# $\Delta U = Q - W$



Echevarria, 2020

It has been found experimentally that the internal energy of a system may be changed either by doing work on the system or by heating it. Whereas we may know how the energy transfer has occurred (because we can see if a weight has been raised or lowered in the surroundings, indicating transfer of energy by doing work, or if ice has melted in the surroundings, indicating transfer of energy as heat), the system is blind to the mode employed.

Heat and work are equivalent ways of changing a system's internal energy. A system is like a bank: it accepts deposits in either currency but stores its reserves as internal energy. It is also found experimentally that, if a system is isolated from its surroundings, then no change in internal energy takes place. This summary of observations is known as the First Law of Thermodynamics.

Module Learning Objectives (ST. 2 & 8)

Upon completion of this module, you will be able to:

- 1. Solve problems using the First Law of Thermodynamics.
- 2. Use the relationship between heat and work in the transaction of energy.
- 3. Analyze thermodynamics cycles.

# Lesson 1: Energy Accounting: Energy Balance for Closed Systems

As indicated in previous modules, **the only way the energy of a closed system can be changed is through a transfer of energy by work or by heat**. Furthermore, based on the experiments of Joule and others, a fundamental aspect of the energy concept is that **energy is conserved**. We call this the First Law of Thermodynamics, and one its many enunciates is:

#### The internal energy of an isolated system is constant

These considerations are summarized in figure 1:



Figure 1. First Law of Thermodynamics. (Echevarria, 2020)

This statement is a way of saying that the first law of thermodynamics is a mean of accounting for an energy balance. It requires that in **any process of a closed system the energy of the system increases or decreases by an amount equal to the net amount of energy transferred across its boundary**.

The phrase "net amount" used in the statement of the energy balance must be carefully interpreted, for there may be heat or work transfers of energy at many different places on the boundary of a system. At some locations, the energy transfers may be into the system, whereas at others they are out of the system.

The two terms on the left side of figure 1 account for the net amount of all the energy transfers by heat and work, respectively, taking place during the time interval under consideration.

# We cannot use a system to do work, leave it isolated for a period, and then come back expecting to find it restored to its original state and ready to do the same work again.

The evidence for this property is that no 'perpetual motion machine' (a machine that does work without consuming fuel or some other source of energy) has ever been built.

These remarks may be summarized as follows. If we write W for the work done on a system, Q for the energy transferred as heat to a system, and  $\Delta U$  for the resulting change in internal energy, then it follows that:

$$\Delta U = Q + W \tag{1}$$

Equation 1 is the mathematical statement of the First Law, for it summarizes the equivalence of heat and work and the fact that **the internal energy is constant in an isolated system** (for which Q = 0 and W = 0).

The equation states that the change in the internal energy of a closed system is equal to the energy that passes through its boundary as heat or work. It employs the 'acquisitive convention', in which:

W < 0 or Q > 0 if energy is transferred to the system as work or heat

and

W > 0 or Q < 0 if energy is lost from the system as work or heat.

In other words, we view the flow of energy as work or heat from the system's perspective.

If an electric motor produced 15 kJ of energy each second as mechanical work and lost 2 kJ as heat to the surroundings, then the change in the internal energy of the motor each second is

 $\Delta U = -2 kJ + 15 kJ = 13 kJ$ 

Suppose that, when spring was wound, 100 kJ of work was done on it but 15 kJ escaped to the surroundings as heat. The change in internal energy of the spring is:

 $\Delta U = -15 \, kJ - 100 \, kJ = -115 \, kJ$ 

An alternative form of Eqn. 1 is:

$$\Delta KE + \Delta PE + \Delta U = Q + W \tag{2}$$

Which shows that an energy transfer across the system boundary results in a change in one or more of the macroscopic energy forms: kinetic energy ( $\Delta KE$ ), gravitational potential energy ( $\Delta PE$ ), and internal energy ( $\Delta U$ ).

The sign convention for  $Q \neq W$  is the same at the previous adopted.

In this module, most applications of the energy balance will not involve significant kinetic or potential energy changes.

Thus, to expedite the solutions of many subsequent examples and end-of-chapter problems, we indicate in the problem statement that such changes can be neglected.

If this is not made explicit in a problem statement, you should decide based on the problem at hand, the best way to handle the kinetic and potential energy terms of the energy balance.

#### Subtheme 1.1: Heat transactions

In general, the change in internal energy of a system is:

$$dU = \delta Q + \delta W_{expansion} + \delta W_{extra} \tag{3}$$

Where  $\delta W_{extra}$  is work additional ('extra') to the expansion work,  $\delta W_{expansion}$ . For instance,  $\delta W_{extra}$  might be the electrical work of driving a current through a circuit.

A system kept at constant volume can do no expansion work, so  $\delta W_{expansion} = 0$ . If the system is also incapable of doing any other kind of work (if it is not, for instance, an electrochemical cell connected to an electric motor), then  $\delta W_{extra} = 0$  too. Under these circumstances:

$$dU = dQ$$
 (at constant volume, no additional work) (4)

We express this relation by writing  $dU = dQ_V$ , where the subscript implies a **change at constant volume**. For a measurable change:

$$\Delta U = Q_V \tag{5}$$

It follows that by measuring the energy supplied to a constant-volume system as heat (Q > 0) or obtained from it as heat (Q < 0) when it changes state, we are measuring the change in its internal energy. Version 1.5\_V10 2019\_PUPR as of April 5\_2019

# Subtheme 1.2: Heat capacity

The internal energy of a substance increases when its temperature is raised. The increase depends on the conditions under which the heating takes place and for the present, we suppose that the sample is confined to a **constant volume**.

For example, the sample may be gas in a container of fixed volume. If the internal energy is plotted against temperature, then a curve like that in Fig. 2 may be obtained. The slope of the tangent to the curve at any temperature is called the heat capacity of the system at that temperature. The heat capacity at constant volume is denoted  $C_V$  and is defined formally as:

$$\boldsymbol{C}_{\boldsymbol{V}} = \left(\frac{\partial \boldsymbol{U}}{\partial \boldsymbol{T}}\right)_{\boldsymbol{V}} \tag{6}$$



Figure 2. The internal energy of a system increases as the temperature is raised. The slope of the tangent to the curve at any temperature is the heat capacity at the constant volume at that temperature. (Atkins, 2006)

In this case, **the internal energy varies with the temperature and the volume of the sample**, but we are interested only in its variation with the temperature, the volume is held constant.

**Heat capacities are extensive properties**: 100 g of water, for instance, has 100 times the heat capacity of 1 g of water (and therefore requires 100 times the energy as heat to bring about the same rise in temperature).

The molar heat capacity at constant volume,  $C_{V,m} = C_V/n$ , is the heat capacity per mole of material and is an intensive property (all molar quantities are intensive). Typical values of  $C_{V,m}$  for polyatomic gases are close to  $25 J K^{-1} mol^{-1}$ .

For certain applications it is useful to know the **specific heat capacity** (more informally, the 'specific heat') of a substance, which is **the heat capacity of the sample divided by the mass**, usually in grams:  $C_{V,S} = C_V/m$ .

The specific heat capacity of water at room temperature is close to  $4 J K^{-1} g^{-1}$ . In general, heat capacities depend on the temperature and decrease at low temperatures.

However, over small ranges of temperature at and above room temperature, the variation is quite small and for approximate calculations, heat capacities can be treated as almost independent of temperature.

The heat capacity is used to relate a change in internal energy to a change in temperature of a constant-volume system. It follows from Eqn. 6 that:

$$dU = C_V dT$$
 (at constant volume) (7)

That is, at constant volume, an infinitesimal change in temperature brings about an infinitesimal change in internal energy, and the constant of proportionality is  $C_V$ .

If the heat capacity is independent of temperature over the range of temperatures of interest, a measurable change of temperature,  $\Delta T$ , brings about a measurable increase in internal energy,  $\Delta U$ , where:

$$\Delta U = C_V \Delta T \text{ (at constant volume)}$$
(8)

Because a change in internal energy can be identified with the heat supplied at constant volume (Eqn. 8), the last equation can be written:

$$\boldsymbol{Q}_{\boldsymbol{V}} = \boldsymbol{C}_{\boldsymbol{V}} \boldsymbol{\Delta} \boldsymbol{T} \tag{9}$$

This relation provides a simple way of measuring the heat capacity of a sample: a measured quantity of energy is transferred as heat to the sample (electrically, for example), and the resulting increase in temperature is monitored.

The ratio of the energy transferred as heat to the temperature rise it causes  $(Q_V/\Delta T)$  is the constant-volume heat capacity of the sample.

A large heat capacity implies that, for a given quantity of energy transferred as heat, there will only be a small increase in temperature (the sample has a large capacity for heat).

An infinite heat capacity implies that there will be no increase in temperature no matter how much energy is supplied as heat.

At a phase transition, such as at the boiling point of water, the temperature of a substance does not rise as energy is supplied as heat: the energy is used to drive the endothermic transition, in this case, to vaporize the water, rather than to increase its temperature.

Therefore, at the temperature of a phase transition, the heat capacity of a sample is infinite.

# Lesson 2: Energy Analysis of Cycles

In this section the energy concepts developed thus far are illustrated further by application to systems undergoing thermodynamic cycles.

When a system at a given initial state goes through a sequence of processes and finally returns to that state, the system has executed a thermodynamic cycle.

The study of systems undergoing cycles has played an important role in the development of the subject of engineering thermodynamics.

Both the First and Second Laws of Thermodynamics have roots in the study of cycles.

Also, there are many important practical applications involving power generation, vehicle propulsion, and refrigeration for which an understanding of Thermodynamic cycles is necessary.

In this section, cycles are considered from the perspective of the conservation of energy principle.

Cycles are studied in greater detail in subsequent modules, using both the conservation of energy principle and the Second Law of Thermodynamics.

# Subtheme 2.1: Cycle Energy Balance

The energy balance for any system undergoing a Thermodynamic cycle takes the form:

$$\Delta U_{cycle} = Q_{cycle} + W_{cycle} \tag{10}$$

Where  $Q_{cycle}$  and  $W_{cycle}$  represent net amounts of energy transfer by heat and work, respectively, for the cycle. Since the system is returned to its initial state after the cycle, there is no net change in its energy. Therefore, the left side of Eqn. 10 equals zero, and the equation reduces to:

$$W_{cycle} = -Q_{cycle} \tag{11}$$

Equation 11 is an expression of the conservation of energy principle that must be satisfied by every Thermodynamic cycle, regardless of the sequence of processes followed by the system undergoing the cycle or the nature of the substances making up the system.

Figure 3 provides simplified schematics of two general classes of cycles considered in this book: power cycles and refrigeration and heat pump cycles. In each case pictured, a system undergoes a cycle while communicating thermally with two bodies, one hot and one cold.



Figure 3. Schematic diagrams of two important classes of cycles. (a) Power cycles. (b) Refrigeration and heat pump cycles. (Shapiro, 2006)

These bodies are systems located in the surroundings of the system undergoing the cycle.

During each cycle, there is also a net amount of energy exchanged with the surroundings by work.

Carefully observe that in using the symbols  $Q_{in}$  and  $Q_{out}$  on Fig. 3a we have departed from the previously stated sign convention for heat transfer.

In this section, it is advantageous to regard  $Q_{in}$  and  $Q_{out}$  as transfers of energy in the directions indicated by the arrows.

The direction of the total work of the cycle,  $W_{cycle}$ , is also indicated by an arrow.

Finally, note that the directions of the energy transfers shown in Fig. 3b are opposite to those of Fig. 3a.



Systems undergoing cycles of the type shown in Fig. 3a **delivers a total work transfer of energy to their surroundings** during each cycle.

Any such cycle is called a power cycle. From Eqn. 11, the total work output equals the net heat transfer to the cycle, or:

$$W_{cycle} = Q_{in} - Q_{out} \qquad (power cycle) \tag{12}$$

Where  $Q_{in}$  represents the heat transfer of energy into the system from the hot body, and  $Q_{out}$  represents heat transfer out of the system to the cold body. From Eqn. 12 it is clear that  $Q_{in}$  must be greater than  $Q_{out}$  for a power cycle.

The energy supplied by heat transfer to a system undergoing a power cycle is normally derived from the combustion of fuel or a moderated nuclear reaction; it can also be obtained from solar radiation.

The energy  $Q_{out}$  is generally discharged to the surrounding atmosphere or a nearby body of water.

The performance of a system undergoing a power cycle can be described in terms of the extent to which the energy added by heat,  $Q_{in}$ , is converted to total work output,  $W_{cycle}$ .

The extent of the energy conversion from heat to work is expressed by the following ratio, commonly called the **thermal** efficiency.

$$\eta = \frac{W_{cycle}}{Q_{in}}$$
 (power cycle) (13)

Introducing Eqn. 12, an alternative form is obtained as:

$$\eta = \frac{Q_{in} - Q_{out}}{Q_{in}} = 1 - \frac{Q_{out}}{Q_{in}} \qquad \text{(power cycle)} \tag{14}$$

Since energy is conserved, it follows that the thermal efficiency can never be greater than unity (100%).

That is, not all the energy added to the system by heat transfer is converted to work; a portion is discharged to the cold body by heat transfer.

Using the Second Law of Thermodynamics, we will show in the following modules that the conversion from heat to work cannot be fully accomplished by any power cycle.

The thermal efficiency of every power cycle must be less than unity:  $\eta < 1$ .

# Lesson 3: Refrigeration and Heat Pump Cycles

Next, consider the refrigeration and heat pump cycles shown in Fig. 2.b. For cycles of this type,  $Q_{in}$  is the energy transferred by heat into the system undergoing the cycle from the cold body, and  $Q_{out}$  is the energy discharged by heat transfer from the system to the hot body.

To accomplish these energy transfers requires a total work input,  $W_{cycle}$ . The quantities  $Q_{in}$ ,  $Q_{out}$ , and  $W_{cycle}$  are related by the energy balance, which for refrigeration and heat pump cycles takes the form:

$$W_{cycle} = Q_{out} - Q_{in}$$
 (refrigeration and heat pump cycles) (15)

Since  $W_{cycle}$  is negative in this equation, it follows that  $Q_{out}$  is smaller than  $Q_{in}$ . Although we have treated them as the same to this point, refrigeration and heat pump cycles have different objectives.

The objective of a refrigeration cycle is to cool a refrigerated space or to maintain the temperature within a dwelling or other building below that of the surroundings.

The objective of a heat pump is to maintain the temperature within a dwelling or other building above that of the surroundings or to provide heating for certain industrial processes that occur at elevated temperatures.

Since refrigeration and heat pump cycles have different objectives, their performance parameters, called coefficients of performance, are defined differently.

These coefficients of performance are considered next.

#### Subtheme 3.1: Refrigeration Cycles

The performance of refrigeration cycles can be described as the ratio of the amount of energy received by the system undergoing the cycle from the cold body,  $Q_{in}$ , to the total work into the system to accomplish this effect,  $W_{cycle}$ . Thus, the coefficient of performance,  $\beta$ , is:

$$\beta = \frac{Q_{in}}{W_{cycle}} \quad \text{(refrigeration cycle)} \tag{16}$$

Introducing Eqn. 15, an alternative expression for  $\beta$  is obtained as:

$$\beta = \frac{Q_{in}}{Q_{out} - Q_{in}} \quad \text{(refrigeration cycle)} \tag{17}$$

For a household refrigerator,  $Q_{out}$  is discharged to the space in which the refrigerator is located.  $W_{cycle}$  is usually provided in the form of electricity to run the motor that drives the refrigerator.

For example, in a refrigerator the inside compartment acts as the cold body and the ambient air surrounding the refrigerator is the hot body.

Energy *Q<sub>in</sub>* passes to the circulating refrigerant from the food and other contents of the inside compartment (see Fig. 4).





For this heat transfer to occur, the refrigerant temperature is necessarily below that of the refrigerator contents. Energy  $Q_{out}$  passes from the refrigerant to the surrounding air. For this heat transfer to occur, the temperature of the circulating refrigerant must necessarily be above that of the surrounding air. To achieve these effects, work input is required. For a refrigerator,  $W_{cycle}$  is provided in the form of electricity.

# Subtheme 3.2: Heat Pump Cycles

The performance of heat pumps can be described as the ratio of the amount of energy discharged from the system undergoing the cycle to the hot body,  $Q_{out}$ , to the total work into the system to accomplish this effect,  $W_{cycle}$ .

Thus, the coefficient of performance,  $\gamma$ , is:

$$\gamma = \frac{Q_{out}}{W_{cycle}} \qquad \text{(heat pump cycle)} \tag{18}$$

Introducing Eqn. 15, an alternative expression for this coefficient of performance is obtained as:

$$\gamma = \frac{Q_{out}}{Q_{out} - Q_{in}} \quad \text{(heat pump cycle)} \tag{19}$$

From this equation, the value of  $\gamma$  is never less than unity. For residential heat pumps, the energy quantity  $Q_{in}$  is normally drawn from the surrounding atmosphere, the ground, or a nearby body of water.  $W_{cycle}$  is usually provided with electricity.

The coefficients of performance  $\beta$  and  $\gamma$  are defined as ratios of the desired heat transfer effect to the cost in terms of work to accomplish that effect.

Based on the definitions, it is thermodynamically desirable that these coefficients have values that are as large as possible.

#### **Lesson 4: Practical Examples**

# Example 4.1: Cooling a Gas in a Piston–Cylinder

Four kilograms (4 kg) of a certain gas is contained within a piston-cylinder assembly. The gas undergoes a process for which the pressure-volume relationship is:

 $pV^{1.5} = constant$ 

The initial pressure is 3 *bar*, the initial volume is  $0.1 m^3$ , and the final volume is  $0.2 m^3$ . The change in specific internal energy of the gas in the process is  $U_2 - U_1 = -4.6 kJ/kg$ . There are no significant changes in kinetic or potential energy. Determine the net heat transfer for the process, in kJ.

Gas within a piston-cylinder assembly undergoes an expansion process for which the pressure-volume relation and the change in specific internal energy are specified. Determine the net heat transfer for the process.



Assumptions:

- 1. The gas is a closed system.
- 2. The process is described by  $pV^{1.5} = constant$ .
- 3. There is no change in the kinetic or potential energy of the system.

An energy balance for the closed system takes the form:

$$\Delta U = Q + W$$

Where the kinetic and potential energy terms drop out by assumption 3. Then, writing  $\Delta U$  in terms of specific internal energies, the energy balance becomes:

$$m(\Delta U) = Q + W$$

Where m is the system mass. Solving for Q:

$$Q = m(\Delta U) - W$$

According to expression found in module 4, the value of the work for this process is determined by:

$$W = \frac{(p_2 V_2^n) V_2^{1-n} - (p_1 V_1^n) V_1^{1-n}}{1-n} = \frac{p_2 V_2 - p_1 V_1}{1-n}$$

This expression is valid for all values of n except n = 1.0. To evaluate W, the pressure at state 2 is required. This can be found by using  $p_1V_1^n = p_2V_2^n$  which on rearrangement yields:

$$p_2 = p_1 \left(\frac{V_1}{V_2}\right)^n = (3 \text{ bar}) \left(\frac{0.1}{0.2}\right)^{1.5} = 1.06 \text{ bar}$$

Accordingly:

$$W = \left(\frac{(1.06 \ bar)(0.2 \ m^3) - (3)(0.1)}{1 - 1.5}\right) \left(\frac{10^5 \frac{N}{m^2}}{1 \ bar}\right) \left(\frac{1 \ kJ}{10^3 \ Nm}\right) = +17.6 \ kJ$$

The change in internal energy is obtained using given data as:

$$m\Delta U = 4 \, kg \, (-4.6 \, kJ/kg) = -18.4 \, kJ$$

Substituting values

$$Q = -18.4 - 17.6 = -36 \, kJ$$

- The given relationship between pressure and volume allows the process to be represented by the path shown in the accompanying diagram. The area under the curve represents the work.
- Since they are not properties, the values of the work and heat transfer depend on the details of the process and cannot be determined from the end states only.
- > The minus sign for the value of Q means that a net amount of energy has been transferred from the system to its surroundings by heat transfer.

### Example 4.2: A gas undergoes a thermodynamic cycle

A gas undergoes a thermodynamic cycle consisting of three processes:

- Process 1–2: constant volume,  $V = 0.028 m^3$ ,  $U_2 U_1 = 26.4 kJ$
- Process 2–3: expansion with pV = constant,  $U_3 = U_2$
- Process 3–1: constant pressure, p = 1.4 bar,  $W_{31} = -10.5 \text{ kJ}$

There are no significant changes in kinetic or potential energy.

(a) Sketch the cycle on a p–V diagram.

(b) Calculate the total work for the cycle, in kJ.

(c) Calculate the heat transfer for process 2-3, in kJ.

(d) Calculate the heat transfer for process 3-1, in kJ. Is this a power cycle or a refrigeration cycle?

Solution:

(a) Sketch the cycle on a P-V diagram:





Assumptions:

- The gas is a closed system.
- For the system, the variation of kinetic and potential energies is zero.
- Volume change is the only source of work.

Analysis: Calculate  $W_{cycle}$ ,  $Q_{23}$ ,  $Q_{31}$ , and determine whether the cycle is a power or refrigeration cycle.

(b)  $W_{cycle} = W_{12} + W_{23} + W_{31}$ . Since volume is constant in 1-2 process,  $W_{12} = 0$ . To find  $W_{23}$ :

$$W_{23} = \int_{V_2}^{V_3} p dV = \int_{V_2}^{V_3} \frac{constant}{V} dV = (constant) ln\left(\frac{V_3}{V_2}\right)$$

 $V_2 = V_1$ , to evaluate  $V_3$ :

$$W_{31} = \int_{V_2}^{V_3} p dV = p(V_1 - V_3)$$

$$V_3 = V_1 - \frac{W_{31}}{p}$$

$$V_3 = 0.028 \ m^3 - \left(\frac{-10.5 \ kJ}{1.4 \ bar}\right) \left(\frac{1 \ bar}{10^5 \ \frac{N}{m^2}}\right) \left(\frac{10^3 \ Nm}{1 \ kJ}\right) = 0.103 \ m^3$$

Therefore:

$$W_{23} = 1.4 \ bar\left(\frac{10^5 \ N/m^2}{1 \ bar}\right)(0.103 \ m^3) \ ln\left(\frac{0.103}{0.028}\right)\left(\frac{1 \ kJ}{10^3 \ Nm}\right) = 18.78 \ kJ$$

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(c) Finally:

$$W_{cycle} = 0 + 18.78 \, kJ + (-10.5 \, kJ) = 8.28 \, kJ$$
$$\Delta U_{23} = Q_{23} + W_{23} = 0$$
$$Q_{23} = -W_{23} = -18.78 \, kJ$$

(d) To evaluate  $Q_{31}$  begin with an energy balance together with assumptions:

$$U_1 - U_3 = Q_{31} + W_{31}$$
$$Q_{31} = (U_1 - U_3) + W_{31}$$

Since there is no overall change in internal energy for the cycle (internal energy is a state function):

$$(U_2 - U_1) + (U_3 - U_2) + (U_3 - U_1) = 0$$
  
 $(U_3 - U_1) = -26.4 kJ - 0 = -26.4 kJ$ 

Then:

$$Q_{31} = (-26.4 \, kJ) - (-10.5 \, kJ) = -15.9 \, kJ$$

As a check note that  $Q_{cycle} = -W_{cycle}$ ,  $Q_{cycle} = Q_{12} + Q_{23} + Q_{31}$ . An energy balance for 1-2 gives  $Q_{12} = 26.4 kJ$ . So  $Q_{cycle} = 26.4 kJ - 18.78 kJ - 15.9 kJ = -8.28 kJ$ , which checks the result of part (b). Due to  $W_{cycle} > 0$ , this is a power cycle.

# Conclusion

Thus far, we have been careful to emphasize that the quantities symbolized by W and Q in the foregoing equations account for transfers of energy and not transfers of work and heat, respectively.

The terms work and heat denote different means by which energy is transferred and not what is transferred.

However, to achieve the economy of expression in subsequent discussions, W and Q are often referred to simply as work and heat transfer, respectively.

This less formal manner of speaking is commonly used in engineering practice.

In this module, we have considered the concept of energy from an engineering perspective and have introduced energy balances for applying the conservation of energy principle to closed systems.

A basic idea is that energy can be stored within systems in three macroscopic forms: internal energy, kinetic energy, and gravitational potential energy.

Work and heat transfer are identified at the system boundary and are not properties. In mechanics, work is energy transfer associated with macroscopic forces and displacements at the system boundary.

The thermodynamic definition of work introduced in this chapter extends the notion of work from mechanics to include other types of work, like electrical work.

Energy transfer by heat is due to a temperature difference between the system and its surroundings and occurs in the direction of decreasing temperature.

Heat transfer modes include conduction, radiation, and convection. These sign conventions are used for work and heat transfer:

W	Q
> 0 : work is done by the system	> 0 : heat transfer to the system
< 0 : work is done on the system	< 0 : heat transfer from the system

Energy is an extensive property of a system.

Only changes in the energy of a system have significance.

Energy changes are accounted for by the energy balance.

The energy balance for the process of a closed system is  $\Delta U = Q + W$ .

Equation  $W_{cycle} = -Q_{cycle}$  is a special form of the energy balance for a system undergoing a thermodynamic cycle.

# **Questions for Discussion Board:**

**1.1.1.** If the change in energy of a closed system is known for a process between two end states, can you determine if the energy change was due to work, heat transfer, or some combination of work and heat transfer?

**1.1.2.** Two power cycles each receive the same energy input Qin and discharge energy  $Q_{out}$  to the same lake. If the cycles have different thermal efficiencies, which discharges the greater amount  $Q_{out}$ ? Does this have any implications for the environment?

#### Activity 1.2 (ST. 3, 5, 6 & 8) Please read Notes 3-4 for more information about the activities

# **Questions:**

**1.2.1.** Each line in the following table gives information about the process of a closed system. Every entry has the same energy units. Fill in the blank spaces in the table.

Process	Q	W	$U_1$	$U_2$	$\Delta U$
а	+50	-20		+50	
b	+50	+20	+20		
С	-40			+60	+20
d		-90		+50	0
е	+50		+20		-100

**1.2.2.** A closed system of mass 20 kg undergoes a process in which there is a heat transfer of 1000 kJ from the system to the surroundings. The work done on the system is 200 kJ. If the initial specific internal energy of the system is 300 kJ/kg, what is the final specific internal energy, in kJ/kg? Neglect changes in kinetic and potential energy.

**1.2.3.** A gas expands in a piston-cylinder assembly from  $p_1 = 8 \text{ bar}$ ,  $V_1 = 0.02 m_3$  to  $p_2 = 2 \text{ bar}$  in a process during which the relation between pressure and volume is  $pV^{1.2} = \text{constant}$ . The mass of the gas is 0.25 kg. If the specific internal energy of the gas decreases by 55 kJ/kg during the process, determine the heat transfer, in kJ. Kinetic and potential energy effects are negligible.

**1.2.4.** 2.47 The following table gives data, in kJ, for a system undergoing a thermodynamic cycle consisting of four processes in series. For the cycle, kinetic and potential energy effects can be neglected. Determine

(a) the missing table entries, each in kJ. (b) whether the cycle is a power cycle or a refrigeration cycle.

Process	$\Delta U$	Q	W
1-2	600		-600
2-3			-1300
3-4	-700	0	
4-1		500	700

Results: 1-2: Q = 0, 2-3:  $\Delta U = 300, Q = -1000, 3-4$ : W = 700, 4-1:  $\Delta U = -200$ 

**1.2.5.** A gas undergoes a thermodynamic cycle consisting of three processes:

Process 1–2: compression with pV = constant, from  $p_1 = 1 bar$ ,  $V_1 = 1.6 m^3$  to  $V_2 = 0.2 m^3$ ,  $U_2 - U_1 = 0$ Process 2–3: constant pressure to  $V_3 = V_1$ Process 3–1: constant volume,  $U_1 - U_3 = -3549 kJ$ 

There are no significant changes in kinetic or potential energy. Determine the heat transfer and work for Process 2–3, in kJ. Is this a power cycle or a refrigeration cycle?

See the following videos:

https://www.youtube.com/watch?v=iiFWoXQPOJc&t=1106s

https://www.youtube.com/watch?v=aAfBSJObd6Y&t=858s

https://www.youtube.com/watch?v=ixRtSV3CXPA&t=3s