

FIRST LAW OF THERMODYNAMICS

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The subject of thermodynamics is strongly related to the two forms of energy work and heat. These two form can convert naturally to each other but the conversion is not random. Scientists found from experimental observations that this conversion is governed by natural rules or laws. A group of these laws are termed as the thermodynamic laws which are:

1-The first law of thermodynamics

2-The second law of thermodynamics

3-The third law of thermodynamics.

Sometimes the zeroth law mentioned earlier is added to this group. In engineering studies we are concerned with the first and second laws only at this stage.

THE FIRST LAW OF THERMODYNAMICS

This law governs the relation between heat and work during any process. It is a restricted statement of the PRINCIPLE OF CONSERVATION OF ENERGY which is stated as follows “ENERGY IS NEVER CREATED NOR DESTRUCTED BUT CONVETED FROM ONE FORM THE ANOTHER”. Therefore the first law is stated as follows “**when a system undergoes a thermodynamic cycle then the net heat supplied to the system equals the net work done by the system**”.

In order to understand this statement let us consider the piston cylinder mechanism shown in fig (5-1).

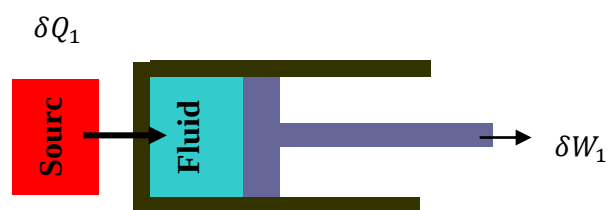


Fig (5-1A) Heat transfer from Source to Working Fluid



Fig (5-1B) Heat transfer from Working Fluid to Sink

Fig (5-1)

Let the cylinder is considered as a closed system contains a certain working fluid. Assume that an amount of heat (δQ_1) is transferred to the working fluid from an external source so that it expands and pushes the piston outward. The working fluid is doing work (δW_1) on the piston during this movement. Since the piston is part of the surroundings then the working fluid is doing work on the surroundings.

Assume that the source is replaced by a sink so that the working fluid is cooled due to transfer of heat (δQ_2) to the sink and the working fluid returns to its initial temperature. In order to restore the system to the initial state the piston must be pushed inside the cylinder by external work (δW_2) which means work is done by the surroundings on the working fluid. In this case the working fluid (the system) undergoes a thermodynamic cycle. Experimental results showed that the net heat supplied to the working fluid (the system) equals the net work done by the system. This results can be written in a mathematical form as follows.

$$\oint \delta Q = \oint \delta W \quad (5-1)$$

$$\oint \delta W = \delta W_1 + \delta W_2 \quad (5-2)$$

$$\oint \delta Q = \delta Q_1 + \delta Q_2 \quad (5-3)$$

The terms $\oint \delta Q$ and $\oint \delta W$ represent the net heat supplied and the net work done during the cycle respectively and their values depend on type of processes involved in the cycle. There is another statement for the first law of thermodynamics which is “When a system undergoes a thermodynamic cycle the net energy interaction between the system and its surroundings equals zero”. It is written mathematically as,

$$\oint \delta Q - \oint \delta W = 0 \quad (5-4)$$

Example 5-1

In a closed cycle gas turbine unit the turbine produces 300 kJ/kg of work while the compressor consumes 240 kJ/kg work. The heat added in the heater equals 388 kJ/kg. Calculate the heat rejected in the cooler.

Since the working fluid passes through a thermodynamic cycle,

$$\oint \delta Q = \oint \delta W$$

$$Q_{supp} + Q_{rej} = W_{tur} + W_{comp}$$

Now the heat supplied is positive while the heat rejected is negative.

The work done by the turbine is positive while the work consumed by the compressor is negative.

$$\therefore 388 + Q_{rej} = 300 + (-240)$$

$$\therefore Q_{rej} = -328 \text{ kJ/kg}$$

The minus sign confirm that this heat is lost in the cooler.

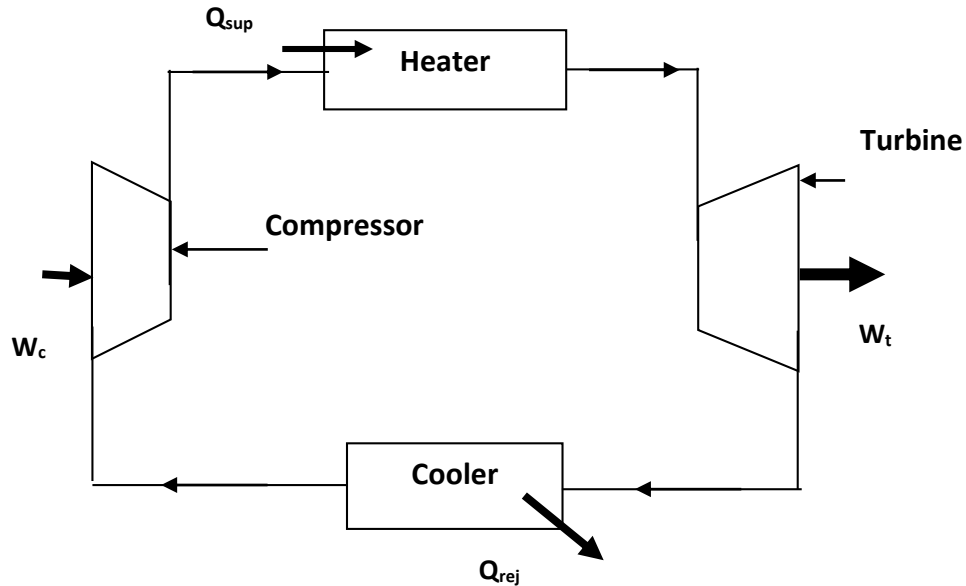


Fig (5-2)

COROLLARIES OF THE FIRST LAW OF THERMODYNAMICS

There are three corollaries for the first law of thermodynamics.

The First Corollary

This corollary is stated as follows “There exists a property of a closed system the change in the value of this property during a process is given by the difference between the heat supplied and the work done”. This property is known as the internal energy.

The truth of this property is proved as bellow.

Assume a closed system undergoes a process and the difference between heat supplied and work done ($\int_1^2 (\delta Q - \delta W)$) during the process does not equal the change in the value of a property of the system. In other words this difference is a path function.

Assume a closed system undergoes two processes between state (1) and state (2) on paths (A) and (B) as on the properties diagram in fig (5-2). According to this assumption,

$$\int_1^2 (\delta Q - \delta W)_A \neq \int_1^2 (\delta Q - \delta W)_B \quad (5-5)$$

Assume that the system at the end of both processes is restored to its original state (1) along the path (C). Therefore the system completes two cycles i.e. cycle 1-2-1 along path A-C and cycle 1-2-1 along path B-C. Now the net interaction during each cycle can be expressed mathematically as follows:

$$\oint (\delta Q - \delta W)_{A-C} = \int_1^2 (\delta Q - \delta W)_A + \int_2^1 (\delta Q - \delta W)_C \quad (5-6)$$

$$\oint (\delta Q - \delta W)_{B-C} = \int_1^2 (\delta Q - \delta W)_B + \int_2^1 (\delta Q - \delta W)_C \quad (5-7)$$

We can conclude according to equation (5-5) that

$$\oint (\delta Q - \delta W)_{A-C} \neq \oint (\delta Q - \delta W)_{B-C} \quad (5-8)$$

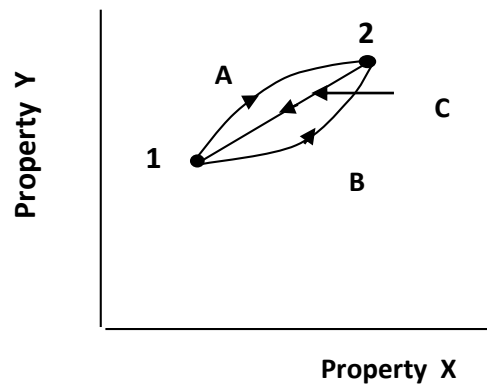


Fig (5-3)

But this is incorrect according to the first law of thermodynamics since both side of equation (5-8) must equal zero and hence they are equal. Therefore our initial assumption is incorrect since it violated the first law of thermodynamics. Hence the difference between heat supplied and work done during a process must equal the change in the value of a property of the system and this property is known as the internal energy and given the symbol (U) for total internal energy and (u) for specific internal energy. This corollary is expressed mathematically as,

$$\int_1^2 (\delta Q - \delta W) = U_2 - U_1 \quad (5-9)$$

OR

$$Q - W = U_2 - U_1 \quad (5-10)$$

Where,

Q=amount of heat crosses the system boundary during the process (J).

W=amount of work done during the process (J).

U₁=total internal energy of system at the initial state (J).

U_2 = total internal energy of system at the final state (J).

Equation (5-10) is referred to as the energy equation for non-flow processes or for closed system.

The sum of internal energy, kinetic energy and potential energy is known as intrinsic energy (E).

$$E = U + KE + PE \quad (5-11)$$

Therefore,

$$Q - W = E_2 - E_1 \quad (5-12)$$

The Second Corollary

This corollary is stated as follows “There is no change in the internal energy of a closed system isolated from its surroundings”

For an isolated closed system there is no interaction with its surroundings. This means,

$$Q = 0 \quad \text{and} \quad W = 0$$

$$Q - W = U_2 - U_1$$

$$\therefore U_1 = U_2$$

The Third Corollary

This corollary is stated as follows “It is impossible to build a perpetual motion machine of the first kind”.

The perpetual motion machine of the first kind is the machine that produces work continuously with no supply of heat. This means that this machine creates energy from nothing since work is energy. This machine violates the first law of thermodynamics since according to this law,

$$\oint \delta Q = \oint \delta W$$

If δQ equals zero then δW must equal zero.

Therefore this machine is impossible.

Sometimes it is possible to obtain a limited amount of work from a specific system such as a compressed gas, to a pressure higher than the atmospheric pressure, expanding in a thermally isolated cylinder behind a piston. The work is done on the piston until the pressure inside the cylinder equals the atmospheric pressure.

$$Q = U_2 - U_1 + W$$

$$\therefore Q = 0$$

$$\therefore W = U_1 - U_2$$

Example (5-2)

In a piston cylinder mechanism the cylinder contains 0.5 kg of steam at 7 bar with a volume of 0.13 m^3 . The steam expands inside the cylinder until its volume triples and its pressure becomes 2 bar. The work done during the expansion process of steam equals 188 kJ. Calculate the heat exchanged with the surroundings and its direction.

Since the expansion process inside the cylinder is a non-flow process we can apply the non-flow energy equation.

$$Q = (U_2 - U_1) + W$$

Find the initial state of steam,

$$v_1 = \frac{V}{m} = \frac{0.13}{0.5} = 0.26 \text{ m}^3/\text{kg}$$

From saturated steam table we find v_g at 7 bar which is,

$$v_g = 0.273 \text{ m}^3/\text{kg}$$

Since $v_1 < v_g$ the steam is wet.

$$v_1 = x_1 v_g$$

$$\therefore x_1 = \frac{v_1}{v_g} = \frac{0.26}{0.273} = 0.95$$

$$u_1 = u_f + x_1(u_g - u_f)$$

$$\therefore u_1 = 696.3 + 0.95 \times (2571.1 - 696.3) = 2477.36 \text{ kJ/kg}$$

$$V_2 = 3V_1 = 3 \times 0.13 = 0.39 \text{ m}^3$$

$$v_2 = \frac{V_2}{m} = \frac{0.39}{0.5} = 0.78 \text{ m}^3/\text{kg}$$

From saturated steam table we find v_g at 2 bar which is,

$$v_g = 0.885 \text{ m}^3/\text{kg}$$

Since $v_2 < v_g$ the steam is wet.

$$x_2 = \frac{v_2}{v_g} = \frac{0.78}{0.885} = 0.881$$

$$u_2 = u_f + x_2(u_g - u_f)$$

$$\therefore u_2 = 504.5 + 0.881 \times (2529.2 - 504.5) = 2288.26 \text{ kJ/kg}$$

$$Q = m(u_2 - u_1) + W$$

$$\therefore Q = 0.5 \times (2288.26 - 2477.36) + 188 = 93.45 \text{ kJ}$$

The heat is supplied to the cylinder since its sign is positive.

First Law of Thermodynamics as a Rate Equation

In many engineering applications we must consider the time duration of the process i.e. the time rate at which work and heat cross the system boundaries.

Consider a closed system undergoes a process during a time period of (δt) where a quantity of heat (δQ) and a quantity of work (δW) cross the system boundaries which causes a change in its internal energy equals (ΔU) and a change in its kinetic energy (ΔKE) and a change in its potential energy (ΔPE).

Apply equation (5-12) we obtain,

$$\delta Q - \delta W = \Delta U + \Delta KE + \Delta PE \quad (5-13)$$

If we divide the above equation by (δt) we obtain the time rate of energy crossing the system boundaries.

$$\frac{\delta Q}{\delta t} - \frac{\delta W}{\delta t} = \frac{\Delta U}{\delta t} + \frac{\Delta KE}{\delta t} + \frac{\Delta PE}{\delta t} \quad (5-14)$$

As (δt) approaches zero,

$$\lim_{\delta t \rightarrow 0} \frac{\delta Q}{\delta t} = \dot{Q}, \quad \lim_{\delta t \rightarrow 0} \frac{\delta W}{\delta t} = \dot{W}, \quad \lim_{\delta t \rightarrow 0} \frac{\Delta U}{\delta t} = \frac{dU}{dt}, \quad \lim_{\delta t \rightarrow 0} \frac{\Delta KE}{\delta t} = \frac{d(KE)}{dt}, \quad \lim_{\delta t \rightarrow 0} \frac{\Delta PE}{\delta t} = \frac{d(PE)}{dt}$$

$$\therefore \dot{Q} - \dot{W} = \frac{dU}{dt} + \frac{d(KE)}{dt} + \frac{d(PE)}{dt}$$

$$\therefore dE = dU + d(KE) + d(PE)$$

$$\therefore \dot{Q} - \dot{W} = \frac{dE}{dt}$$

$$\dot{Q} = \frac{dE}{dt} + \dot{W}$$

The term $\frac{dE}{dt}$ represents the change of intrinsic energy of mass within the system.

Example (5-3)

A wet steam with a dryness fraction of 0.95 expanding inside the cylinder of a steam engine from 7 bar to 0.34 bar. The expansion process follows the law $Pv^{1.1} = C$. Calculate the work done and the heat exchanged per kg steam during the process.

Since the steam is expanding inside a closed cylinder it follows the non-flow energy equation.

$$Q = (U_2 - U_1) + W$$

From saturated steam table find v_g at 7 bar,

$$v_g = 0.2728 \text{ m}^3/\text{kg}$$

$$v_1 = x_1 v_g = 0.95 \times 0.2728 = 0.259 \text{ m}^3/\text{kg}$$

$$P_1 v_1^{1.1} = P_2 v_2^{1.1}$$

$$v_2 = v_1 \left(\frac{P_1}{P_2} \right)^{\frac{1}{1.1}} = 0.259 \times \left(\frac{7}{0.34} \right)^{\frac{1}{1.1}} = 4.05 \text{ m}^3/\text{kg}$$

$$w = \int_1^2 P dv = \int_1^2 C \frac{dv}{v^{1.1}}$$

$$w = \frac{P_1 v_1 - P_2 v_2}{n - 1}$$

$$\therefore w = \frac{7 \times 10^5 \times 0.259 - 0.34 \times 10^5 \times 4.05}{1.1 - 1} \times 10^{-3} = 436 \text{ kJ/kg}$$

From saturated steam table find v_g at 0.34 bar,

$$v_g = 4.649 \text{ m}^3/\text{kg}$$

Since $v_2 < v_g$ the steam remains wet at the end of process.

$$x_2 = \frac{v_2}{v_g} = \frac{4.05}{4.649} = 0.873$$

$$u_1 = u_f + x_1 (u_g - u_f) = 696 + 0.95 \times (2573 - 696) = 2476.8 \text{ kJ/kg}$$

$$u_2 = u_f + x_2 (u_g - u_f) = 302 + 0.873 \times (2472 - 302) = 2196.4 \text{ kJ/kg}$$

$$q - w = u_2 - u_1$$

$$q = (u_2 - u_1) + w = (2196.4 - 2476.8) + 436 = 155.6 \text{ kJ/kg}$$

Since the sign is positive the heat is supplied to the cylinder.

Example (5-4)

A closed solid vessel contains 1 m³ of steam at 20 bar and 400 °C. The vessel is cooled until the steam inside becomes saturated steam. Calculate the mass of steam inside the vessel, the final pressure and the heat lost due to cooling.

Since the vessel is closed the steam follows the non-flow energy equation.

$$Q = (U_2 - U_1) + W$$

First find the initial quality of steam.

From saturated steam table the saturation temperature at 20 bar is 212.42 °C. Since the actual temperature of steam is higher than the saturation temperature at the same pressure the steam is superheated.

From superheated steam table we find,

$$u_1 = 2945 \text{ kJ/kg}$$

$$v_1 = 0.1512 \text{ m}^3/\text{kg}$$

$$m = \frac{V}{v_1} = \frac{1}{0.1512} = 6.614 \text{ kg}$$

Since the vessel is solid,

$$v_2 = v_1 = 0.1512 \text{ m}^3/\text{kg}$$

Since the steam is saturated at the end of cooling process then,

$$\therefore v_g = v_2 = 0.1512 \text{ m}^3/\text{kg}$$

From saturated steam table we find that the pressure corresponds to this value of v_g is 1.3 bar.

$$\therefore P_2 = 1.3 \text{ bar}$$

$$u_2 = u_g = 2591 \text{ kJ/kg}$$

Since the vessel is solid and closed its volume remains constant and no work is done during the process.

$$W = 0.0$$

$$\therefore Q = m(u_2 - u_1) + W$$

$$\therefore Q = m(u_2 - u_1) = 6.614 \times (2591 - 2945) = -2341.4 \text{ kJ}$$

This is a heat lost since it is a cooling process.