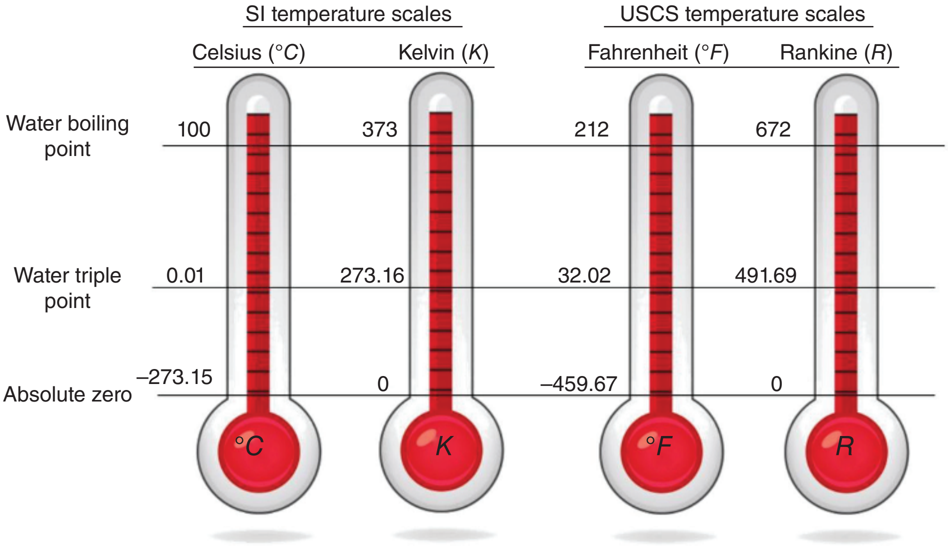


Figure 1.20 A comparative illustration of two temperature scales.

may refer to Figure 1.18 for a graphical illustration of the four common temperature scales, we essentially consider both Celsius and Kelvin as the most common scales to use in the international unit system (SI) throughout this book.

The different temperature scales can be related to one another by using one or more of the following:

$$T(K) = T(^oC) + 273.15 \tag{1.3}$$

$$T(^oF) = 1.8T(^oC) + 32 \tag{1.4}$$

$$T(R) = T(^oF) + 459.67 \tag{1.5}$$

$$T(R) = 1.8T(K) \tag{1.6}$$

Example 1.7 Let us determine the temperature of a cup of coffee at 80 $^\circ C$ on other temperature scales, in a) Kelvin (K), b) Fahrenheit ($^\circ F$) and c) Rankine (R).

Solution

a) $T(K) = T(^oC) + 273.15 = 80 + 273.15 = \mathbf{353.15\ K}$
b) $T(^oF) = 1.8T(^oC) + 32 = 1.8 \times 80 + 32 = \mathbf{176\ ^oF}$
c) $T(R) = T(^oF) + 459.67 = 176 + 459.67 = \mathbf{635.67\ R}$

---

d) Pressure

Pressure is defined as the force that a fluid exerts per unit area and is written as:

$$P = F/A \tag{1.7a}$$

Accordingly, the pressure at a point that is located on an area that has an area of A and has a body with mass m covering it is calculated as follows:

$$P = mg/A \tag{1.7b}$$

Here, m denotes the mass and g denotes the gravity acceleration. Obviously, mg is the force.

Note that the counterpart of pressure in solids is referred to as stress.

Over the years different pressure units have been developed and introduced; some of them are more commonly used than others. Here, some the pressure units are listed in terms of each other to have a way to convert between them:

$$1\ bar = 10^5\,Pa = 0.1\,MPa = 100\ kPa$$

$$1\ atm = 101{,}325\,Pa = 101.335\ kPa = 1.01325\ bar$$

$$1\ kgf/cm^2 = 9.807\ N/cm^2 = 9.807 \times 10^4\ N/m^2 = 9.807 \times 10^4\ Pa = 0.9807\ bar = 0.96788\ atm$$

$$1\ atm = 14.696\,psi$$

$$1\ kgf/cm^2 = 14.223\,psi$$

$$1\ Pa = 2.953 \times 10^{-4}\,\text{in}\ \ Hg = 4.015 \times 10^{-3}\,\text{in water}$$

As shown in Figure 1.21, the gage pressure is measured relative to the atmospheric pressure, and the gage pressure is used to present pressures that are higher than the atmospheric pressure. The gage pressure can be calculated from the absolute pressure and the atmospheric pressure as follows:

$$P_{gage} = P_{abs} - P_{atm} \tag{1.8}$$

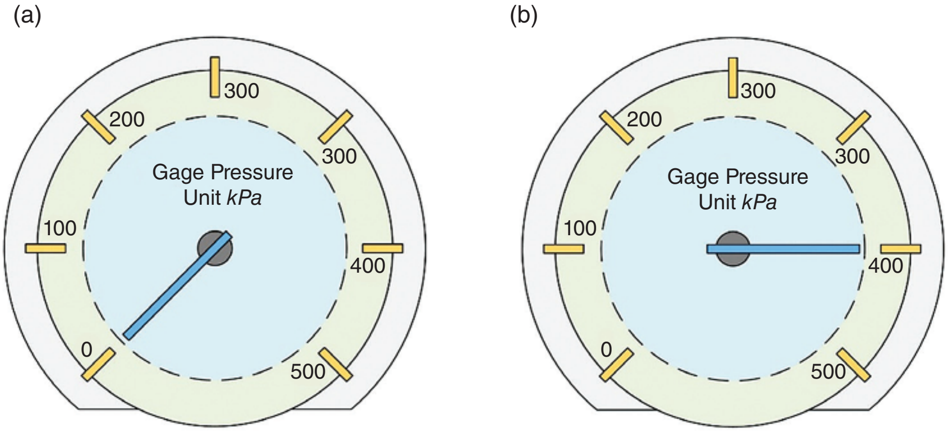


Figure 1.21 A pressure gage example (a) the gage pressure reads zero for a reading for an atmospheric pressure (b) the gage pressure reads 400 *kPa*, which is 400 *kPa* above the atmospheric pressure.

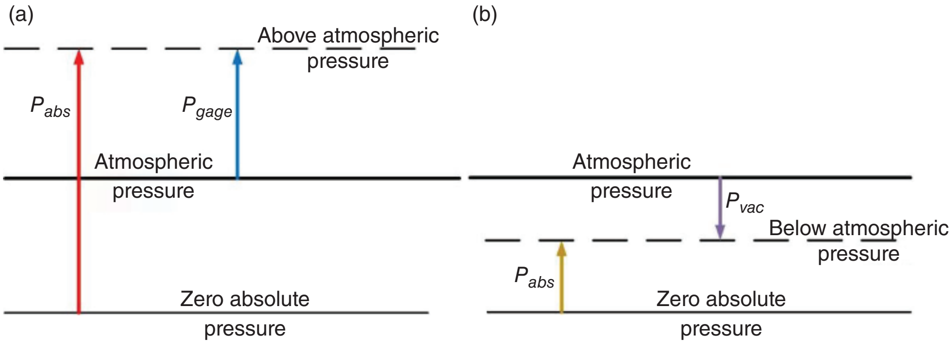


Figure 1.22 Graphical illustration of (a) the gage pressure used when the pressure is above the atmospheric pressure and (b) the vacuum pressure used when the pressure is below the atmospheric pressure.

Here, the absolute pressure is referred to as P_{abs} and it presents the actual pressure at a given point. However, pressure values that are less than the atmospheric pressure are referred to as vacuum pressure and can be calculated as follows:

$$P_{vac} = P_{atm} - P_{abs} \tag{1.9}$$

Equations (1.7) and (1.8) are graphically presented in Figure 1.22, where in Figure 1.22a the gage pressure is the absolute pressure subtracted from it the atmospheric pressure. The gage pressure is used when the absolute pressure is higher than the atmospheric pressure, while the vacuum pressure is used when the absolute pressure is lower than the atmospheric pressure as shown in Figure 1.22b.

Example 1.8 The absolute pressure in a gas container is found to equal to 50 kPa. Express the pressure of the container relative to the atmospheric pressure.

Solution

Since the absolute pressure of the gas container is lower than the atmospheric pressure, then when the gas container pressure is presented relative to the atmospheric pressure we will use Eq. (1.9), which is the vacuum pressure.

$$P_{vac} = P_{atm} - P_{abs} = 101.325 - 50 = \mathbf{51.325}\ \boldsymbol{kPa}$$

However, in a fluid the pressure varies with the depth and does not change in the horizontal direction as gravity is in the vertical direction. The pressure variation in a fluid as a function of the depth is calculated as follows:

$$P_{abs}(h) = P_{atm} + \rho g h \tag{1.10}$$

or

$$P_{gage}(h) = \rho g h \tag{1.11}$$

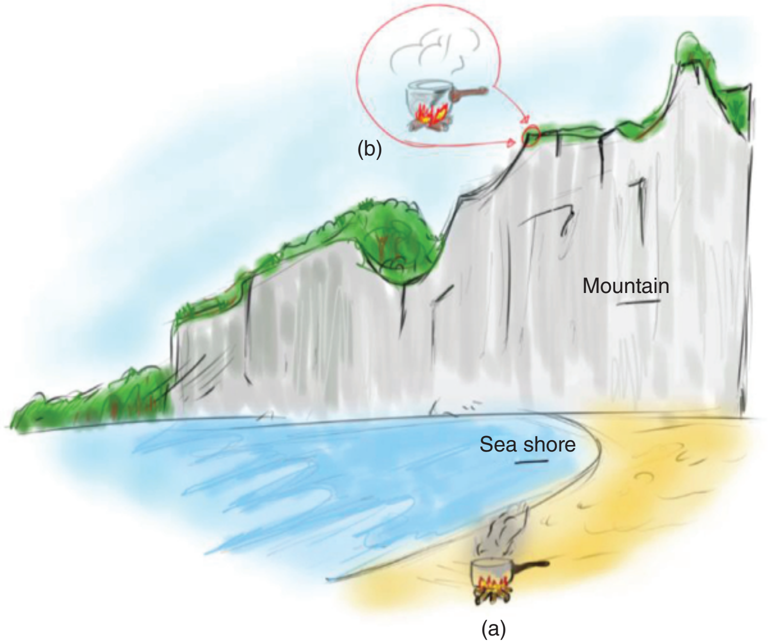


Figure 1.23 Cooking a chicken soup at lower elevation at (a) the sea shore is faster than on (b) the top of the mountain.

Based on Eqs. (1.10) and (1.11) the pressure in fluids varies with depth, and since the atmospheric pressure on the Earth's surface is the result of the weight of the atmosphere above a specified area on the Earth's surface, then the atmospheric pressure varies with the elevation from the Earth's surface. One should note that, as will be discussed in the next chapter, the thermophysical properties of water in liquid state vary with pressure; an example of such a property is the water boiling temperature. Cooking a chicken soup depends on the water boiling temperature, since the boiling temperature is the highest temperature one can cook in water. Since the boiling temperature depends on the pressure, then cooking at lower elevations results in faster cooking compared to cooking at higher elevation, as shown in Figure 1.23, since the boiling temperature of water increases as the pressure of the water increases.

Figure 1.24 shows that points that are at the same depth from the surface have the same pressure, for example points C and B have the same pressure, which is greater than the pressure at the points A, E, and D. Since points A and E are at the same depth then both have equal pressure, which is higher than the pressure at point D. The conclusion that was drawn from Eqs. (1.10) and (1.11) and was highlighted in Figure 1.24 has led to Pascal's principle.

Pascal's law (or Pascal's principle) highlights that the pressure in a fluid remains constant in the horizontal direction and, as a conclusion, the pressure applied to a fluid in a confined space is transmitted throughout the fluid at the same amount.

$$P_1 = P_2 \rightarrow \text{where } P = \frac{F}{A} \text{ then } \frac{F_1}{A_1} = \frac{F_2}{A_2} \tag{1.12}$$

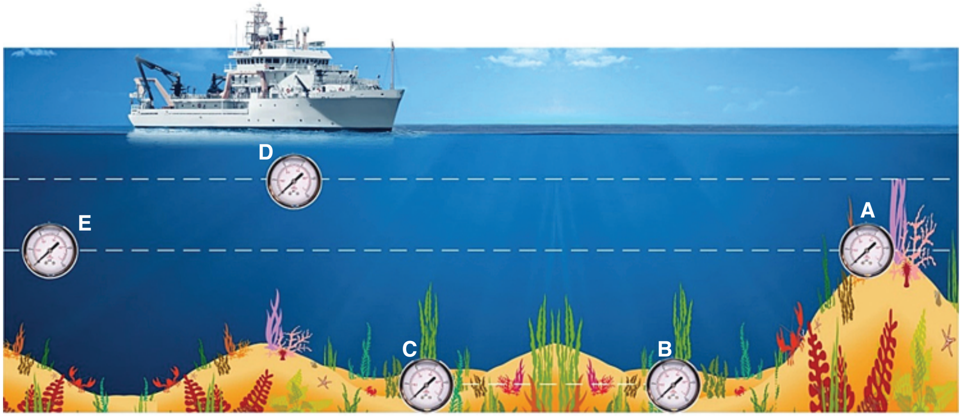


Figure 1.24 The pressure at points that are at the same depth from the free surface is equal.

Here, the subscripts 1 and 2 refers to the points in Figure 1.25, F refers to the force exerted on the piston, and A is the area of the piston.

Figure 1.25 shows an example of Pascal's principle, which uses the fact that if there are two points at the same height that are connected within the same fluid domain, they have the same pressure. In this case, a man standing on the side (at point 2), where the piston cross-sectional area is A_2 with a pressure of P_2, will be able to lift a much heavier group of containers sitting on the piston (at point 1) with a cross-sectional area of A_1 at pressure P_1.

Example 1.9 The lift shown in Figure 1.25 is designed to lift a number of containers that weigh 1590 *kg* and sit on a piston with an area of 15 m^2. Calculate the mass that needs to be used on piston 2, which has an area of 0.1 m^2, to lift these containers.

Solution

Based on the Pascal's principle:

$$P_1 = P_2 \rightarrow \frac{F_1}{A_1} = \frac{F_2}{A_2}$$

$$\frac{1590\ kg \times 9.81\, m/s^2}{15\ m^2} = \frac{F_2}{0.1\ m^2}$$

$$F_2 = 103.99\ N = m \times 9.81\ m/s^2$$

$$\boldsymbol{m_2 = 10.6\ kg}$$

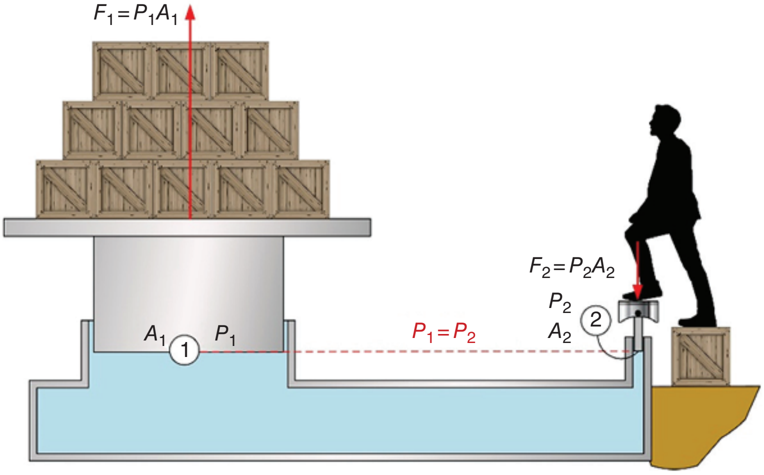


Figure 1.25 By using Pascal's principle many containers are lifted with a small force being applied at point 2, which has a small area.

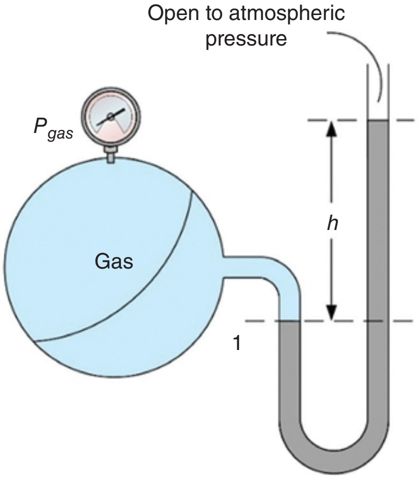
- **Manometer**

One of the most commonly used pressure measuring devices is the manometer, which is employed to measure the pressure difference through the height of a fluid column. Manometers are often made of a glass or plastic U-tube containing one or more type of fluids that vary in density. Materials that will be encountered in this book are mercury, water, oil, and alcohol; however, mercury is often the fluid of choice in such devices aiming to maintain a small and a compact manometer because of its density, which is 13.6 times higher than that of water. Figure 1.26 shows a basic one link manometer is used to measure the pressure of a gas tank.

As shown in Figure 1.26, the pressure in the gas spherical tank can be expressed in terms of the height of the fluid column filling up the manometer tube as follows:

$$P_1 = P_2 = \rho gh + P_{atm} \tag{1.13}$$

Figure 1.26 A basic manometer.



where the absolute pressure P_1 is calculated by summing the pressure produced by the column of fluid filling the manometer tube and the pressure of the atmosphere acting on the free surface of the tube fluid open to the atmosphere. However, the gage shown in Figure 1.26 measures the gage pressure, which is calculated as follows:

$$P_1 - \rho gh = P_{atm} \rightarrow P_{gas} = P_{1,gage} = P_1 - P_{atm} = (\rho gh + P_{atm}) - P_{atm} = \rho gh \tag{1.14}$$

Although the manometer shown in Figure 1.26 is a simple/basic one, there are manometers in a more complicated manner with multiple tubes, as illustrated in Figure 1.27.

⇒ Remember

There is a basic rule in solving these manometer pressure problems:

a) if we go above the sea level, we subtract hydrostatic pressure (ρgh), but
b) if we go below the sea level, we add hydrostatic pressure (ρgh).

This is illustrated in Figure 1.28.

Based on the manometer system given in Figure 1.27, one may need to find the pressure after going through the solution methodology to write the pressure balance equation:

$$P_1 - \rho_A gh_1 - \rho_B gh_2 + \rho_C g(h_1 + h_2) - \rho_D g(h_3 + h_4 + h_5) = P_{atm}$$

which comes out of the following steps:

Step 1: Start with the point assigned in the system (usually preferable to start with the gas container pressure), which is point 1 in Figure 1.27. Note that the pressure variation with depth is negligible in the case where the fluid is the gaseous state, which means the pressure in the gas container is equivalent to the pressure at point 1.

Step 2: Write the pressure for each fluid or segment. While moving through the tubes as a maze, for each segment that has a height h and constant density (constant fluid) a ρgh is added to the pressure selected in step 1 if the you are going down the tube segment while

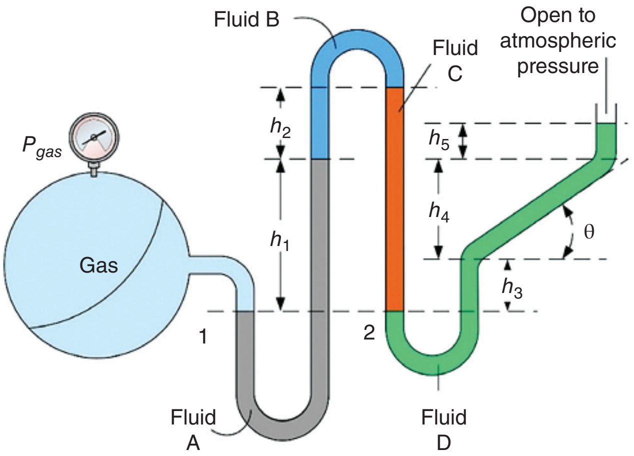


Figure 1.27 An advanced manometer with four different types of fluid, where each has a different density.

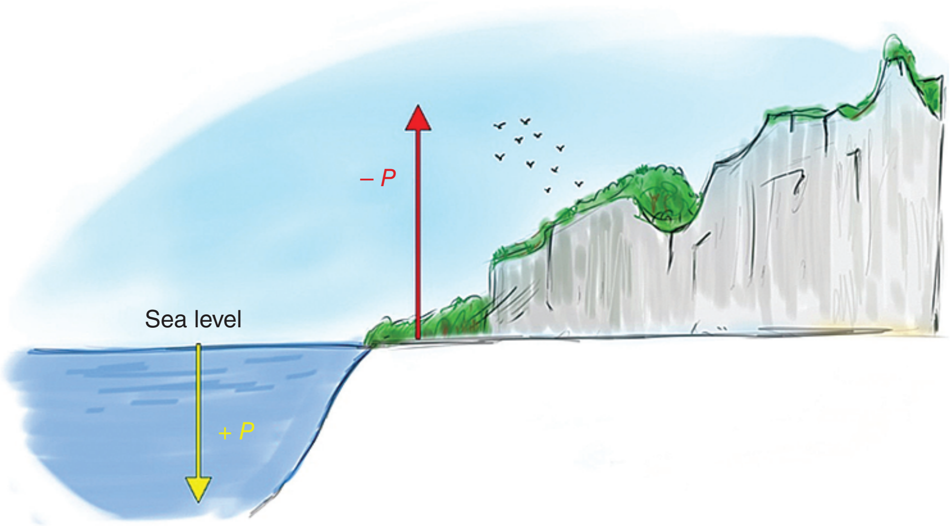


Figure 1.28 Illustration of how pressure will be taken into account based on the reference level (i.e., sea level): going down is positive, as we sum, which is illustrated with +P and going up is negative, as we subtract, which is illustrated with −*P*.

solving the maze; a ρgh is subtracted if you are moving up the tube segment while solving the maze. In this regard, we go down to the bottom and make a U turn up to point 2 where the pressure will remain the same since there is no elevation difference. After going beyond point 2, the pressure becomes $P_1 - \rho_A g h_1$ for fluid A.

Step 3: In a similar fashion, the pressure becomes $P_1 - \rho_A g h_1 - \rho_B g h_2$ for fluid B.

Step 4: The pressure becomes $P_1 - \rho_A g h_1 - \rho_B g h_2 + \rho_C g(h_1 + h_2)$ for fluid C.

Step 5: In a similar fashion, the pressure becomes

$$P_1 - \rho_A g h_1 - \rho_B g h_2 + \rho_C g(h_1 + h_2) - \rho_D g(h_3 + h_4 + h_5)$$

since the vertical heights are only consider in writing the balance equation.

Step 6: It finally reaches the last point where it is open to the atmosphere where the total pressure is equivalent to the atmospheric pressure as follows:

$$P_1 - \rho_A g h_1 - \rho_B g h_2 + \rho_C g(h_1 + h_2) - \rho_D g(h_3 + h_4 + h_5) = P_{\text{atm}}$$

Example 1.10 There are two pipes in a system connected by a double U-tube manometer as shown in Figure 1.29 where the brine pipe is connected to a tank filled with different fluids. Oil and brine are flowing in parallel horizontal pipelines. The pressure at the center of the oil pipe is 200 kPa. Take the density of water is 1000 kg/m^3.

a) Write the pressure balance equation between points 1 and 2.
b) Find the pressure at point 2.
c) Write the pressure balance equation between points 2 and 3.
d) Find the pressure of point 3.

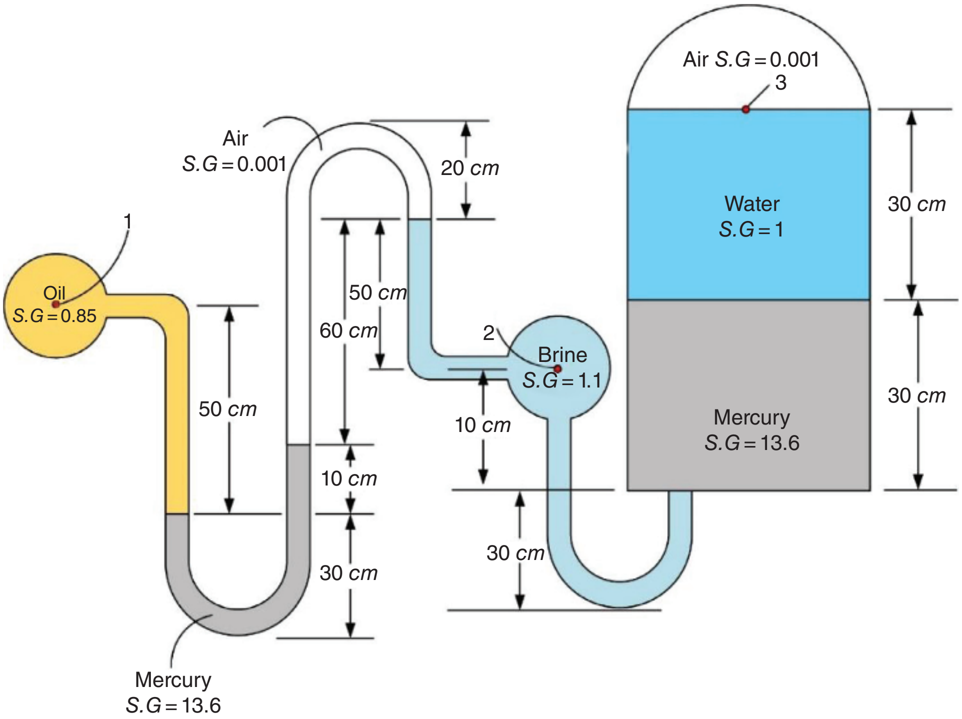


Figure 1.29 Graphical illustration of the system discussed in Example 1.10.

Solution

a) Write the pressure balance equation between points 1 and 2

$$P_1 + \rho_o g(0.5) - \rho_m g(0.1) - \rho_a g(0.6) + \rho_B g(0.5) = P_2$$

b) Find the pressure at point 2

$$200\ kPa \times \frac{1000\ \text{Pa}}{1\ kPa} + 850\,\frac{kg}{m^3} \times 9.81\,\frac{m}{s^2} \times (0.5\ m) - 13600\,\frac{kg}{m^3} \times 9.81\,\frac{m}{s^2} \times (0.1\ m)$$
$$-1\,\frac{kg}{m^3} \times 9.81\,\frac{m}{s^2} \times (0.6\ m) + 1100\,\frac{kg}{m^3} \times 9.81\,\frac{m}{s^2} \times (0.5\ m) = P_2$$

$\boldsymbol{P_2 = 196{,}217.3\ Pa}$

c) Write the pressure balance equation between points 2 and 3

$$P_2 + \rho_B g(0.1) - \rho_m g(0.3) - \rho_w g(0.3) = P_3$$

d) Find the pressure of point 3

$$196217.3\ Pa + 1100\,\frac{kg}{m^3} \times 9.81\,\frac{m}{s^2} \times (0.1\,m) - 13600\,\frac{kg}{m^3} \times 9.81\,\frac{m}{s^2} \times (0.3\ m)$$
$$-1000\,\frac{kg}{m^3} \times 9.81\,\frac{m}{s^2} \times (0.3\ m) = P_3$$

$\boldsymbol{P_3 = 154{,}328.6\ Pa}$

Figure 1.30 A snowman with some features/details to describe it.

1.9.2 State

State is defined as the condition that can be described by at least two thermodynamic properties (or sometimes one property and some information such as saturated liquid or saturated vapor type would be sufficient). The state properties may either be measured or calculated at the respective state points for thermodynamic analysis and calculations. For anything and hence everything around us in our daily life we always define their states by describing two to three specific details about the person to distinguish from others, such as wearing eye glasses and a hat and having mustache. These specific details are like the properties provided for a system in thermodynamics. Figure 1.30 shows a drawing of a snowman with three specific details, such as magician hat, carrot nose, and winter scarf to be able to distinguish and/or describe it.

a) Equilibrium

In thermodynamics, we also deal with equilibrium states, which refer to a state of balance since there are no driving forces or unbalanced potentials within the system that might drive the system to change state by changing properties. There are different modes or types of thermodynamic equilibriums; for example:

- Thermal equilibrium is a state where the same temperature is reached throughout the entire system. Figure 1.31 shows two cases. The first one (Figure 1.31a shows no thermal equilibrium while the second (Figure 1.31b shows thermal equilibrium within the system at the same, uniform temperature. Note that both system and its surroundings may also reach thermal equilibrium if they have the equivalent temperatures.

There are also numerous other types of equilibrium, ranging from mechanical to chemical types as briefly listed below:

- Mechanical equilibrium is defined as a state where the system has the same pressure throughout and does not change during the process.
- Phase equilibrium is defined as a condition where the system has reached the same phase, such as liquid or vapor, that does not change during the process.

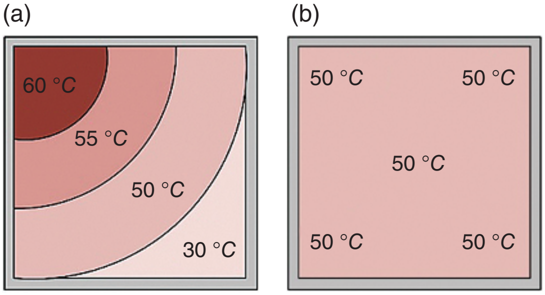


Figure 1.31 Graphical illustrations of (a) a system which is not in thermal equilibrium and (b) a system which has reached thermal equilibrium.

- Chemical equilibrium is defined as a state where the system has uniform chemical composition that does not change during the process.

Note that a quasi-static or quasi-equilibrium process is a process processing in a sufficiently slow manner that the system remains infinitesimally close to an equilibrium state at all times.

For a system where there are no electrical, gravitational, magnetic, motional, and surface tension effects, it is referred to as simple compressible system and the state of such system can be completely described by specifying two independent intensive properties. A final note on the equilibrium is that a system will not be in equilibrium unless all the relevant equilibrium criteria are satisfied.

1.9.3 Process

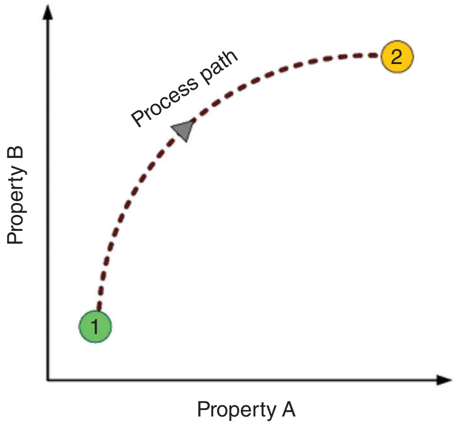
Process is defined as a change from one state point to another state point for a chosen system to study. There are many processes in thermodynamics, for example:

- isothermal (constant temperature) process
- isobaric (constant pressure) process
- isochoric (constant volume) process
- isenthalpic (constant enthalpy) process
- isentropic (constant entropy) process
- adiabatic (no heat transfer) process

Shown in Figure 1.32 is an example to illustrate a process from state 1 to state 2 on a thermodynamic diagram, which is a useful method to present a process especially for a common two-coordinate system in x and y (here x refers to property A and y refers to property B), such as pressure, temperature, volume, enthalpy, and entropy. Since the process is treated as a path function, some paths can take the system from one equilibrium state to another while having the temperature of the system remaining constant, such process is called an isothermal process. The system can also go from one equilibrium state to another while having a constant volume, such process is called an isochoric process, whereas if the system changed its state while having a constant pressure then the process is referred to as an isobaric process.

In addition, Figure 1.33 shows the four types of configurations as illustrated by two types of closed and two types of open systems. Figure 1.33a shows a closed system with a fixed

Figure 1.32 An illustration of a process between state points 1 and 2.



amount of mass within the system where there is no mass flow crossing the boundary while Figure 1.33b exhibits a closed system with moving boundary. In both these systems there are energy (heat and work) transfers crossing the boundary. The other two illustrations (Figure 1.33c and d) show open systems with mass flows and energy transfers crossing the boundary.

A process can be defined as a system going from one state to another, where a system is a quantity of matter or a region in space chosen for analysis and study, while this quantity of matter or region in space can be fixed or it can move and accelerate. Figure 1.30 shows the definition of a system as described earlier. Note that as shown Figure 1.30 a system is often bounded and separated from what is outside the system by a real or an imaginary line referred to as the boundary. Everything else outside the boundary is referred to as the surroundings.

a) Steady-state Steady-flow and Uniform-state Uniform-flow Processes

When we deal with systems, we need to look at the processes and see how the properties behave during these processes. This is especially important if open systems are considered for investigation and when there will be two types of processes, such as steady-state steady-flow (SSSF), where the properties within the system do not change with time and become

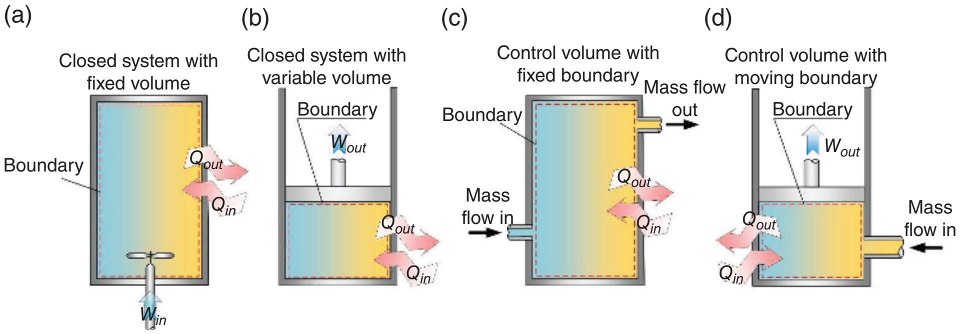


Figure 1.33 Four types of systems in closed and open forms.

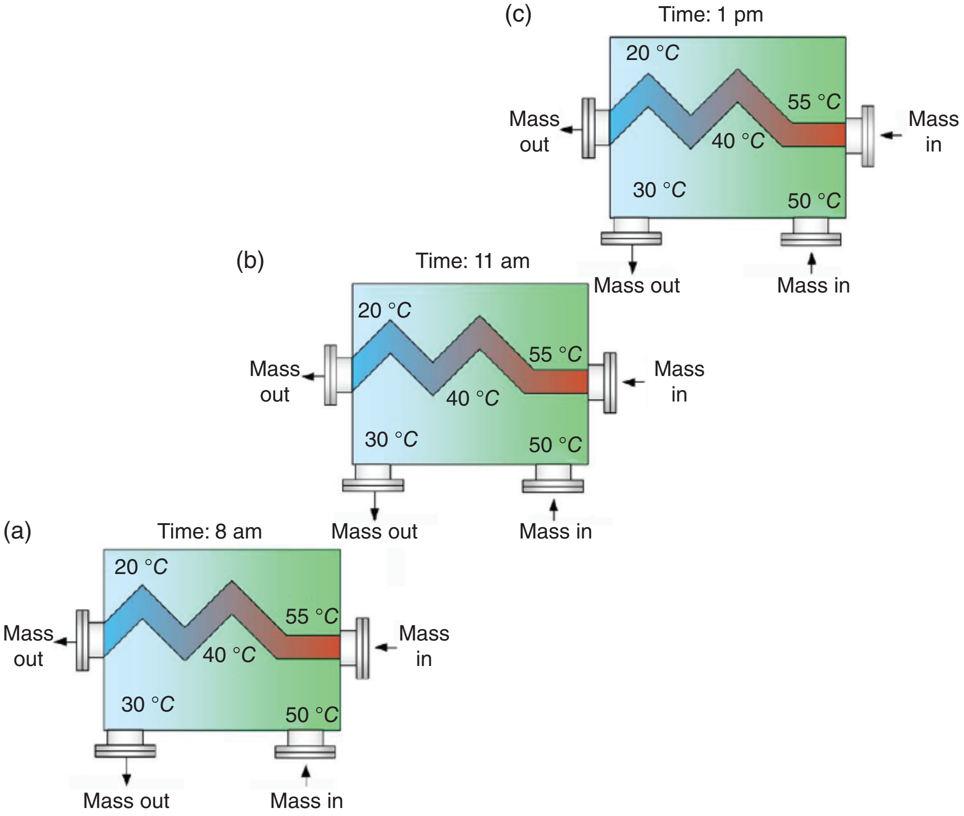


Figure 1.34 Illustration of a steady-state steady-flow (SSSF) process for an open system at various times (a) 8:00 a.m., (b) 11:00 a.m., and (c) 1:00 p.m. where there are mass flows cross the boundary.

steady state, and uniform-state uniform-flow (USUF), where the properties and mass within the system change with time and become time dependent (i.e. transient). Figure 1.34 shows an SSSF open system where we have the incoming and outgoing mass flow rates remaining the same and the temperatures at various points within the system remaining the same as time progresses from 8 : 00 a.m. until 1 : 00 p.m.

Figure 1.35 shows a typical USUF process where one has a container filled with water over time, which becomes time dependent (unsteady) since the mass within the system increases from 8:00 a.m. to 1:00 p.m. Such examples are very common in daily life where we see filling and discharging tanks, containers, reservoirs, etc. We will further elaborate on these systems along with examples in the forthcoming chapters.

1.9.4 Cycle

A thermodynamic cycle is defined as the operation of coming back to the original starting state point, after going through a number of processes, to achieve generating the desired output. Thermodynamically, we need a minimum of two processes to be able to complete a cycle (Figure 1.36). In thermodynamic there is nothing fishy! Everything is logical. Here is

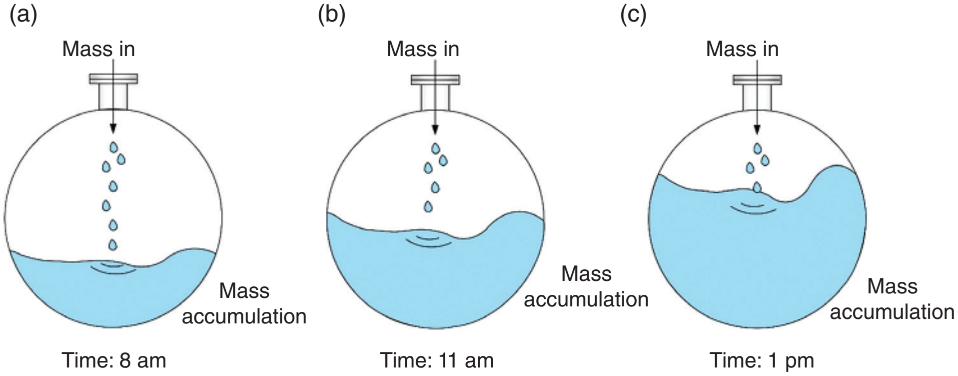


Figure 1.35 Illustration of a uniform-state uniform-flow (USUF) process for an open system at various times (a) 8:00 a.m., (b) 11:00 a.m., and (c) 1:00 p.m. where there is mass accumulation over time within the system.

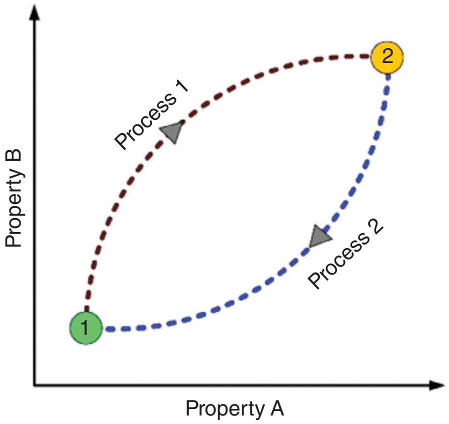
an observation: there is a need for two properties to define a state point, two state points to define a process, and two processes to define a cycle, respectively.

Note that most of the basic power and refrigeration cycles, in addition to Carnot cycles, consist of four processes to make a cycle. Figure 1.37a shows a cycle where there are four processes on a property diagram, while Figure 1.37b is a T-s diagram of a Carnot heat engine cycle (which is treated as an ideal, reversible cycle) that consists of two isothermal processes (1–2: isothermal expansion and 3–4: isothermal compression) and two isentropic processes (2–3: isentropic expansion and 4–1: isentropic compression).

1.9.5 First Law of Thermodynamics

The FLT is recognized as one of the fundamental guiding laws of life, which is the principle of conservation of energy. The conservation of energy principle states that energy cannot be created nor destroyed, but it can just change from one form to another. The FLT has been

Figure 1.36 A property diagram of a cycle consisting of two processes.



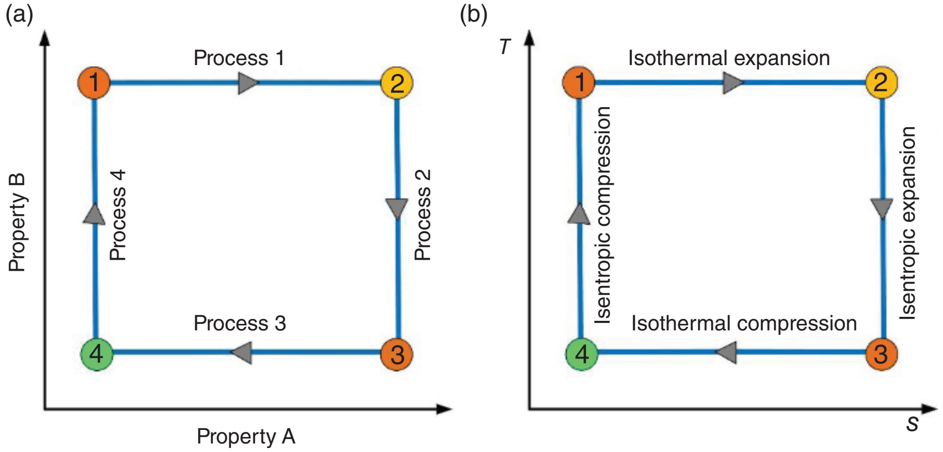


Figure 1.37 Illustration of (a) a cycle with four processes on a property diagram and (b) a Carnot heat engine cycle with four processes.

extensively used for design and analysis of energy systems as it maintains the energy balance and keeps track of all energy interactions. The FLT can then be expressed as follows:

$$E_{in} - E_{out} = \Delta E_{system} \tag{1.15}$$

Here, the subscripts in and out refer to the energy interactions crossing the system boundary into and out of the system domain. If the system operates as a steady-state process, then Eq. (1.15) can reduce to:

$$\dot{E}_{in} = \dot{E}_{out} \tag{1.16}$$

The dot above the energy symbol (E) refers to a rate property. Note that the system does not gain or lose energy, meaning that the rate change of the energy of the system equal to zero.

Since energy is introduced as the fifth step in the seven-step approach, we will have two forms of energy, namely heat and work, to talk about in thermodynamics. These are thoroughly discussed in subsequent chapters.

One of the forms of energy is heat that transfer from one body to another based on the temperature of each of the two bodies, which means the temperature difference is the driving force of the heat transfer. For example, when a body gains a total of 10 kJ of heat then we can present this as:

$$Q_{in} = 10\,kJ = mc_p(T_2 - T_1) \tag{1.17}$$

Here, Q is the heat, c_p is the specific heat capacity of the body being heated, and T is the temperature of the body, with subscript 1 for initial and subscript 2 for final state. Note that Eq. (1.17) is known as a simplified form with assumptions for a specific case.

Another common form of energy is work, and there are generally two types of work considered in thermodynamics, namely (i) boundary movement work (such as compression and expansion processes in piston–cylinder mechanisms) and (ii) shaft work (such as rotating machineries, like a pump). Some simple examples are given here and details are discussed later within specific sections.

Example 1.11 A tea glass with approximately 175 g of tea initially at a temperature of 80 °C losses heat to the surrounding air in a room temperature of 25 °C as shown in Figure 1.38. Calculate the amount of heat lost to surrounding air to be able to reach the surrounding air temperature. Consider tea with sugar specific heat capacity $c_p = 2000\ J/kg\,^\circ C$.

Solution

The amount of heat lost to the surrounding air to be able to reach the surrounding air temperature:

$$\dot{E}_{in} = \dot{E}_{out}$$

$$m_{tea} c_p T_{initial} = m_{tea} c_p T_{final} + Q_{loss}$$

$$0.175\ kg \times 2 \frac{kJ}{kg\,^oC} \times 80\,^oC = 0.175\ kg \times 2.0 \frac{kJ}{kg\,^oC} \times 25\,^oC + Q_{loss}$$

$$Q_{loss} = 0.175\ kg \times 2 \frac{kJ}{kg\,^oC} \times (80\,^oC - 25\,^oC)$$

$$\boldsymbol{Q_{loss} = 19.25\ kJ}$$

Figure 1.38 Tea glass at a temperature 80 °C loses heat to the surrounding air at a temperature of 25 °C.

Example 1.12

One kilogram of warm milk, as shown in Figure 1.39, at a temperature of 60 °C is cooled by stirring resulting in a heat loss of 100 kJ from the milk to its surroundings to reach a temperature of 25 °C. Calculate the work input to the stirrer to achieve the required cooling. Consider milk specific heat capacity $c_p = 4180 \dfrac{J}{kg\,^oC}$

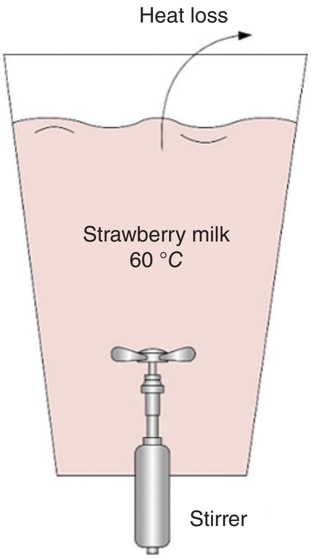


Figure 1.39 Warm milk being cooled by stirring.

Solution

The amount of work added to the milk to enhance the cooling and achieve a heat loss of 100 kJ and final temperature 25 °C is calculated as follows:

$$m_{milk}c_pT_{initial} + W_{in} = m_{milk}c_pT_{final} + Q_{loss}$$

$$1\ kg \times 4.18\,\frac{kJ}{kg\,^oC} \times 60\,^oC + W_{in} = 1\,kg \times 4.18\,\frac{kJ}{kg\,^oC} \times 25\,^oC + 100\ kJ$$

$$W_{in} = kg \times 4.18\,\frac{kJ}{kg\,^oC} \times (25\,^oC - 60\,^oC) + 100\ kJ$$

$$\boldsymbol{W_{in} = -46.3\ kJ}$$

1.9.6 Second Law of Thermodynamics

The SLT is considered the most significant law of thermodynamics for practical systems and applications. Without this law, nothing can easily and truly be explained in the universe. The SLT is about several critical things, such nonconservation of available energy, irreversible behavior, entropy generation, exergy destruction, etc.

While the FLT brings energy analysis as a solution methodology for analysis and energy efficiency for system performance assessment, the SLT offers both entropy and exergy analyses for all irreversible, practical systems and applications in order to better design and analyze and exergy efficiency for a true system performance assessment. In order to analyze any system one must write balance equations for mass, energy, entropy, and exergy after placing the system boundary and identifying all inputs and outputs. These balance equations will be introduced later for different types of systems, including closed and open systems.

The SLT becomes instrumental in providing insights into environmental impact and sustainable development. The most appropriate link between the second law and environmental impact has been suggested to be exergy, in part because it is a measure of the departure of the state of a system from that of the environment. The magnitude of the exergy of a system depends on the states of both the system and the environment. This departure is zero only when the system is in equilibrium with its environment.

Energy has always been the most critical issue for humanity and is recognized as the first priority for all activities in the world. Humans started using wood as the first source of energy; this was then followed by coal, oil, natural gas and nuclear, as shown in the energy source historical ladder in Figure 1.40. We are now moving into an era where clean fuels are badly required to minimize environmental impact and increase sustainability.

Note that historically energy has been the source and cause of conflicts, wars, and peace. Since the industrial revolution, energy competition has been even stiffer. It has become more apparent that humanity needs more efficient, more cost effective, more environmentally benign, and more sustainable energy options and solutions. Such a requirement has been the main motivation behind going beyond traditional analysis methods and techniques. Traditionally, the FLT, which is recognized as the conservation law, has been the only tool comprehensively used in design, analysis, and assessment of thermodynamic systems. It is now crystal clear to everyone that the FLT is insufficient and incapable in addressing practical systems with irreversibilities (or losses, inefficiencies, etc.). That is why the SLT has been brought into the picture to account for irreversibilities or destruction through entropy and exergy. Exergy is distinguished itself to be a primary tool under the SLT.

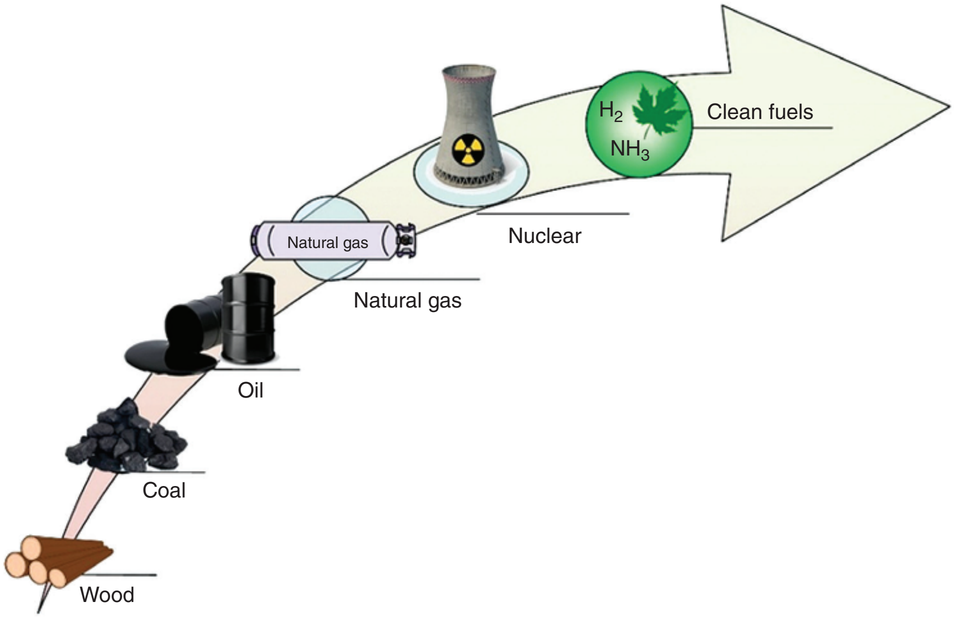


Figure 1.40 The development of energy sources throughout humanity past and present, and prediction of future sources.

Generally, thermodynamics is defined by many as the science of energy (referring to the FLT) and entropy (referring to the SLT). Here, thermodynamics is redefined as the science of energy and exergy, which makes it more correct to cover both laws of thermodynamics, make both energy and exergy quantities of the same unit consistently, and reach out two key efficiencies through energy and exergy efficiencies. This way the concepts dwell on the right pillars of practical applications. The exergy efficiency becomes important for practical systems and applications as it is a true measure of system performance and indicates how much the actual performance deviates the ideal performance.

Exergy analysis is now a recognized thermodynamic analysis technique based primarily on the SLT and appears to be the only tool for assessing and comparing processes and systems rationally and meaningfully. Consequently, exergy analysis can assist in improving and optimizing designs and analyses. Two key features of exergy analysis become more attractive, such that (i) it determines the true locations, types, and magnitudes of irreversibilities, losses, destruction and inefficiencies, and (ii) it identifies the potential for a system to be more efficient.

1.9.7 Performance Assessment

In thermodynamics, the description of an energy conversion system is usually followed by an appropriate efficiency definition of the system. A concentrated study of thermodynamics may be accomplished by the study of various efficiencies and other performance criteria and possible ways to improve these.

For an engineering system, efficiency, in general, can be defined as the ratio of desired output to required input.

In general, the efficiency of any system can be defined as follows:

$$Efficiency = \frac{Useful\ output}{Required\ input} \tag{1.18}$$

The above general efficiency definition can be written in more specific form for an energy system as follows:

$$Energy\ efficiency = \frac{Useful\ energy\ output}{Required\ energy\ input} \tag{1.19}$$

In thermodynamics, the description of an energy conversion system is usually followed by an appropriate efficiency definition of the system that evaluates the system conversion performance in terms of a ratio which presents how much of the inputted energy was successfully converted to the desired form in the outputs. A concentrated study of thermodynamics may be accomplished by the study of various efficiencies and ways to increase them.

For an engineering system, efficiency, in general, can be defined as the ratio of desired output to required input.

$$\eta = \frac{Desired\ output}{Required\ input} \tag{1.20}$$

Although this definition provides a simple general understanding of efficiency, a variety of specific efficiency relations for different engineering systems and operations have been developed. Different efficiency definitions based on the first and second laws of thermodynamics have been the subject of a large number of publications. Various efficiency definitions used for common energy conversion systems is the topic of this book. Many approaches that can be used to define efficiencies are provided and their implications are discussed. This book uses a logical and intuitive approach in defining efficiencies, and it is intended to provide a clear understanding of various efficiencies used in many common energy systems. In an exception to the energy efficiency definition, the performances of heat pumps and refrigeration units are assessed using the coefficient of performance (*COP*) principle. The coefficient of performance of a heat pump and a refrigeration unit can be written respectively as follows:

$$COP_{HP} = \frac{Heat\ output}{Work\ input} \tag{1.21}$$

$$COP_{R} = \frac{Cooling\ output}{Work\ input} \tag{1.22}$$

where *COP* denotes the coefficient of performance and the subscripts *HP* and *R* denotes the heat pump and the refrigeration unit respectively. Here, heat output is obtained from the condenser for heating purposes while the cooling output is the useful output in the evaporator where both systems need work input to drive them.

a) Energy Efficiency of a Compressor

The compressor is a mechanical device that consumes power to increase the pressure of a gas. From the simple definition of the compressor that was introduced in the previous sentence and the general energy efficiency definition, the energy efficiency of a compressor can be written as follows:

$$\eta_{comp} = \frac{\dot{m}(h_{out} - h_{in})}{\dot{W}_{in}} \tag{1.23}$$

where $\dot{m}$ is the mass flow rate of the gas being compressed, $(h_{out} - h_{in})$ is the amount of specific energy that the compressed air received when it was being compressed, and $\dot{W}_{in}$ the amount of power supplied to the compressor. Note that h is a thermophysical property known as enthalpy and it will be introduced in detail in the forthcoming chapters. Similar to the above compressor energy efficiency, the energy efficiency definitions of the most common thermodynamic devices are tabulated in Table 1.4.

Table 1.4 Energy efficiency definitions of some common thermodynamic devices.

Device	Energy efficiency
Pump	$\eta_{pump} = \frac{\dot{m}(h_{out} - h_{in})}{\dot{W}_{in}}$
Turbine	$\eta_{T} = \frac{\dot{W}_{out}}{\dot{m}(h_{in} - h_{out})}$
Electric motor	$\eta_{m} = \frac{\dot{W}_{elec}}{\dot{W}_{shaft}}$

Table 1.5 Energy efficiencies of some devices and cycles.

Device	Energy efficiency (%)
Pump	85
Gas turbine	33
Screw compressor	73
Throttling valve	100
Wind turbine	38
Photovoltaic (monocrystalline)	22
Reheat Rankine Cycle	38
Combined cycle (Rankine and Brayton)	56
Automobile (gasoline)	18
Automobile (electric)	60
PEM fuel cell	55
Electric kettle	85
Thermoelectric generator	5

Table 1.5 summarizes the average energy efficiencies of devices used in day to day activities, as well as power production modules and cycles that are used to produce electricity daily. These are not of course solid numbers, but are intended to give an idea about these for practical applications.

Example 1.13 A propane fueled water heater, as shown in Figure 1.41 receives energy from the supplied propane fuel, which heats the water by burning the propane and producing heat. Then the hot water is used to heat up the house. Define the energy conversion efficiency of the propane fueled water heater and make the necessary calculations to find it.

Solution

The desired output of the propane fueled water heater is the heat the hot water provides for the house.

The required input is the amount of fuel supplied to the water heater.

Then the conversion efficiency is written as:

$$\eta = \frac{Desired\ output}{Required\ input} = \frac{(Heat\ supplied\ to\ the\ \mathrm{hot}\ water)}{(Fuel\ supplied\ to\ the\ water\ heater)}$$

The energy delivered with the fuel can be defined through the heating value of the fuel, which is the amount of heat released when a specific amount of fuel at room temperature is completely burned and the combustion products cool down to the room temperature if it is the higher heating value (*HHV*). However, for the case where the water leaves the combustion in the form of water vapor then the amount of heat released is referred to as

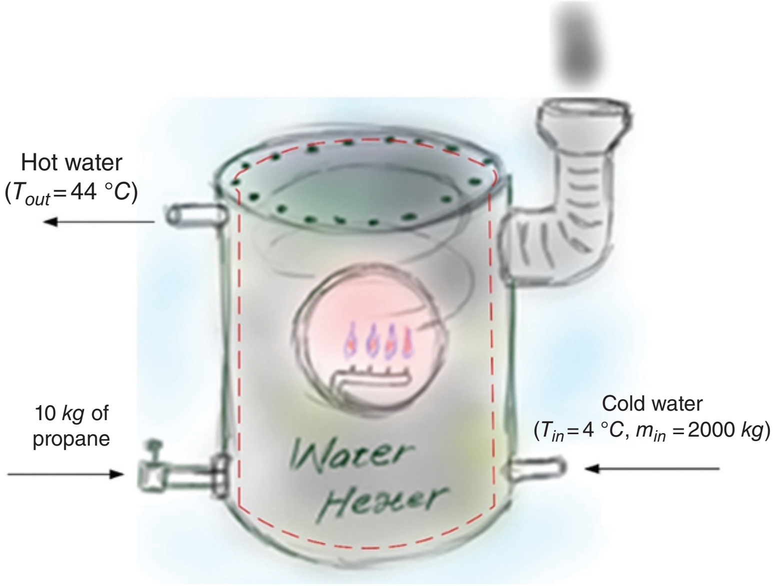


Figure 1.41 Propane fueled water heater.

the lower heating value (*LHV*). The *HHV* and the *LHV* have the unit of energy units over mass units (*kJ*/*kg* or *Btu*/*lb*). Then the above-mentioned efficiency can be presented as follows:

$$\eta = \frac{Q}{m_{propane} \times LHV_{propane}}$$

Here, *LHV* is used in the efficiency equation as the water from the combustion leaves the combustion chamber in the form of water vapor. The *LHV* of propane can be taken as 46,400 *kJ*/*kg* and the mass can be taken as 1 *kg*.

$$Q_{in} = m_{propane} \times LHV_{propane}$$

$$Q_{in} = 10\ kg \times 46{,}400\,\frac{kJ}{kg}$$

$$Q_{in} = 464{,}000\ kJ$$

One can then find the output of the system to determine the energy efficiency of the system. *Q* is defined as the output of the system, which is the heat gained by the water to reach 44 °*C*. *Q* can be defined by the following equation:

$$Q_{in} = m \times Cp \times \Delta T$$

where m is the mass of the water, *Cp* is the specific heat capacity (*kJ*/*kg* °*C*), and ΔT is the change in temperature of the water.

$$Q_{out} = 2000\ kg \times 4.2\,\frac{kJ}{kg\,^{\circ}C} \times (44-4)$$

$$Q_{out} = 336{,}000\ kJ$$

Finally, the efficiency can be calculated as follows:

$$\eta = \frac{336{,}000\ kJ}{464{,}000\ kJ}$$

$$\eta = 0.724 = 72.4\%$$

The energy efficiency of the boiler is rated at 72.4%, meaning that not all the heat was transferred to the water and/or some of the heat was lost to the surroundings.

Example 1.14 A coal fueled power plant converts 156.25 MW of coal energy into 50 MW of electrical power through three steps. Define the conversion efficiency for each step and the overall efficiency of this coal fueled thermal power plant. Note that the main energy conversion steps of the power plant, as shown in Figure 1.42, are:

Step 1: Burning the coal to generate the amount of heat needed.
Step 2: Converting thermal energy into mechanical energy through a power generating cycle.
Step 3: Converting mechanical energy into electrical power through a generator.

These three conversion steps are illustrated in Figure 1.42 with the efficiency definitions. We now follow the steps given above to finalize the solution.

Solution

The first energy conversion step converts the chemical energy to thermal energy by combustion of coal. Similar to the propane fed water heater efficiency, the first step energy conversion efficiency is written as follows:

$$\eta_{S1} = \frac{\dot{Q}_{thermal}}{\dot{E}n_{in,coal}}$$

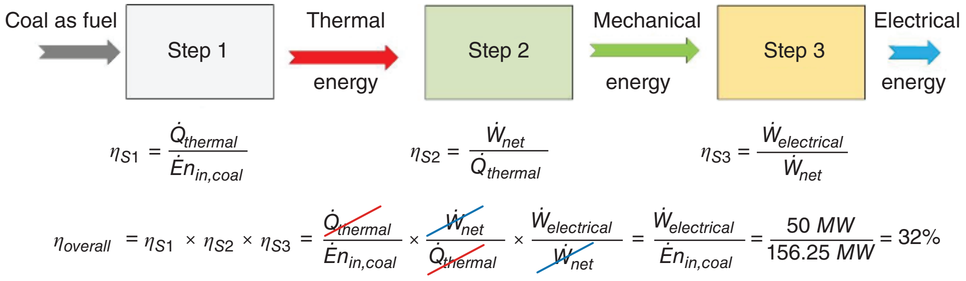


Figure 1.42 Illustration of power generation from coal with efficiencies.

The second energy conversion step converts the thermal energy to rotational mechanical energy. The second energy conversion step efficiency is written as:

$$\eta_{S2} = \frac{\dot{W}_{net}}{\dot{Q}_{thermal}}$$

Here, net refers to the rotational mechanical energy. The third and final step in the coal power plant is the conversion of rotational mechanical energy into electrical energy; its efficiency can be expressed as follows:

$$\eta_{S3} = \frac{\dot{W}_{electrical}}{\dot{W}_{net}}$$

However, by looking at the overall system, where it has a single input, coal, and a single output, which is electrical energy, then the overall system conversion efficiency is expressed as follows:

$$\eta_{ov} = \frac{\dot{W}_{electrical}}{\dot{E}n_{in,coal}}$$

Note that the overall power plant efficiency can also be presented in terms of the energy conversion efficiency of its main components or main energy conversion steps as follows:

$$\eta_{ov} = \eta_{S1} \times \eta_{S2} \times \eta_{S3} = \frac{\dot{W}_{electrical}}{\dot{E}n_{in,coal}} = \frac{50\ MW}{156.25\ MW} = \mathbf{32}\%$$

Example 1.15 This example is about how to make profit from different electricity cost in day and night as illustrated in Figure 1.43. The electricity cost during the night is \$0.06/kWh and the electricity cost during the day is \$0.12/kWh. The water volume flow rate in the system in both directions is 2 m^3/s. Assume the energy efficiency of the motor and pump combination is 100% (working during the night), whereas the energy efficiency of the turbine and generator is 90% (working during the day). Neglecting the frictional losses in the pipes and assuming that the pump and motor combination is used from 10 : 00 p.m. to 8 : 00 a.m., and the turbine and generator are used from 10 : 00 a.m. to 8 : 00 p.m, calculate the potential revenue generated by the proposed system per year.

Solution

At night:

The system consumes electrical energy, which means that the system owner is paying money to the electrical distribution company.

The total mass pumped during the 10 hours' night (10 p.m. to 8 a.m.) is calculated as follows:

$$m_{\text{tot}} = \rho_w \dot{V}(operation\ time)$$

$$m_{tot} = 1000\ \frac{kg}{m^3} \times 2\ \frac{m^3}{s} \times 10\ h \times 3600\ \frac{s}{h} = 72{,}000{,}000\ kg/day$$

Writing the energy balance equation:

$$E_{in} = E_{out}$$

$$m_{tot}gh = W_{pump}$$

$$W_{pump} = 72{,}000{,}000\,\frac{kg}{day}\times 9.81\,\frac{m}{s^2}\times 50\ m = 3.53\times 10^{10}\,\frac{J}{day}$$

The total amount of money paid during the night:

$$C_{night}2wsx = 3.53\times 10^{10}\,\frac{J}{day}\times\frac{1\,kJ}{1000\,J}\times\frac{\$0.06}{kWh}\times\frac{1\,h}{3600\,s}\times = \frac{\$588.6}{day}$$

The amount of energy recovered during the day is the same as the energy stored during the night. However, we have to consider the efficiency of the motor–turbine, which is 90% compared to 100% efficiency in motor–pump system:

$$\eta_{motor-turbine} = \frac{electrical\ power\ produced}{potential\ energy\ stored\ in\ elevated\ water}$$

$$0.9 = \frac{Electrical\ power\ produced}{3.53\times 10^{10}\ J/day}$$

$$Electrical\ power\ produced = 3.18\times 10^{10}\,\frac{J}{day}$$

$$The\ revenues = 3.18\times 10^{10}\,\frac{J}{day}\times\frac{1\,kJ}{1000\,J}\times\frac{\$0.12}{kWh}\times\frac{1\,h}{3600\,s} = \frac{\$1060}{day}$$

Then the profit per year is calculated as follows:

$$\frac{Profit}{year} = \frac{revenue}{year} - \frac{cost}{year}$$

$$\frac{Profit}{year} = \left(\frac{\$1060}{day}\times\frac{365\ days}{year}\right) - \left(\frac{\$588.6}{day}\times\frac{365\ days}{year}\right) = \frac{\$\mathbf{172,061}}{\boldsymbol{year}}$$

1.10 Engineering Equation Solver as a Potential Software

EES (pronounced “ease”) is a general equation-solving program that can numerically solve thousands of coupled nonlinear algebraic and differential equations. The program can also be used to solve differential and integral equations, do optimization, provide uncertainty analyses, perform linear and nonlinear regression, convert units, check unit consistency, and generate publication-quality plots. A major feature of EES is the high accuracy thermodynamic and transport property database that is provided for hundreds of substances in a manner that allows it to be used with the equation solving capability.

Next in this section, two examples of the use of EES in solving thermodynamics problems are presented. However, a good practice is to make sure that once a new EES window is open, as shown in Figure 1.43, the units selected to run the simulation are also

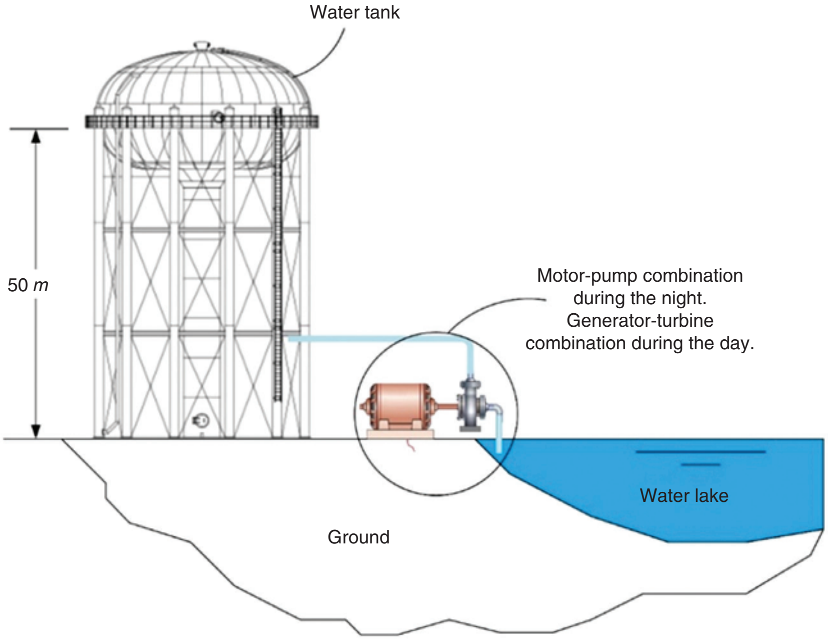
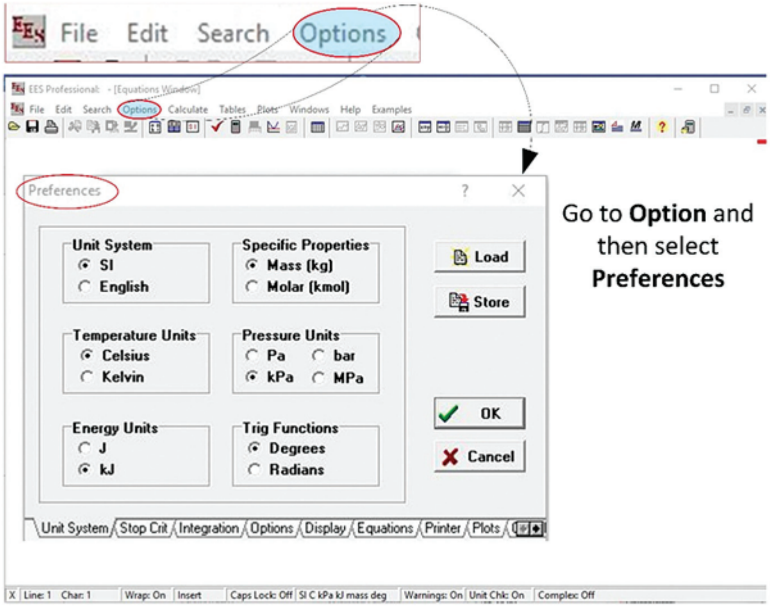


Figure 1.43 Night pumping and day turbine system.

checked as well. In order to open a file, go to file and then select from the dropdown menu new.

In order to open the window, go to options and then select unit system. The window shown in Figure 1.44 will open. After setting up the desired unit system and units, click on the OK button. Table 1.6 presents the procedure of writing Greek letters in EES accordingly.



Unit System: ● SI ○ English

Specific Properties: ● Mass (kg) ○ Molar (kmol)

Temperature Units: ● Celsius ○ Kelvin

Pressure Units: ○ Pa ○ bar ● kPa ○ MPa

Energy Units: ○ J ● kJ

Trig Functions: ● Degrees ○ Radians

Go to **Option** and then select **Preferences**

Figure 1.44 An EES window with unit system and parameter unit selection window in it.

Table 1.6 Some of the Greek letters and the corresponding EES expression.

EES expression	Corresponding Greek letter
rho	ρ
mu	μ
gamma	γ
delta (case sensitive)	δ
DELTA (case sensitive)	Δ
zeta	ζ
beta	β
alpha	α

Example 1.16 Find the following properties at the specified temperature and pressure:

a) Density of water at a temperature of 25 °*C* and a pressure of 1 *bar*,
b) Density of water at a temperature of 90 °*C* and a pressure of 101 325 *Pa*,
c) Viscosity of water at a temperature of 90 °*C* and a pressure of 101 325 *Pa*.

Solution

The following are the steps to follow to find material properties where the first two steps are shown in Figure 1.45:

a) Density of water at a temperature of 25 °*C* and a pressure of 1 *bar*:

Line 1: *T_1* = 25 [*C*]
Line 2: *P_1* = 1∗*convert*(*bar*,*Pa*)
Line 3: *Rho_1* = *density*(*water*,*T* = *T_1*,*P*=*P_1*)

The density at the previous mentioned temperature and pressure is equal to 997.1 kg/m^3.

b) Density of water at a temperature of 90 °*C* and a pressure of 101 325 *Pa*:

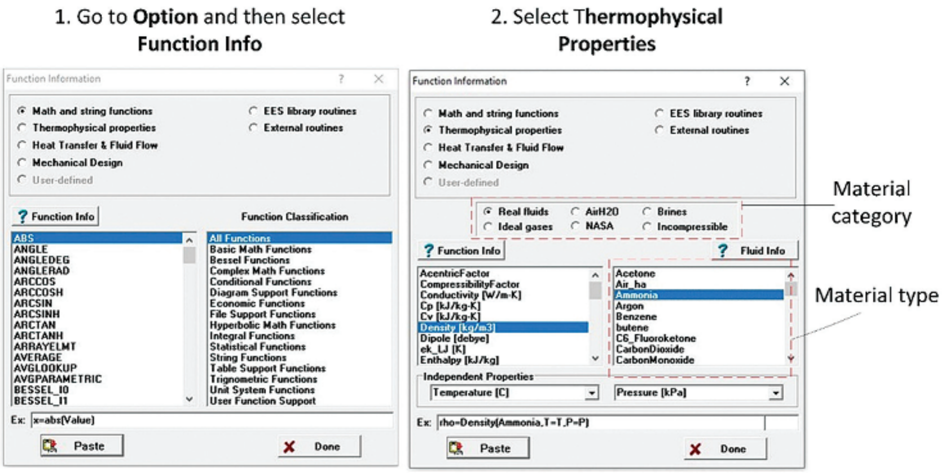
Line 1: *T_1* = 90 [*C*]
Line 2: *P_1* = 101325 [*Pa*]
Line 3: *Rho_1* = *density*(*water*,*T* = *T_1*,*P*=*P_1*)

The density at the previous mentioned temperature and pressure is equal to 1038 kg/m^3.

c) Viscosity of water at a temperature of 90 °*C* and a pressure of 101 325 Pa:

Line 1: *T_1* = 90 [*C*]
Line 2: *P_1* = 101325 [*Pa*]
Line 3: *mu_1* = *viscosity*(*water*,*T* = *T_1*,*P*=*P_1*)

The viscosity at the previous mentioned temperature and pressure is equal to 0.0008903 kg/ms.



1. Go to **Option** and then select **Function Info**

2. Select **Thermophysical Properties**

Ex: x=abs(Value)

Ex: rho=Density(Ammonia,T=T,P=P)

Figure 1.45 The first two steps in the solution in Example 1.16.

1.11 Closing Remarks

This introductory chapter has discussed energy and its importance, thermodynamic fundamentals and basic definitions, a seven-step approach in teaching thermodynamics, thermodynamic laws and performance assessment, and it has provided numerous examples to better understand the concept and recognize the systems and applications from the thermodynamic perspectives.

Study Questions/Problems

This section contains practice questions and problems, including short answer questions, proof questions, true, and false, multiple choice and calculation problems.

a) Concept

1 Although the zeroth law of thermodynamics was introduced after the first and second laws of thermodynamics, it was referred to as the zeroth law, explain why?

2 Which thermodynamics law considers the quality as well as the quantity of energy?

3 Provide an example where the quality of energy is important not just the quantity.

4 Prove that dividing the volume of a system (an extensive property) over the mass of the same system will provide us with an intensive property called the specific volume. (Hint: you can use the dividing space example.)

5 Which feels colder for a bare human touch, a metallic chair or a wooden chair in an ambient temperature space, or will they both feel the same, and why?

6 Provide the definition of energy efficiency and discuss its basic foundation for thermal power plant.

7 Write energy efficiencies for both pump and turbine and discuss the key difference between them.

8 Describe both extensive and intensive properties and compare them at least with three examples.

9 Explain why 3C rule is important.

10 Explain why seven step approach is important in thermodynamics.

b) True or False Type Questions

1 Thermodynamics is the science of energy and entropy.

2 Thermodynamics is the science of energy and enthalpy.

3 FLT considers both the quantity as well as the quality of energy.

4 Based on the FLT, the amount of energy available is constant and will never change.

5 You need a minimum of three independent properties in order to fully define a state.

6 You need a minimum of four processes to make a cycle.

7 One property is enough to define the state of a thermodynamic system.

8 Temperature is an intensive property.

9 Properties that are independent of the size of the system are called extensive properties.

10 Energy cannot be created nor destroyed, however exergy can be destroyed.

c) Multiple Choice Type Questions

1 If objects A and B are in thermal equilibrium with object C, and object C is at 100 $^\circ C$, then the temperature of objects A and B are:

- **a** 50 $^\circ C$ and 50 $^\circ C$.
- **b** 100 $^\circ C$ and 100 $^\circ C$.
- **c** It is impossible to determine since it depends on the sizes of objects A, B, and C.
- **d** It is impossible to determine since it depends on the sizes of objects A and B.
- **e** It is impossible to determine since it depends on the size and material.

2 Which of the following is the hottest?

- **a** 80 $^\circ C$ cup of coffee.
- **b** 100 $^\circ F$ cup of milk.
- **c** 273 K water.
- **d** 400 R metallic structure.

3 Why does a bicyclist pick up speed on a downhill road even when he is not pedaling?

- **a** The PE is converted to KE.
- **b** The KE is converted to PE.
- **c** This should not happen since it is a violation of the conservation of energy principle (FLT).
- **d** The mass of the bicyclist is converted into a KE since the bicyclist is loosing weight.
- **e** The bicyclist is picking up speed since $KE = \frac{1}{2} mv^2$.

4 People living in the mountains develop lungs with a volume:

- **a** Larger than those living at low elevation.
- **b** Smaller than those living at low elevation.
- **c** The same as those living at low elevation.

5 Why when vehicle tires have a hole in them, does air comes out of the tires?

- **a** Because the pressure inside the tires is higher than the atmospheric pressure.
- **b** Because the pressure inside the tires is lower than the atmospheric pressure.
- **c** Because the tires are made of rubber and the rubber is squeezing the air out.
- **d** Because the vehicle is heavy and it squeezes the tires to release the air out.
- **e** Air will not come out, the air someone feels is just an external air circulation.

6 Energy can not be created nor destroyed it can be converted from one from to another, is the definition of the:

- **a** FLT
- **b** SLT
- **c** Zeroth law of thermodynamics
- **d** Third law of thermodynamics
- **e** Fourth law of thermodynamics.

7 A rock falling from a certain elevation above the ground is an example of the:

- **a** FLT
- **b** SLT
- **c** Zeroth law of thermodynamics
- **d** Third law of thermodynamics
- **e** Fourth law of thermodynamics.

8 Why would a cyclist pick up speed as they are going downhill even when he/she is not pedaling?

- **a** Due to the conversion of *PE* to *KE*.
- **b** Due to the conversion of *KE* to *PE*.
- **c** It will never happen because it is violating the FLT.
- **d** It will never happen because it is violating the SLT.

9 A student claims that a cup of coffee on his/her table warmed up to 80 °*C* by picking up energy form the surrounding air, which is at 25 °*C*.

- **a** It will never happen because it is violating the SLT.
- **b** It will never happen because it is violating the FLT.
- **c** Due to the conversion of *PE* to *KE*.
- **d** Due to the conversion of *KE* to *PE*.

10 Thermodynamics is the science of

- **a** Energy and exergy
- **b** Energy and entropy
- **c** Exergy and entropy
- **d** Enthalpy and energy
- **e** None of the above.

11 Which of the following is not listed on the seven-step approach?

- **a** Zeroth law of thermodynamics
- **b** FLT
- **c** SLT
- **d** State
- **e** Property.

12 Which of the following is systems is not a thermodynamics system?

- **a** Ordinary
- **b** Open
- **c** Closed
- **d** Controlled mass
- **e** Controlled volume.

13 A system boundary is:

- **a** A real surface
- **b** An imaginary surface
- **c** A surface that separate the system from its surroundings

- **d** A surface with zero thickness
- **e** All of the above.

14 The Carnot cycle includes
- **a** Two isentropic and two isothermal processes
- **b** Two isenthalpic and two isentropic processes
- **c** Two isobaric and two isenthalpic processes
- **d** None of the above

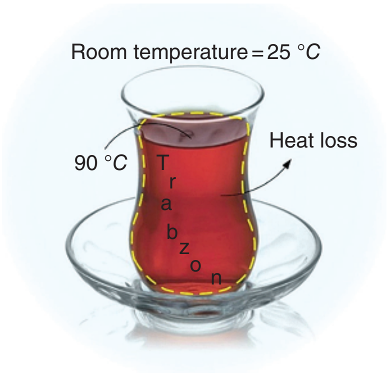
15 The temperature change in Celsius is equivalent to the temperature change in:
- **a** Rankine
- **b** Fahrenheit
- **c** Kelvin
- **d** None of the above

d) Problems

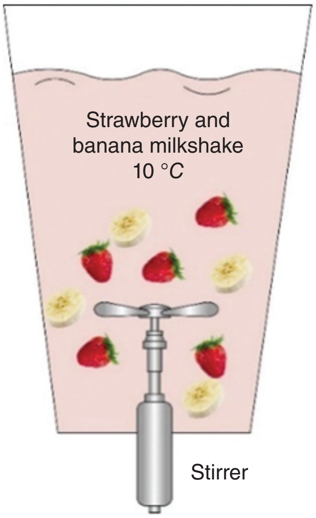
1 Calculate the temperature of a 50 $^\circ C$ cup of coffee in:
- **a** Rankine (R)
- **b** Kelvin (K)
- **c** Fahrenheit ($^\circ F$).

2 An oil fed power plant converts 160 MW of oil into 55 MW of electrical power through various steps. The main energy conversion steps of the power plant are (starting from the component receiving the oil and ending up with the production of electricity):
- Chemical energy to thermal energy.
- Thermal energy to mechanical energy.
- Mechanical energy to electrical energy.

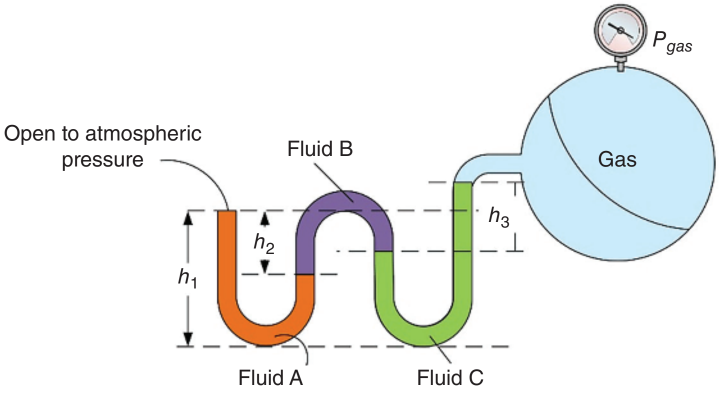
3 A tea glass with 175 g of tea initially at a temperature of 90 $^\circ C$ losses heat to the surrounding air in a room at a temperature of 25 $^\circ C$. Calculate the amount of heat lost to the surrounding air to be able to reach the surrounding air temperature. Consider tea with sugar specific heat capacity $c_p = 2000\ \frac{J}{kg\,^oC}$



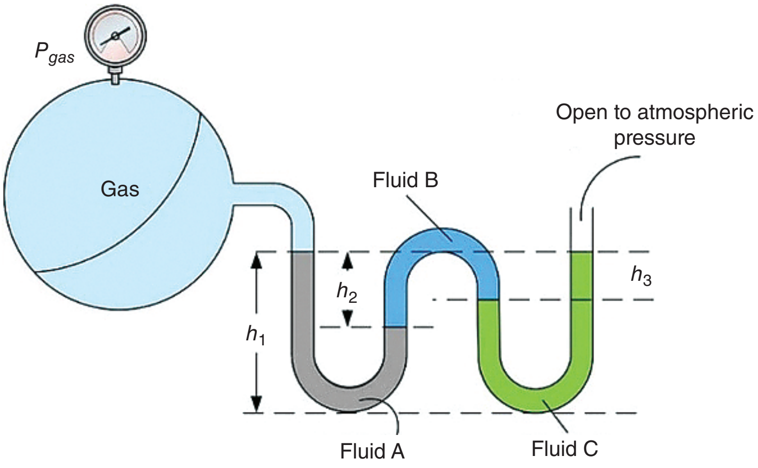
4 1 kg of cold milk at a temperature of 10 °C is mixed with strawberries and bananas. Calculate the work input without increasing the temperature of the milkshake. Consider milk specific heat capacity $c_p = 4180\ \frac{J}{kg\ ^oC}$ and the masses of strawberry and banana as 0.5 kg each.



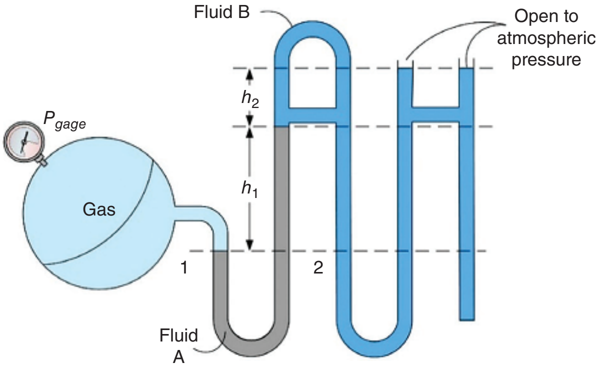
5 Calculate the gage pressure of the spherical tank when fluid A is mercury ($\rho_{Hg} = 13600\ kg/m^3$), fluid B density is $\rho_B = 900\ kg/m^3$, and fluid C has a density of $\rho_C = 760\ kg/m^3$, and if $h_1 = 10\ cm$, $h_2 = 5\ cm$, and $h_3 = 6\ cm$. Take the difference in higher and lower levels of fluid B as 1 cm.



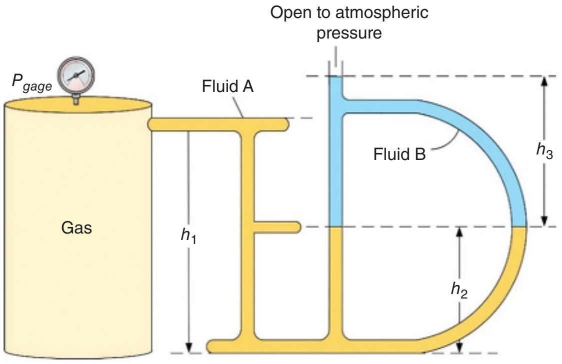
6 What is the gage pressure of the gas tank that is connected the manometer as shown below if the heights values are $h_1 = 10\ cm$, $h_2 = 5\ cm$, and $h_3 = 2\ cm$, where fluid A is mercury with a density of $13\,600\ kg/m^3$, fluid B is water with a density of $1000\ kg/m^3$, and fluid C is oil with a density of $760\ kg/m^3$:



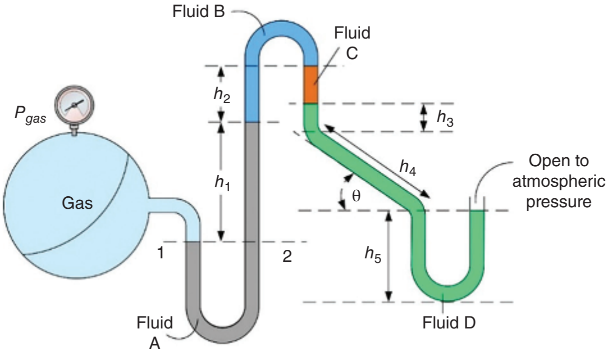
7 What is the gage pressure of the gas tank that is connected the manometer as shown below if the heights values are $h_1 = 15\,cm$ and $h_2 = 5\,cm$, where fluid A is mercury with a density of $13\,600\,kg/m^3$ and fluid B is water with a density of $1000\,kg/m^3$:



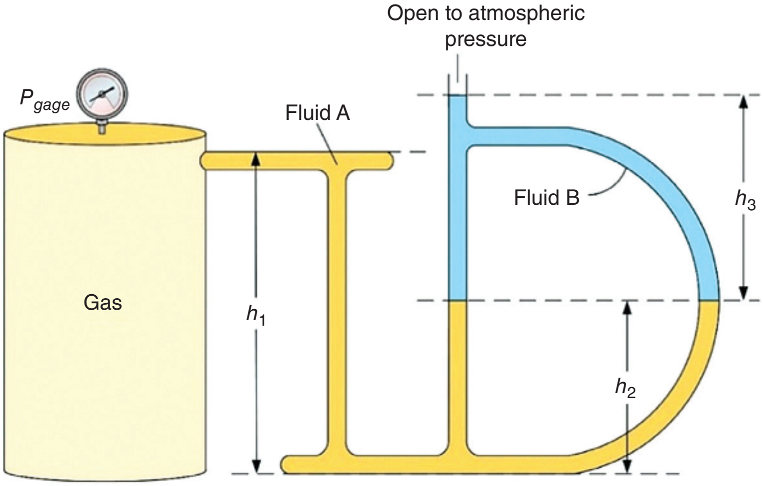
8 What is the gage pressure of the cylindrical gas tank that is connected the manometer as shown below if the heights values are $h_1 = 15\,cm$, $h_2 = 10\,cm$, and $h_3 = 10\,cm$ when fluid A is water with a density of $1000\,kg/m^3$ and fluid B is oil with a density of $760\,kg/m^3$:



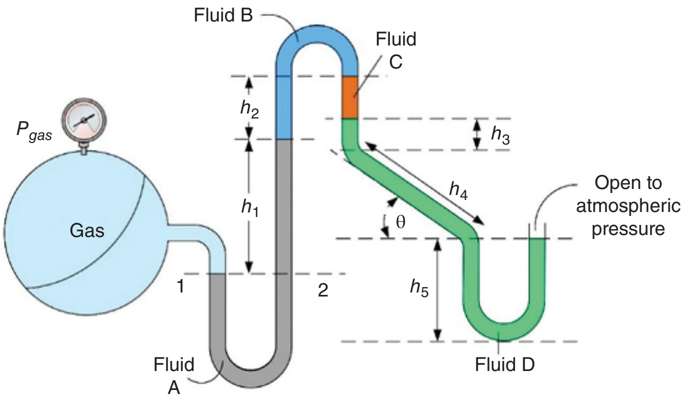
9 What is the gage pressure of the gas tank that is connected the manometer as shown below if the height values are $h_1 = 15\ cm$, $h_2 = 5\ cm$, $h_3 = 2\ cm$, $h_4 = 10\ cm$, and $h_5 = 7\ cm$ when fluid A is mercury with a density of $13\,600\ kg/m^3$, fluid B is water with a density of $1000\ kg/m^3$, fluid C is gasoline with a density of $720\ kg/m^3$, and fluid D is oil with a density of $760\ kg/m^3$ (note that the angle $\theta = 30^o$). Consider the height of fluid C as $1.5\ cm$.



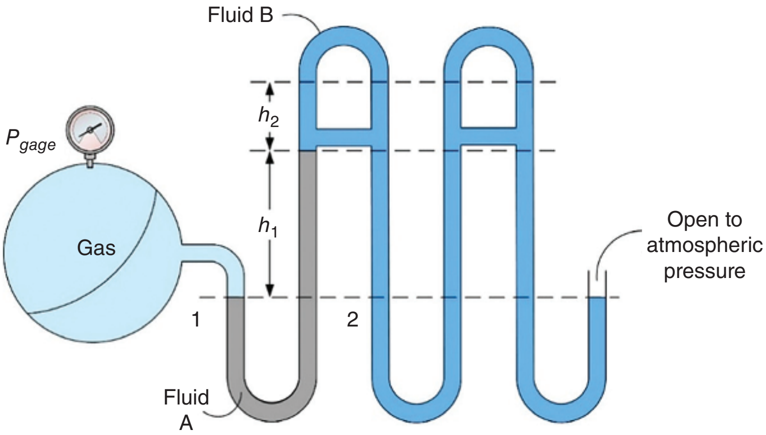
10 What is the gage pressure of the gas tank that is connected to the manometer as shown below if the heights values are $h_1 = 15\ cm$, $h_2 = 5\ cm$, and $h_3 = 12\ cm$. Fluid A is mercury with a density of $13\,600\ kg/m^3$ and fluid B is water with a density of $1000\ kg/m^3$:



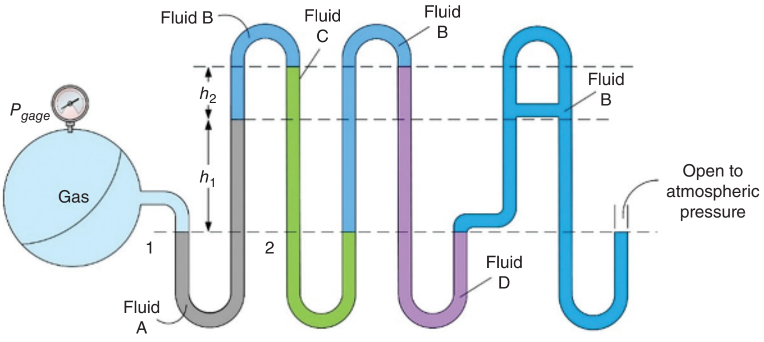
11 What is the gage pressure of the gas tank that is connected the manometer as shown below if the heights values are $h_1 = 15\ cm$ and $h_2 = 5\ cm$, where fluid A is mercury with a density of $13\,600\ kg/m^3$, fluid B is water with a density of $1000\ kg/m^3$, fluid C is gasoline with a density of $720\ kg/m^3$, and fluid D is oil with a density of $760\ kg/m^3$:



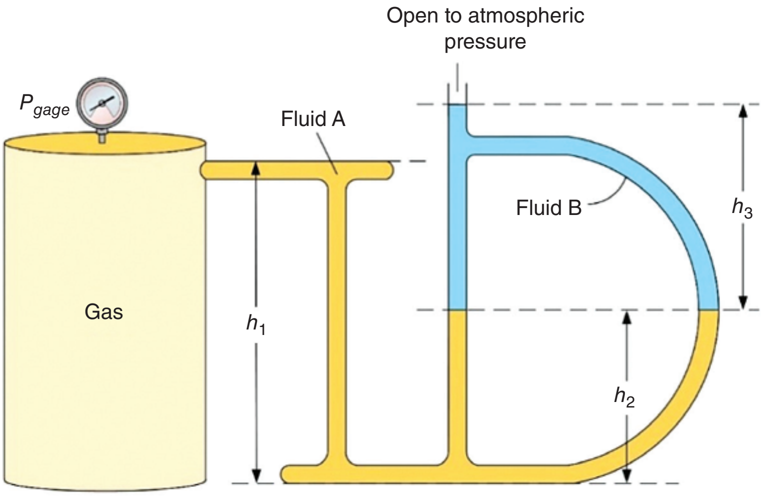
12 What is the gage pressure of the gas tank that is connected the manometer as shown below if the heights values are $h_1 = 15\ cm$ and $h_2 = 5\ cm$, where fluid A is mercury with a density of 13 600 kg/m^3 and fluid B is water with a density of 1000 kg/m^3:



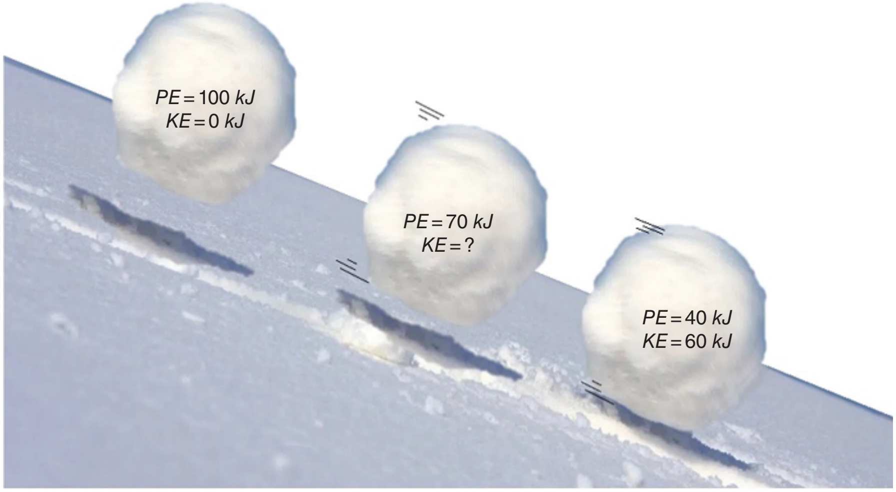
13 What is the gage pressure of the gas tank that is connected the manometer as shown below if the heights values are $h_1 = 15\ cm$ and $h_2 = 4\ cm$, where fluid A is mercury with a density of 13 600 kg/m^3, fluid B is water with a density of 1000 kg/m^3, fluid C is gasoline with a density of 720 kg/m^3, and fluid D is oil with a density of 760 kg/m^3:



14 What is the gage pressure of the cylindrical gas tank that is connected the manometer as shown below if the heights values are $h_1 = 15\,cm$, $h_2 = 10\,cm$, and $h_3 = 10\,cm$ when fluid A is water with a density of $1000\,kg/m^3$ and fluid B is oil with a density of $760\,kg/m^3$:



15 Find the potential and kinetic energies of the rolling snowball in the intermediate position as shown in the figure below (note that you can neglect the increase of the mass of the snowball):



16 A natural gas fueled water heater tank works by burning natural gas and utilizing the thermal energy released to heat water. Consider a water heater tank that contains 50 kg of water and heats it from a temperature of 25 °C to 70 °C. If the water heater is known to have an efficiency of 70%, determine the amount of natural gas required. (Take the lower heating value of natural gas as 47.1 MJ/kg and the specific heat capacity of water as 4.2 $kJ/kg\,^\circ C$.)

17 According to Figure 1.25, a lift is designed to lift containers with the help of a piston. How much weight can be lifted on piston 1 if area of 10 m^2 is available by applying 200 N force on the piston 2 area of 0.2 m^2.

18 Calculate the density of a liquid if the mass and volume are 1 kg and 1 m^3 and convert the density units to g/cm^3.

19 The specific density of two substances are 0.65 and 5.8. Find the density of each substance and describe if the objects will sink or float.

20 The pressure of a gas container relative to the atmospheric pressure is 60 kPa. Find the absolute pressure in the gas container.

21 According to Figure 1.39, 1.5 kg of milk is cooled by stirring which results in the heat loss of 75 kJ from milk to the atmospheric temperature 25 $^\circ C$ surroundings. If 30 kJ of work input in provided for stirring, calculate the temperature of the hot milk before stirring. Consider milk specific heat capacity of 4180 $J/kg\,^\circ C$.

22 According to Figure 1.41, a propane fueled water heater receives energy from supplied propane fuel which heats the water using fuel and hot water is used to heat up the house. If energy conversion efficiency is 76%, make the necessary calculations and calculate heat output.

23 An electric water heater is used to heat water from a temperature of 25 $^\circ C$ to a temperature of 80 $^\circ C$. If the water tank contains 50 L of water, determine the time required by the electric heater if the power rating of the electric heater is 20 W. Consider the density of water as 1000 kg/m^3 and the specific heat as 4.2 $kJ/kg\,^\circ C$.

24 Reconsider Problem 23 this time with a final temperature of 110 $^\circ C$ using an electric heater of 50 W and find the time required for this heating process.

25 Reconsider Problem 23 this time for thermal oil with a final temperature of 250 $^\circ C$ using an electric heater. Calculate the capacity of heater required to heat this in 15 minutes. Take the density of thermal oil as 810 kg/m^3 and the specific heat as 2.14 $kJ/kg\,^\circ C$.

26 An air compressor with an energy efficiency of 80% consumes 50 kW of power input. If the mass flow rate of air is known to be 1.2 kg/s, determine the change in air enthalpy during the compression process.

27 Reconsider Problem 26 this time with an energy efficiency of 91%. Find the change of enthalpy and compare with the result obtained in Problem 26.

28 A steam turbine with an energy efficiency of 85% produces 120 *kW* work rate. If the mass flow rate of air is known to be 1 *kg*/*s*, calculate the change in the enthalpy during this expansion process.

29 A coal-fueled power plant converts 100 *MW* of coal energy into 25 *MW* of electrical power through three steps. Define the conversion efficiency for each step and find the overall energy efficiency of the power plant.

30 Reconsider Problem 29 this time for multiple fuels, oil, natural gas, wood and hydrogen and discuss their impacts on the environment.