Lecture 4

Laws of Thermodynamics

Coverage

- Laws of conservation of energy, first law of thermodynamics (Joule’s experiment), Application of first law of thermodynamics to non-flow systems –Constant volume, constant pressure, Adiabatic and polytropic processes, steady flow energy equation, Application of steady flow energy to equation, turbines, pump, boilers, compressors, nozzles, condenser, limitations. Heat source and heat sinks, statement of second laws of thermodynamics: Kelvin Planck’s statement, Classius statement, equivalence of statements, Perpetual motion Machine of first kind, second kind, Carnot engine, Introduction of third law of thermodynamics, concept of irreversibility, entropy.

Laws of conservation of energy

- Energy can neither be created nor destroyed but can be transformed to other forms
- This law can be dissected into 3 statements;
  - Energy cannot be created
  - Energy cannot be destroyed
  - It can only be converted from one form to another.

Laws of conservation of energy cont…

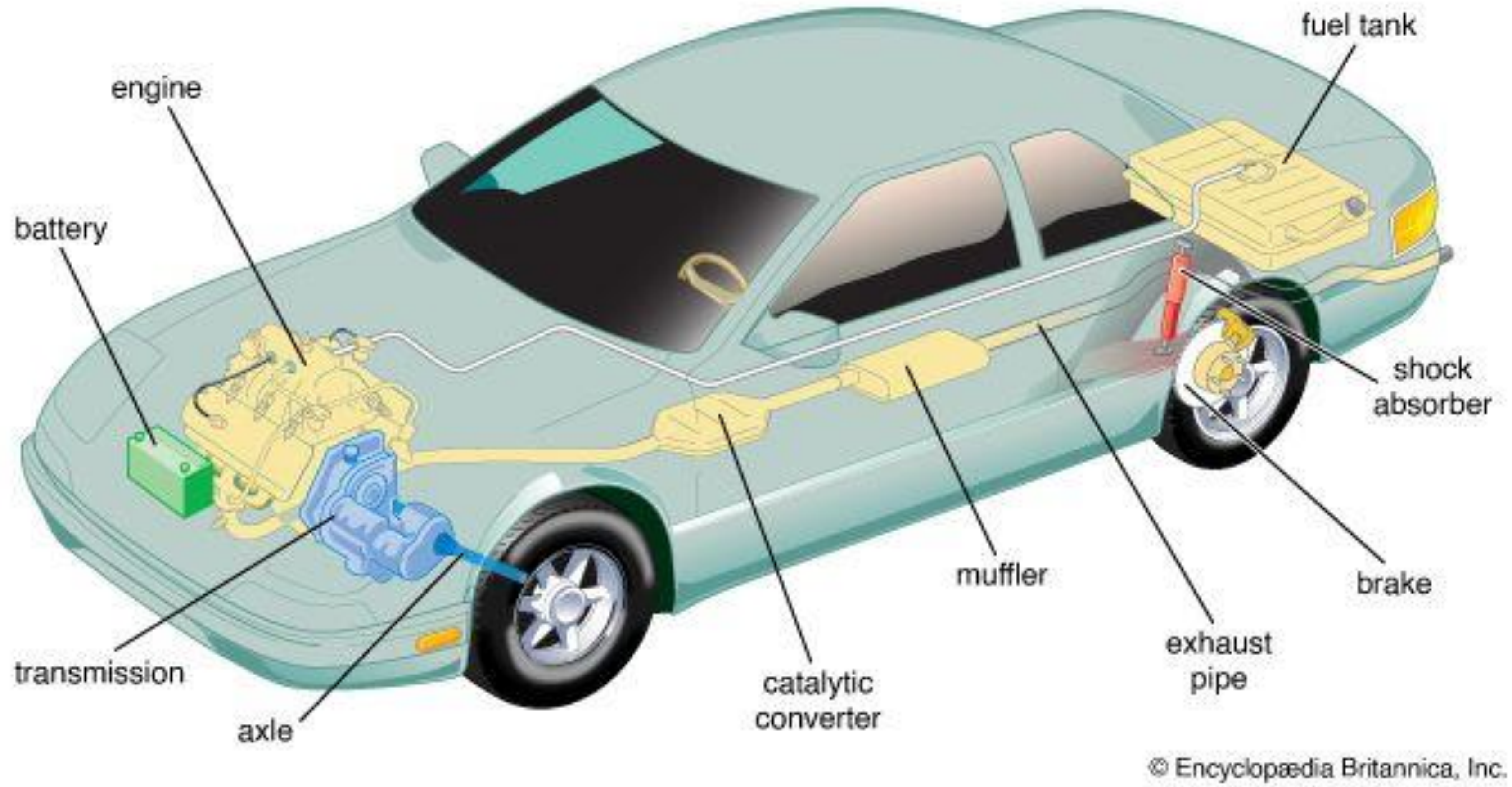
- Energy of an object can be thought of as the sands in an hourglass!
- Energy always remain same or fixed in quantity!
- But this sand can change position, from the top to bottom and bottom to top! likewise energy can change in form eg. From KE <==> PE
- Energy can be changed from one form to another.
- Changes in the form of energy are called energy conversions.
- All forms of energy can be converted into other forms.

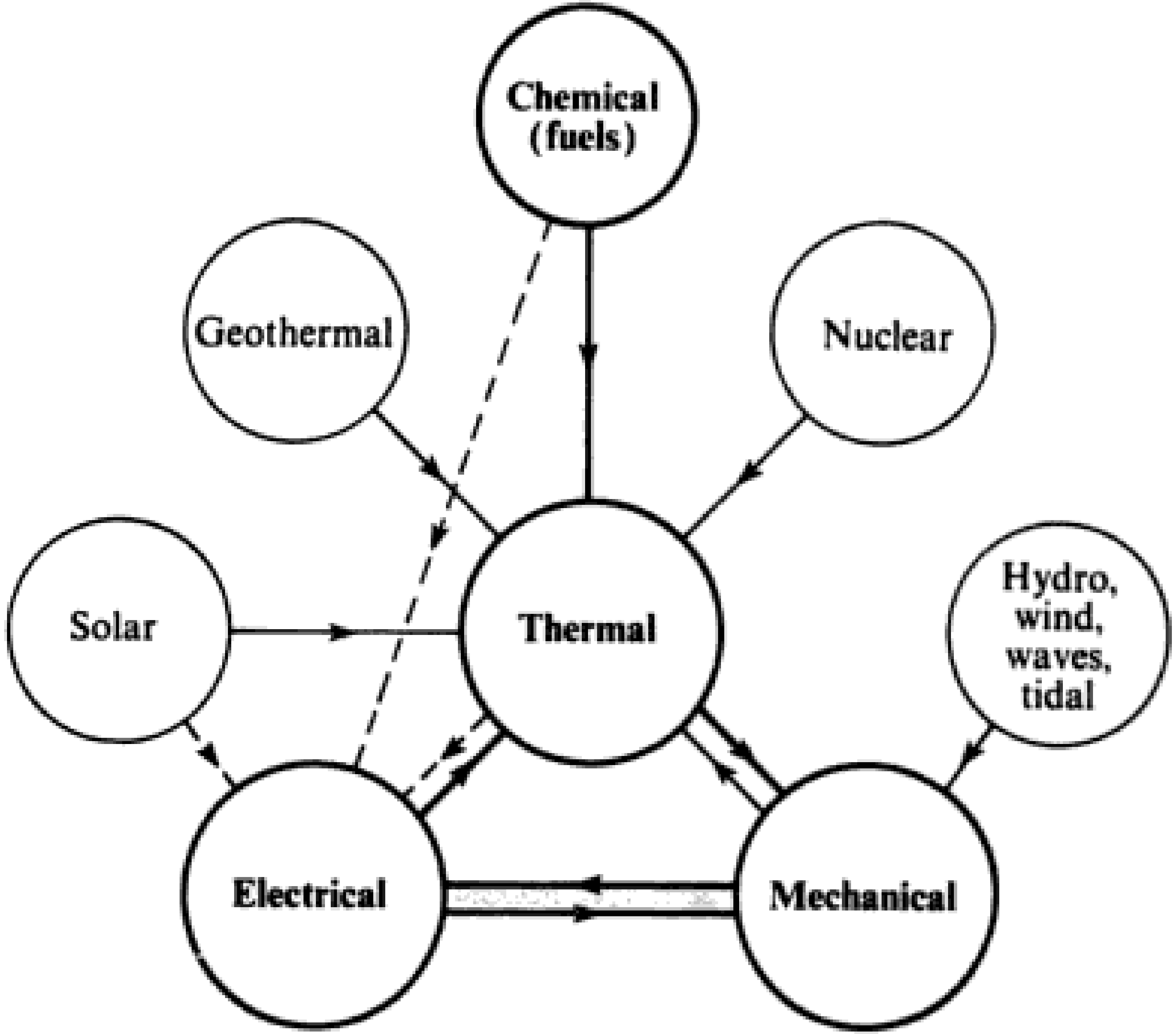
Laws of conservation of energy cont…

- The sun's energy through solar cells can be converted directly into electricity.
- Green plants convert the sun's energy electromagnetic into starches and sugars(chemical energy)
- In an electric motor, electromagnetic energy is converted to mechanical energy.
- In battery, chemical energy is converted into electromagnetic energy.
- The mechanical energy of a waterfall is converted to electrical energy in a generator.

Laws of conservation of energy cont…

- In an automobile engine, fuel is burned to convert chemical energy into heat energy. The heat energy is then changed into mechanical energy.





Chemical (fuels)
Geothermal
Nuclear
Solar
Thermal
Hydro, wind, waves, tidal
Electrical
Mechanical

Application of first law of thermodynamics

- First law of thermodynamics also states that, "the energy can neither be created nor be destroyed it can only be transformed from one form to another”.
- According to this law, when a system undergoes a thermodynamic process, both heat and work transfer takes place.
- The net energy is stored within the system and is termed as stored energy or total energy of the system, Mathematically it is written as:

$$\delta Q - \delta W = dE$$

Application of first law of thermodynamics cont…

First law of thermodynamics for a cyclic process

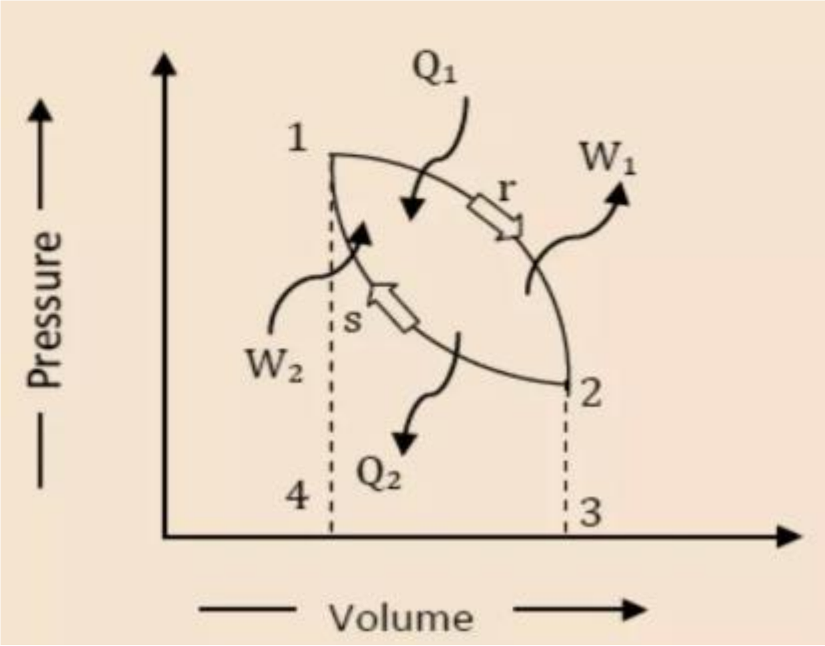
- A process is cyclic if the initial and final states of the system are identical. A system represented by state 1 undergoes a process 1-r-2 and returns to the initial state following the path 2-s-1. All the properties of the system are restored, when the initial and final state is reached.

  During the completion of these processes:

  (a)Area 2-3-4-1-r-2 denotes the work done W1 by the system during expansion process 2-s-1.

  (b)Area 4-3-1-s-2 denotes the net work done W2 supplied to the system during the compression process 4-s-1.

  (c)Area 1-r-2-s-1 denotes the net work done (W1-W2) derived by the system



Application of first law of thermodynamics cont…

According to first law of thermodynamics, "when a closed system undergoes a thermodynamic cycle the net heat transfer is equal to net work done.“

OR

The cyclic integral of heat transfer is equal to cyclic integral of work done" Mathematically it is written as:

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

On integrating the above equation for a thermodynamic state 1 to 2, we get;

$$\int_1^2 \delta Q - \int_1^2 \delta W = \int_1^2 dE$$

$$Q_{1-2} - W_{1-2} = E_2 - E_1$$

Where,

Q1-2 =heat transferred to the system during the process 1 to 2

W1-2= Work transfer by the system during the process 1 to 2

E1 = Total energy of the system at state 1

E2 = Total energy of the system at state 2

Application of first law of thermodynamics cont…

Note: The total energy is the sum of potential energy, kinetic energy and internal energy of the system. Its mathematically written as:

$$E = P.E. + K.E. + U$$

$$E = mgz + \frac{mv^2}{2} + U$$

Where, P.E.= Potential energy

K.E.= Kinetic energy,

U= Internal Energy

Application of first law of thermodynamics cont…

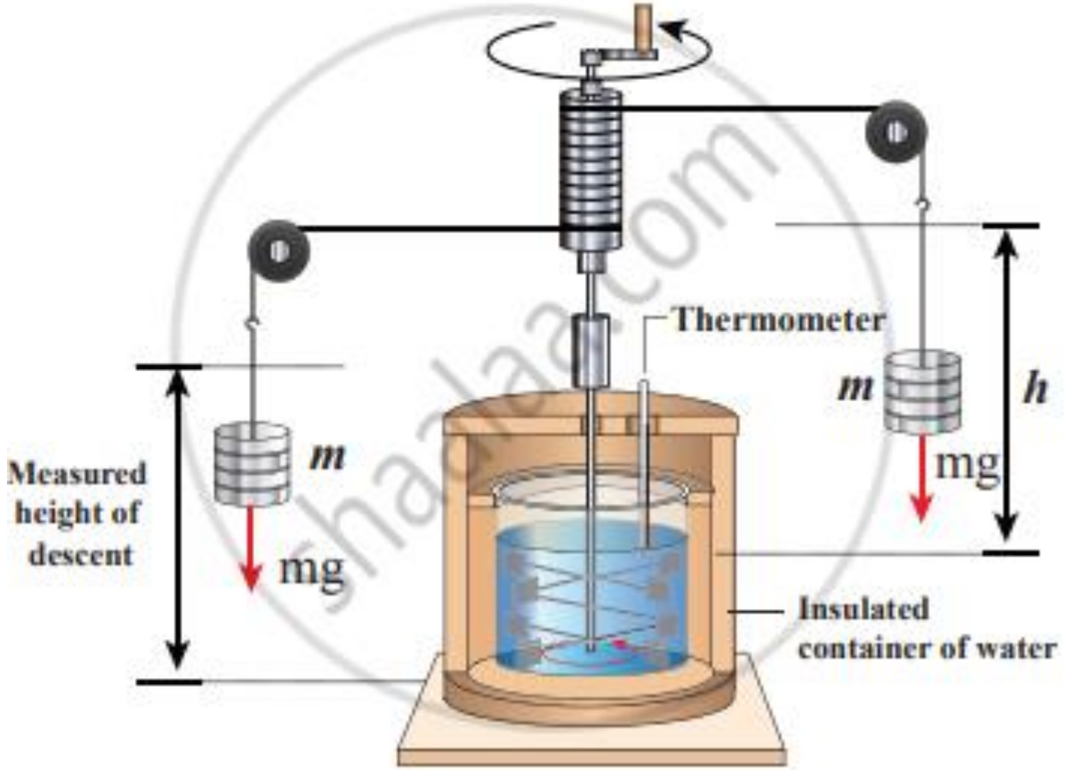
- **Internal Energy**: Internal energy of steam is define as the energy stored in the steam, above 0^{o}C(freezing point) of water. It may be obtained by subtracting the work done during evaporation to the enthalpy of steam, It is represented by U, Mathematically it is written as,

  Internal energy of steam=Enthalpy of steam - Workdone during evaporation

- **Enthalpy**: It is defined as the amount of heat absorbed by water from 0^{o}C (freezing point) to saturation point (sensible heat) plus heat absorbed during evaporation (latent heat). It is represented by hg.
- So that, Enthalpy=Sensible heat + Latent heat

Joule’s experiment

- In his experiment, two masses were attached with a rope and a paddlewheel as shown in Fiqure. When these masses fall through a distance of ***h*** due to gravity, both the masses lose potential energy equal to ***2 mgh***.
- When the masses fall, the paddlewheel turns. Due to the turning of the wheel inside the water, the frictional force comes in between the water and the paddlewheel.



Joule's experiment cont…

- This causes a rise in the temperature of the water. This implies that gravitational potential energy is converted to the internal energy of water. The temperature of water increases due to the work done by the masses, in fact, Joule was able to show that the mechanical work has the same effect as giving heat. He found that to raise of an object by $1^{o}c$, 4.186 J of energy is required. In earlier days the heat was measured in calories.

  1 cal = 4.186J

- This is called Joule's mechanical equivalent of heat.

Steady Flow Energy Equation

- Assume the flow through a system as shown in figure. During a small time interval ***dt*** there occurs a flow of mass and energy into a fixed control volume; entry is at point 1 and exit at point 2.
- The fluid enters the control volume at point 1 with a average velocity V_1, pressure P_1, specific volume v_1, and internal energy U_1.
- The fluid exit the control volume at point 2 and the corresponding values are V_2, P_2, v_2, U_2. During the fluid flow from the two sections, heat ***Q*** and mechanical work ***W*** may also cross the control surface.

Steady Flow Energy Equation cont…

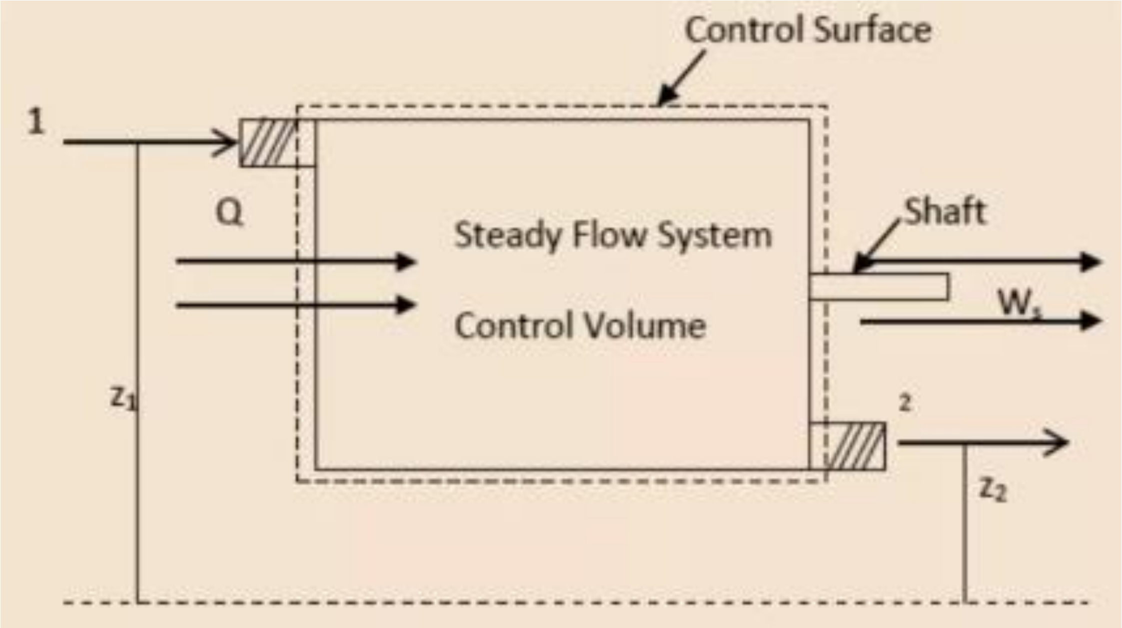
The following points are taken into consideration for energy balance equation:

(i)Internal energy

(ii) Kinetic and potential energies.

(iii) Flow work

(iv)Heat and mechanical work which cross the control volume.



Steady Flow Energy Equation cont…

From the law of conservation of energy, energy neither be created nor be destroyed we can write,

Total energy flow rate into the control volume = Total energy flow rate out of control volume

m(energy carried into the system)+m(flow work)+ rate of heat flow	=	m(energy carried out of the system)+m(flow work)+ rate of work transfer
m(I.E.+P.E.+K,E)$_1$ +m(flow work)$_1$ +$\dot{Q}$	=	m(I.E.+P.E.+K.E.)$_2$ +m(flow work)$_2$ + $\dot{W}$

Where, $\dot{Q} = \frac{dQ}{dt}$ $and\ \dot{W} = \frac{dW}{dt}$

$$m\left(U_1 + qz_1 + \frac{V_1^2}{2}\right) + m(P_1 v_1) + \dot{Q} = m\left(U_2 + qz_2 + \frac{V_2^2}{2}\right) + m(P_2 v_2) + \dot{W}$$

Steady Flow Energy Equation cont…

- Rearranging the equation,

$$m\left(U_1 + P_1 v_1 + g z_1 + \frac{V_1^2}{2}\right) + \dot{Q} = m\left(U_2 + P_2 v_2 + g z_2 + \frac{V_2^2}{2}\right) + \dot{W}$$

- Since *h=U+Pv*, so that $h_1 = U_1 + P_1 v_1$ and $h_2 = U_2 + P_2 v_2$

$$\boldsymbol{m\left(h_1 + q z_1 + \frac{V_1^2}{2}\right) + \dot{Q} = m\left(h_2 + q z_2 + \frac{V_2^2}{2}\right) + \dot{W}}$$

- This is known as steady flow energy equation.
- If mass of fluid is taken as unity then steady flow energy equation is reduced to;

$$\boldsymbol{\left(h_1 + q z_1 + \frac{V_1^2}{2}\right) + q = \left(h_2 + q z_2 + \frac{V_2^2}{2}\right) + w}$$

- All the terms represent energy flow per unit mass fluid [J/kg]

Applications of Steady flow energy equation

Steady flow energy equation is commonly used in flow processes in many engineering plants. Some commonly used engineering systems which works on steady flow energy equation are as follows:

- turbines,
- pump,
- boilers,
- compressors,
- nozzles,
- condenser/ evaporators,

Applications of Steady flow energy equation cont…

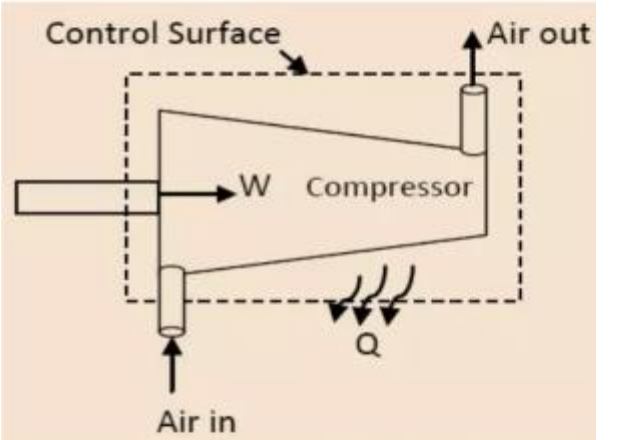
(i)Compressor: Compressor is a device which is used to compress the fluid (may be air) and deliver it at a high pressure and large flow rate. There are two types of compressors as follows:

- (a)Rotary compressor
- (b)Reciprocating compressor

Rotary compressor: Rotary compressors are the devices which are used to develop high pressure and have a rotor as their primary element. The characteristic features of flow through a rotary compressor are:

- Work is done on the system so that W is negative.
- Negligible change in Potential energy.
- Heat is lost from the system so that Q is negative.

Applications of Steady flow energy equation cont…



Steady flow energy equation may be written as follows:

$$m\left(h_1+\frac{V_1^2}{2}\right)+Q=m\left(h_2+\frac{V_2^2}{2}\right)+W$$

Or

$$W=m\left(h_2+\frac{V_2^2}{2}\right)-m\left(h_1+\frac{V_1^2}{2}\right)+Q$$

If the change in velocity is negligible and the flow process is assumed as adiabatic (i.e. Q=0)due to very high flow rates, then

$$W=m(h_2+h_1)$$

Applications of Steady flow energy equation cont…

- **Reciprocating compressor**: Reciprocating compressors are the devices which are used to develop high pressure and have a piston cylinder arrangement as their primary element, The characteristic features of flow through a rotary compressor are:
  - Work is done on the system so that W is negative.
  - Negligible change in Potential energy.
  - Heat is lost from the system so that Q is negative.

Applications of Steady flow energy equation cont…

Steady flow equation may be written as follows

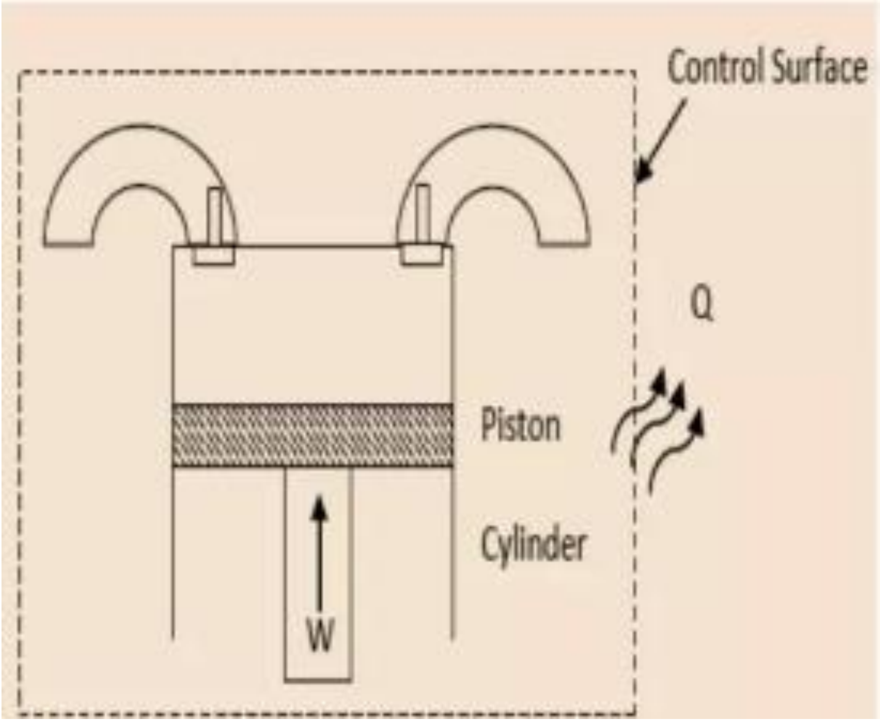
$$m\left(h_1+\frac{V_1^2}{2}\right)+Q=m\left(h_2+\frac{V_2^2}{2}\right)+W$$

Or

$$W=m\left(h_2+\frac{V_2^2}{2}\right)-m\left(h_1+\frac{V_1^2}{2}\right)+Q$$

If the change in velocity is negligible, then;

$$W=m(h_2+h_1)+Q$$



Applications of Steady flow energy equation cont…

(ii)Condenser: Condenser is a type of heat exchanger. It is used to transfer heat from one fluid to another. The characteristic features of a condenser are as follows:

No mechanical work (i.e., W=0).

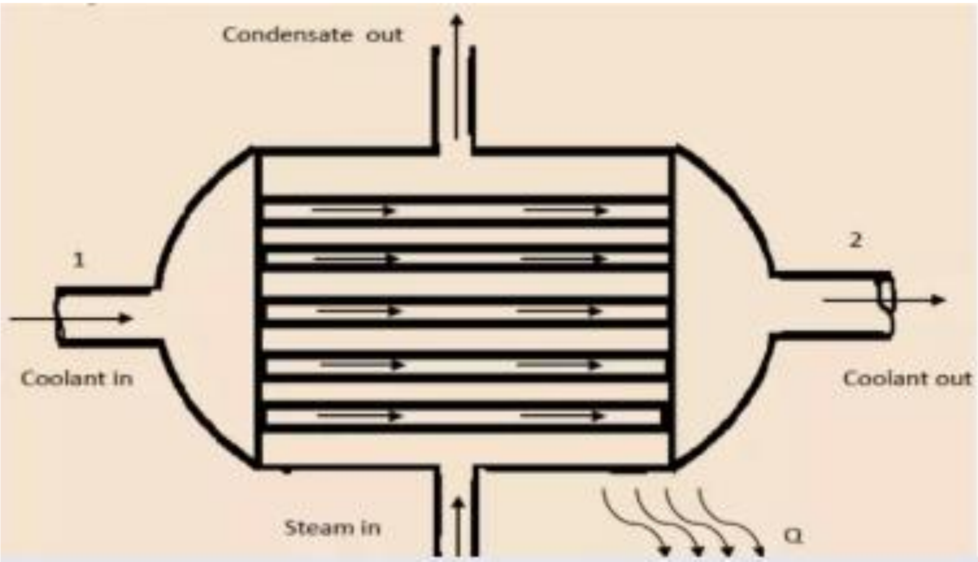
No change in kinetic and potential energies.

No external heat interaction (Since it is perfectly insulated).Heat is absorbed by the one fluid (Steam) to the another fluid (coolant), so that heat is taken negative.

Thus steady flow energy equation reduces to;

- $\boldsymbol{m\left(h_1 + qz_1 + \frac{V_1^2}{2}\right) + Q = m\left(h_2 + qz_2 + \frac{V_2^2}{2}\right) + W}$

$$\boldsymbol{h_1 - Q = h_2}$$
$$\boldsymbol{Q = h_1 - h_2}$$



Applications of Steady flow energy equation cont…

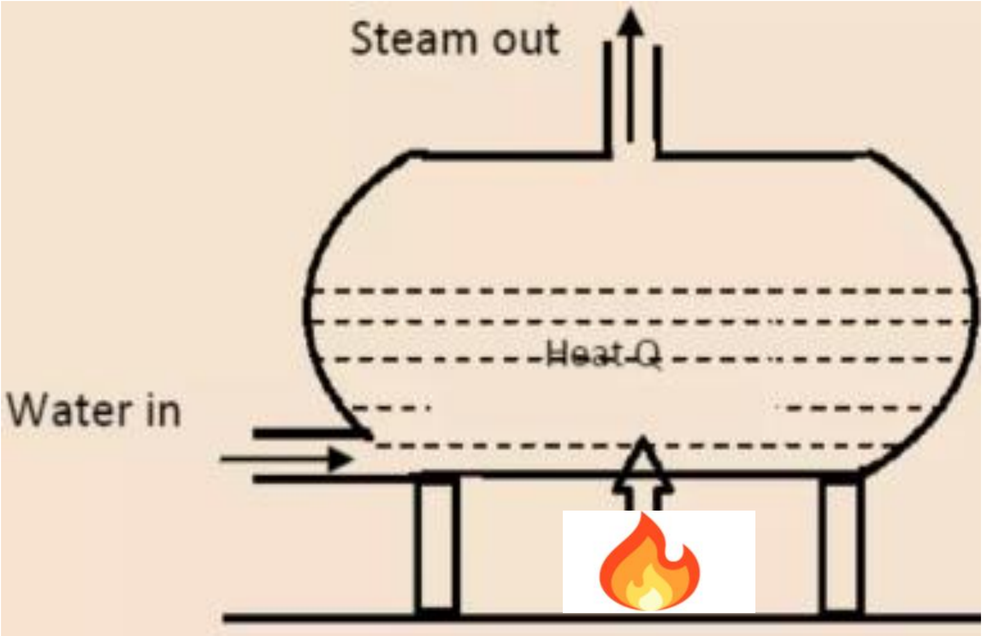
(iii)Boiler: Boiler is an equipment used for generation of steam, Thermal energy released by combustion of fuel is transferred to water which vaporizes and gets converted into steam.

The characteristic features of a boiler are as follows:

No mechanical work (i.e., W=0).
No change in kinetic and potential energies
Height change between inlet and exit point is negligible.
Thus steady flow energy equation reduces to;

$$m\left(h_1 + qz_1 + \frac{V_1^2}{2}\right) + Q = m\left(h_2 + qz_2 + \frac{V_2^2}{2}\right) + W$$

$$h_1 + Q = h_2$$
$$Q = h_2 - h_1$$



Applications of Steady flow energy equation cont…

(iv) Turbine: Turbine is a device which converts thermal energy into useful work. In turbine fluids expand from high pressure to a low pressure. The work output from the turbine may be used to drive a generator to produce electricity. The characteristic features of a turbine are as follows:

Negligible change in velocity so that negligible change in kinetic energy.

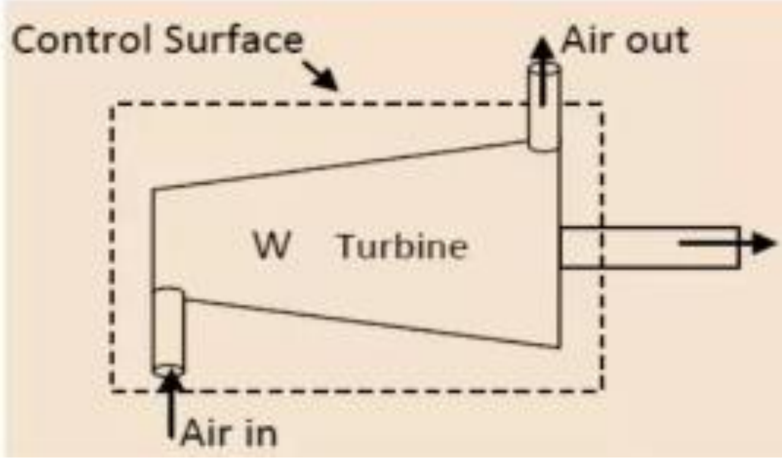
Negligible change in potential energy.

Isentropic expansion takes place since the walls of turbine are thermally insulated.

Thus steady flow energy equation reduces to,

- $$m\left(h_1 + qz_1 + \frac{V_1^2}{2}\right) + Q = m\left(h_2 + qz_2 + \frac{V_2^2}{2}\right) + W$$

$$W = m(h_2 - h_1)$$



Applications of Steady flow energy equation cont…

(v)Nozzle: Nozzle is a device of varying cross-section used for increasing the velocity of a flowing stream at the expense of its pressure drop. In nozzle pressure energy of the fluid is converted into kinetic energy.

It is used in turbines, fuel pumps and jet engines etc.

The characteristic features of a nozzle are as follows:

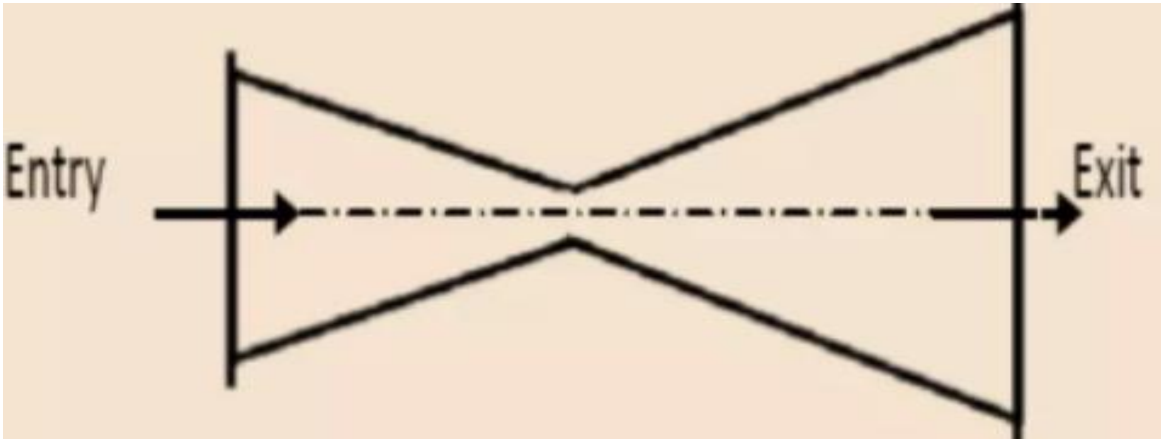
- No mechanical work (i.e. W=0)
- Flow is isentropic (i.e. Q=0)
- Change in height between entry and exit is negligible. (i.e.$z_1=z_2$,)

Thus steady flow energy equation reduces to;

$$\left(\boldsymbol{h_1} + \frac{\boldsymbol{V_1^2}}{\boldsymbol{2}}\right) = \left(\boldsymbol{h_2} + \frac{\boldsymbol{V_2^2}}{\boldsymbol{2}}\right)$$

Let V_1 is known then;

$$V_2 = \sqrt{2(h_1 - h_2) + V_1^2}$$

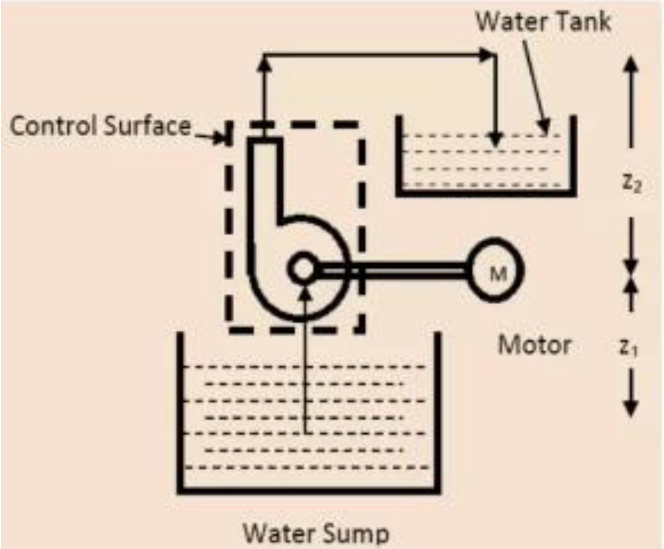


Applications of Steady flow energy equation cont…

(vi) Pump: A pump is a device which takes the fluid from a low level and delivers it to a high level. The characteristic features of a pump are as follows:

- Flow is assumed to be adiabatic (i.e. Q=0)
- No change in internal energy.
- Work is done on the system, so that work is taken negative.

Thus steady flow energy equation reduces to;



$$m\left(h_1 + qz_1 + \frac{V_1^2}{2}\right) + Q = m\left(h_2 + qz_2 + \frac{V_2^2}{2}\right) + W$$

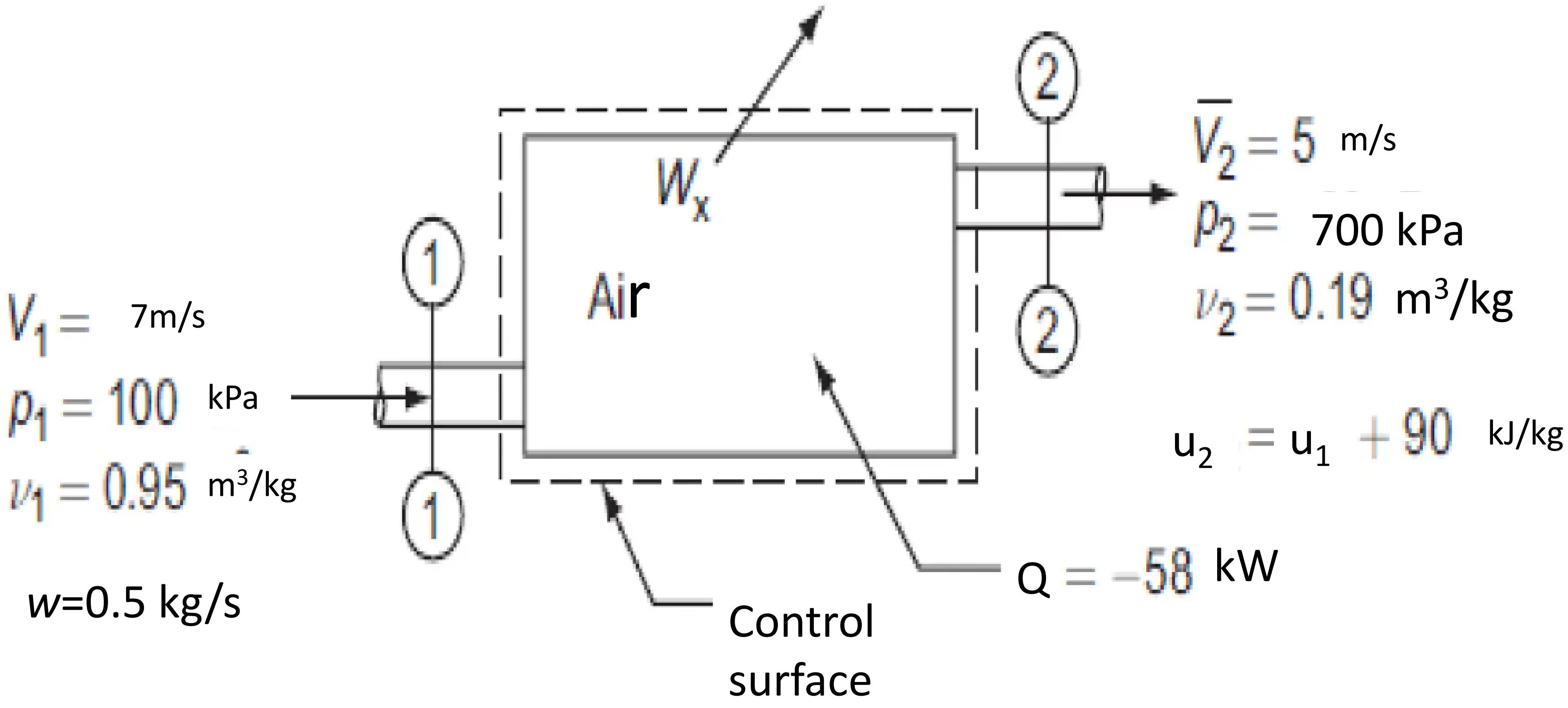
$$m\left(qz_1 + \frac{V_1^2}{2}\right) = m\left(qz_2 + \frac{V_2^2}{2}\right) - W$$

Example 1

Air flows steadily at the rate of 0.5 kg/s through an air compressor, entering at 7m/s velocity, 100 kPa pressure, and 0.95 m^3/kg volume, and leaving at 5 m/s, 700 kPa, and 0.19 m^3/kg. The internal energy of the air leaving is 90 kJ/kg greater than that of the air entering. Cooling water in the compressor jackets absorbs heat from the air at the rate of 58 kW.

(a) Compute the rate of shaft work input to the air in kW.

(b) Find the ratio of the inlet pipe diameter to outlet pipe diameter.



W_x
Air
$V_1 =$ 7m/s
$p_1 = 100$ kPa
$v_1 = 0.95$ m³/kg
w=0.5 kg/s
1
1
2
2
$\bar{V}_2 = 5$ m/s
$p_2 =$ 700 kPa
$v_2 = 0.19$ m³/kg
$u_2 = u_1 + 90$ kJ/kg
$Q = -58$ kW
Control surface

(a) Writing the steady flow energy equation, we have

$$w\left(u_1 + p_1 v_1 + \frac{V_1^2}{2} + z_1 g\right) + \frac{dQ}{d\tau} = w\left(u_2 + p_2 v_2 + \frac{V_2^2}{2} + z_2 g\right) + \frac{dW_x}{d\tau}$$

$$\therefore \quad \frac{dW_x}{d\tau} = -w\left[(u_2 - u_1) + (p_2 v_2 - p_1 v_1) + \frac{V_2^2 - V_1^2}{2} + (z_2 - z_1) g\right] + \frac{dQ}{d\tau}$$

$$\therefore \quad \frac{dW_x}{d\tau} = -0.5\,\frac{\text{kg}}{\text{s}}\left[90\,\frac{\text{kJ}}{\text{kg}} + (7 \times 0.19 - 1 \times 0.95)\,100\,\frac{\text{kJ}}{\text{kg}}\right.$$

$$\left. + \frac{(5^2 - 7^2) \times 10^{-3}}{2}\,\frac{\text{kJ}}{\text{kg}} + 0\right] - 58\ \text{kW}$$

$$= -0.5\ \ 90 + 38 - 0.012\ \ \text{kJ/s} - 58\ \text{kW}$$

$$= -122\ \text{kW}$$

Ans. (a)

Rate of work input is 122 kW.

(b) From mass balance, we have

$$w = \frac{A_1\mathbf{V}_1}{\nu_1} = \frac{A_2\mathbf{V}_2}{\nu_2}$$

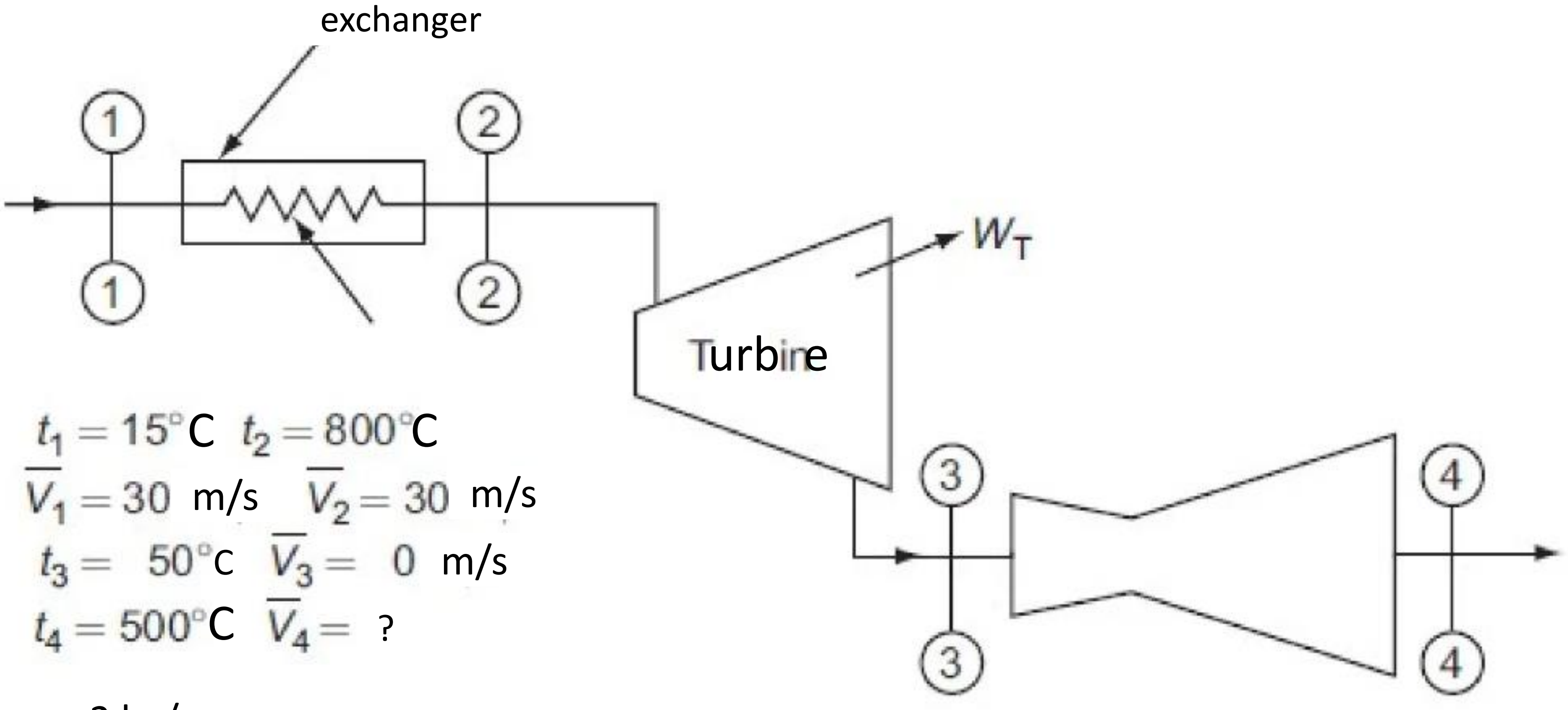
$$\therefore \qquad \frac{A_1}{A_2} = \frac{\nu_1}{\nu_2}\cdot\frac{\mathbf{V}_2}{\mathbf{V}_1} = \frac{0.95}{0.19} \times \frac{5}{7} = 3.57$$

$$\therefore \qquad \frac{d_1}{d_2} = \sqrt{3.57} = 1.89$$

Example 2

Air at a temperature of 15^oC passes through a heat exchanger at a velocity of 30 m/s where its temperature is raised to 800^oC.It then enters a turbine with the same velocity of 30 m/s and expands until the temperature falls to 650^oC. After leaving the turbine, the air is taken at a velocity of 60 m /s to a nozzle where it expands until the temperature has fallen to 500^oc. lf the air flow rate is 2kg/s, calculate (a) the rate of heat transfer to the air in the heat exchanger, (b)the power output from the turbine assuming no heat loss, and (c) the velocity at exit from the nozzle, assuming no heat loss.

Take the enthalpy of air as $\mathbf{h= c_p t}$, where $\mathbf{c_p}$ is the specific heat equal to 1.005 kJ/kgK and **t** is the temperature.



$t_1 = 15°C$ $t_2 = 800°C$
$\overline{V_1} = 30$ m/s $\overline{V_2} = 30$ m/s
$t_3 = 50°C$ $\overline{V_3} = 0$ m/s
$t_4 = 500°C$ $\overline{V_4} =$?

w=2 kg/s

$$w\left(h_1 + \frac{V_1^2}{2} + z_1 g\right) + Q_{1-2} = w\left(h_2 + \frac{V_2^2}{2} + z_2 g\right) + W_{1-2}$$

$$wh_1 + Q_{1-2} = wh_2$$

$$Q_{1-2} = w(h_2 - h_1) = wc_p(t_2 - t_1) = 2 \times 1.005\ (800 - 15) = 2.01 \times 785$$

$$= 1580 \text{ kJ/s}$$ *Ans.* (a)

Energy equation for the turbine gives

$$w\left(\frac{V_2^2}{2} + h_2\right) = wh_3 + w\,\frac{V_3^2}{2} + W_T$$

$$\frac{V_2^2 - V_3^2}{2} + (h_2 - h_3) = W_T/w$$

$$\frac{(30^2 - 60^2) \times 10^{-3}}{2} + 1.005\ (800 - 650) = W_T/w$$

$$\therefore \quad \frac{W_T}{w} = 1.35 + 150.75 = 149.4 \text{ kJ/kg}$$

$$\therefore \quad W_T = 149.4 \times 2 \text{ kJ/s}$$

$$= 298.8 \text{ kW}$$ *Ans.* (b)

Writing the energy equation for the nozzle

$$\frac{V_3^3}{2} + h_3 = \frac{V_4^2}{2} + h_4$$

$$\frac{V_4^2 - V_3^2}{2} = c_p (t_3 - t_4)$$

$$V_4^2 - V_3^2 = 1.005\,(650 - 500) \times 2 \times 10^3 = 301.50 \times 10^3 \text{ m}^2/\text{s}^2$$

$$V_4^2 = 30.15 \times 10^4 + 0.36 \times 10^4 = 30.51 \times 10^4 \text{ m}^2/\text{s}^2$$

$\therefore$ Velocity at exit from the nozzle

$$V_4 = 554 \text{ m/s}$$ *Ans.* (c)

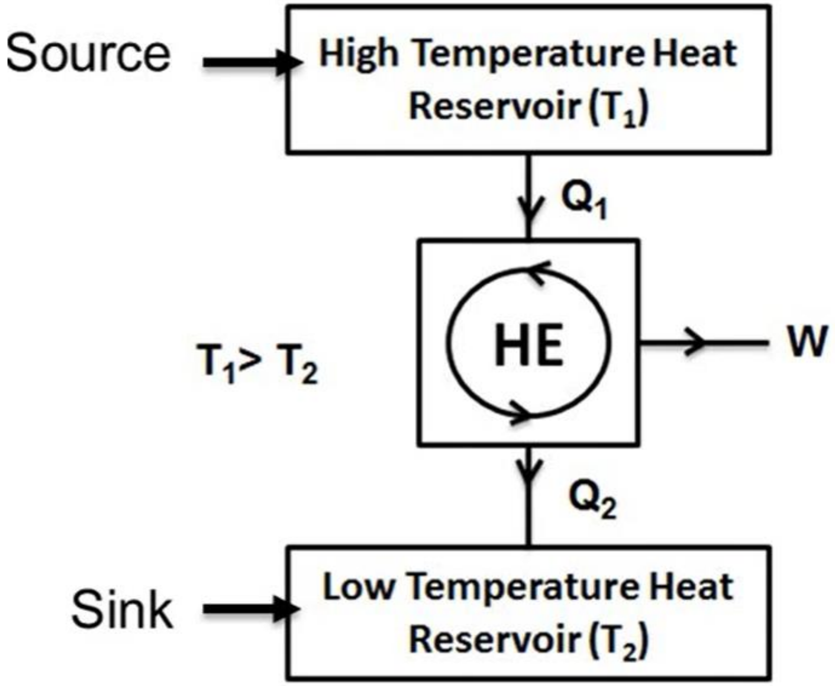
Limitation of the 1st law

- The process can not be proceed in a particular direction only e.g. heat transfer take place from hot body to cold body only. But heat can not be flow naturally from cold body to hot body.
- All processes involving conversion of heat into work and vice-versa are not equivalent. The work can not be full converted in to heat, but conversion of heat completely into work is not possible.
- First law provides a necessary but not a sufficient condition for a process to occur.

Thermal energy reservoirs

- A thermal energy reservoir is defined as sufficiently large system in stable equilibrium that can supply or absorb finite amount of heat without any change in its temperature.
- In practice, large bodies of water such as oceans, lakes rivers, and atmospheric air can be considered thermal energy storage capabilities or thermal masses.
- A reservoir that supplies energy in form of heat is called a source, and a reservoir that absorbs energy in form of heat is called a sink as shown in fig.

Thermal energy reservoirs cont…



- It is thermodynamic system operating in a cycle, in which net heat is transferred and net work is produced.
- Heat engine (HE) is work producing device as shown in fig. it is used to produce maximum work from a given positive heat transfer.
- The characteristics of heat engine as follows:

(1) It receives heat from high temperature source.

(2) It converts the part of this heat into work

(3) It rejects the remaining waste heat to a low temperature sink.

(4) It operates on complete thermodynamic cycle.

Thermal energy reservoirs cont…

- By applying firs law to heat engine

$$Q_1 = W + Q_2 \quad \text{or} \quad W = Q_1 - Q_2$$

- Efficiency; $\eta = \frac{Work\ Output}{Heat\ Input}$

$$\eta_{HE} = \frac{W}{Q_1} = \frac{Q_1 - Q_2}{Q_1} = 1 - \frac{Q_2}{Q_1}$$

- For reversible heat engine, $\frac{Q_2}{Q_1} = \frac{T_2}{T_1}$

$$\eta_{HE,rev} = 1 - \frac{Q_2}{Q_1} = 1 - \frac{T_2}{T_1}$$

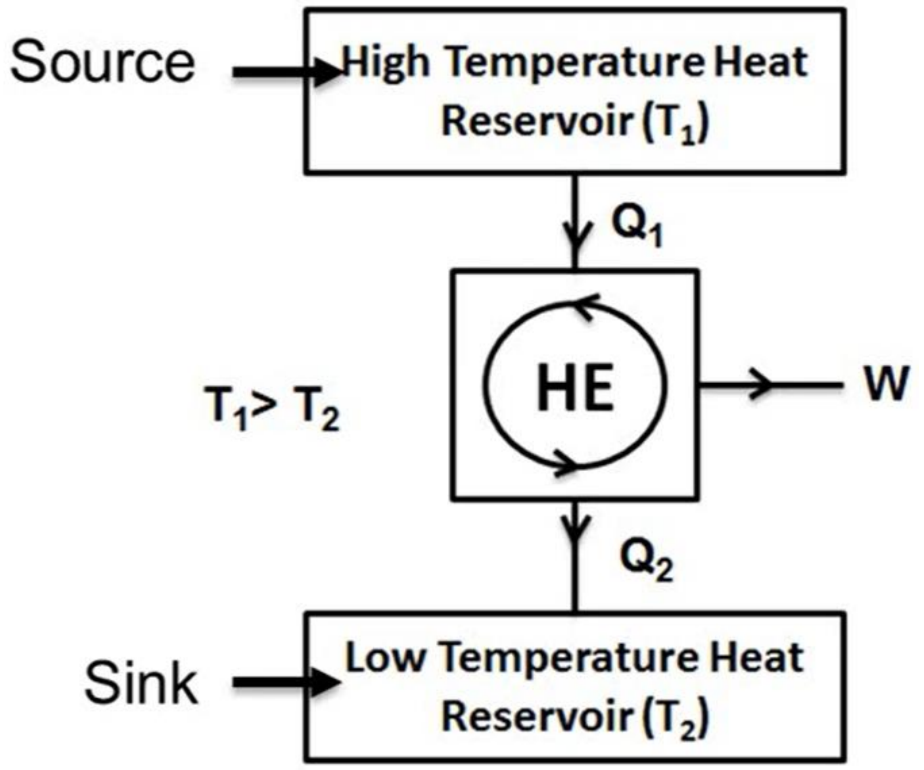
Example

A heat engine operates between source and sink temperatures of 235°C and 30°C respectively, If heat engine receives 35 kW from the source, find

1) Efficiency of the engine.

2) The net work done by the engine and

3) Heat rejected to the sink by the engine



Solution:

Given: $T_1 = 235\ ^oC = 235 + 273 = 508\ K$

$T_2 = 30\ ^oC = 30 + 273 = 303\ K$

$Q_1 = 35\ kW$

$W = ?$, $Q_2 = ?$ and $\eta_{HE} = ?$

$$\eta_{HE,\ rev} = \frac{W}{Q_1} = 1 - \frac{T_2}{T_1}$$

$$\eta_{HE,\ rev} = 1 - \frac{T_2}{T_1} = 1 - \frac{303}{508} = 0.4035 = \underline{\underline{40.35\%}}$$

$$\eta_{HE,\ rev} = \frac{W}{Q_1} \qquad 0.4035 = \frac{W}{35}$$

$$W = 35 \times 0.4035 = \underline{\underline{14.1225\ kW}}$$

$W = Q_1 - Q_2$ $\qquad$ $Q_2 = Q_1 - W$

$$Q_2 = 35 - 14.1225 = \underline{\underline{20.8775\ kW}}$$

Kelvin-Plank statement of 2nd law of thermodynamics

- Kelvin-Plank statement of the second law of thermodynamics, is expressed as follows :

“**It is impossible for any device as heat engine that operates on a cycle to receive heat from a single reservoir and produce a net amount of work”**.

OR

“**No process is possible whose removes heat from a single thermal reservoir at a uniform temperature and performs equal amount of work”.**

Kelvin-Plank statement of 2nd law of thermodynamics cont…

- This statement means that only part of total heat absorbed by heat engine from a high temperature reservoir is converted to work, the remaining must be rejected to a low temperature reservoir.
- A heat engine must exchange heat with at least two thermal reservoirs as a low temperature sink and high temperature source to keep operating.
- A heat engine as shown in figure below, taking heat from a heat source and continuously converting an equal amount of work. This system is satisfying the first law but violating the second law because there is no lower temperature heat reservoir. This type of device (heat engine)is not possible to construct.

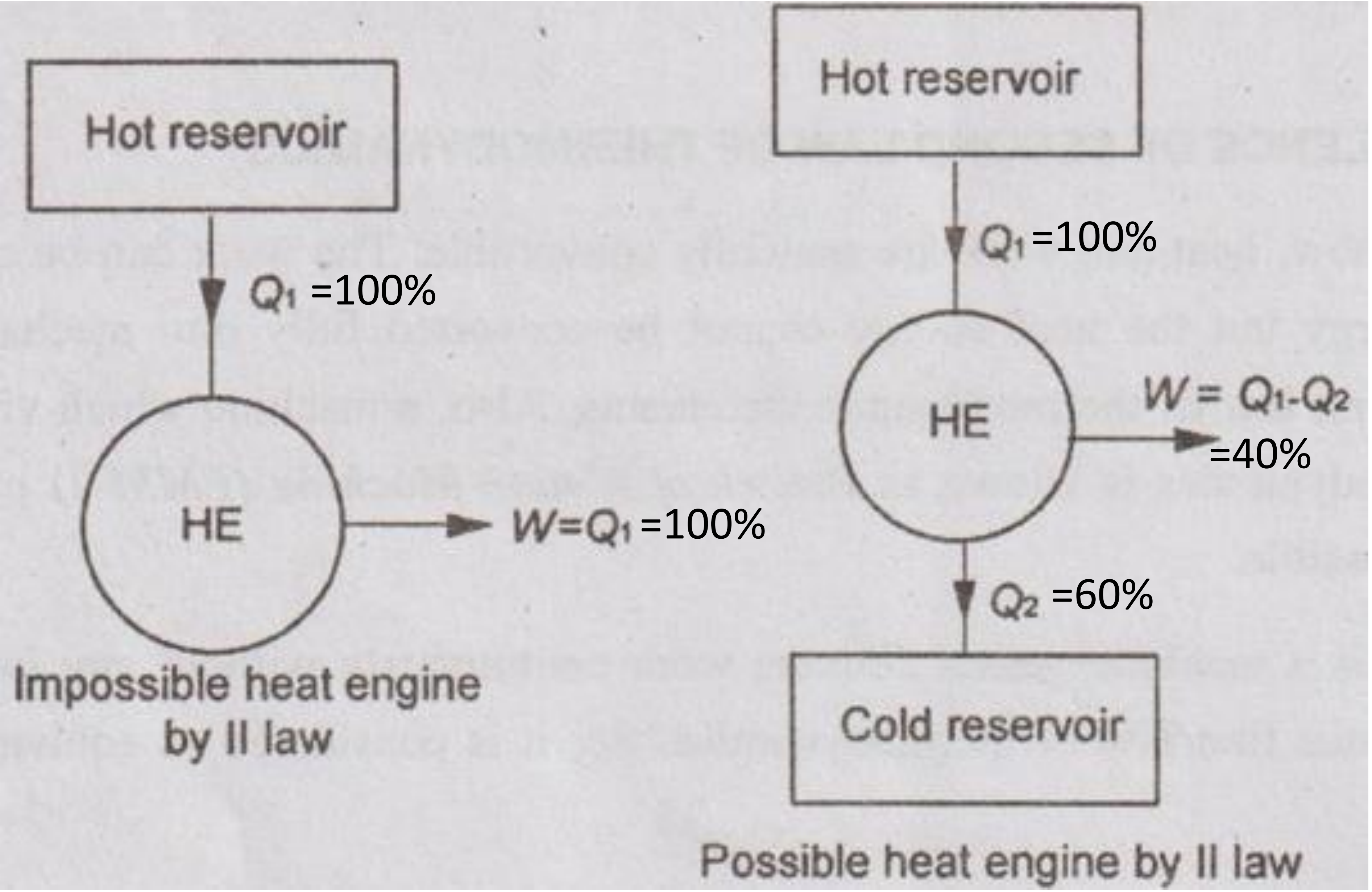


Figure describes ***Kelvin-Planck statement***

Kelvin-Plank statement of 2nd law of thermodynamics cont…

- The Kelvin-Plank statement can also be expressed as follows :

  "No heat engine have a thermal efficiency of 100%."

  OR

  "To operate power plant, working fluid must exchange heat with the furnace as well as the atmosphere."

- Therefore, a heat engine shown in figure, is possible to construct because it is operating between two heat reservoirs one heat source and other heat sink giving efficiency less than 100%, i.e.

$$\frac{W_{net}}{Q_1}\times 100 = \frac{40}{100}\times 100 = 40\%$$

Clausius statement of 2^{nd} law of thermodynamics cont…

- Clausius statement of second law of thermodynamics which is expressed as follows.

“It is impossible to construct a device as heat pump that operates in a cycle and produces no effect other than the transfer of heat from a lower temperature body to a higher temperature body.“

OR

“No process is possible whose removes heat from a reservoir at lower temperature and absorbs equal amount of heat by a reservoir at a higher temperature without any external assistant.“

OR

“Heat cannot itself flow from a colder body to ahotter body."

Clausius statement of 2^{nd} law of thermodynamics cont…

- This statement means that heat cannot flow from cold body to hot body without any energy is supplied inform of work.
- Consider a heat pump as shown in figure, a heat pump absorbs heat from lower temperature body (sink) and rejects heat to higher temperature body(source) without any external work is supplied.
- This is violates second law and it is satisfies the first law.

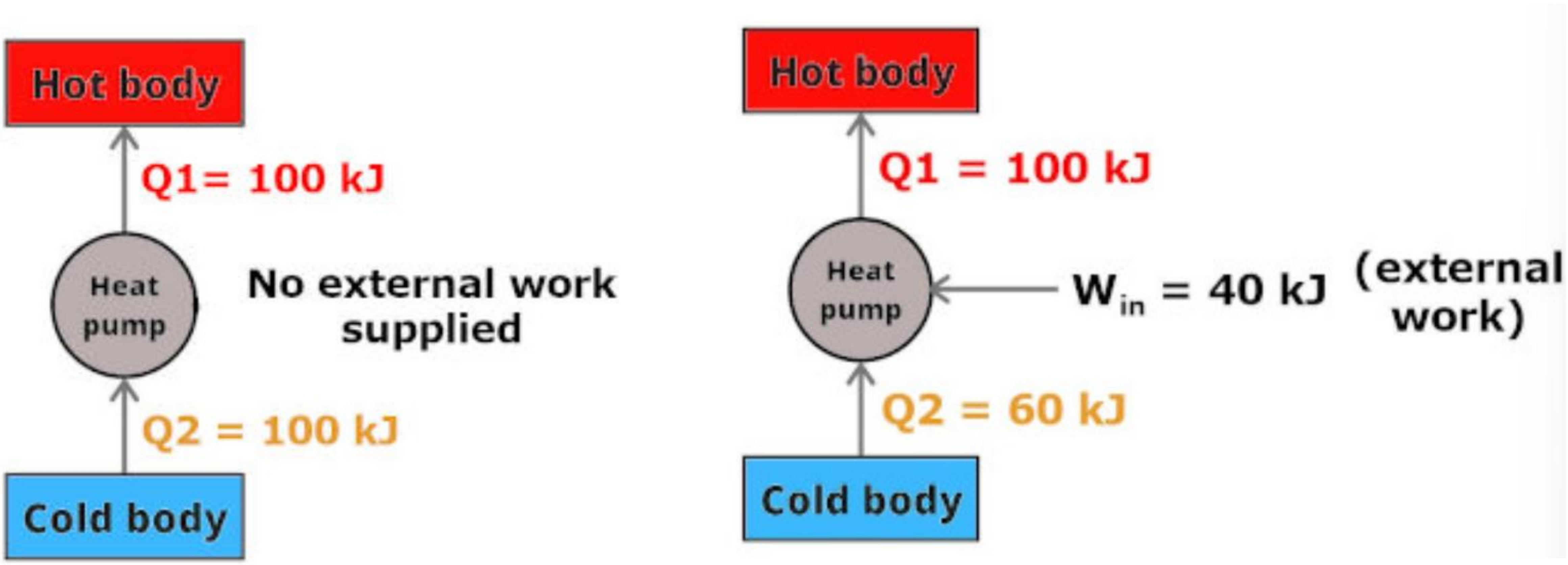


Figure describes Heat Pump for Clausius statement of second law

Clausius statement of 2^{nd} law of thermodynamics cont…

- Now, a heat pump shown in figure, is possible to construct because heat pump in which external work is supplied to transfer heat from a low temperature body to high temperature body. The COP of this system is less than infinity, i.e.

$$COP = \frac{Q_1}{W_{net}} = \frac{100}{40} = 2.5 < \infty$$

- Thus the system satisfies clausius statement of second law as well as first law of thermodynamics.

Equivalence of Kelvin-Plank and Clausius statement

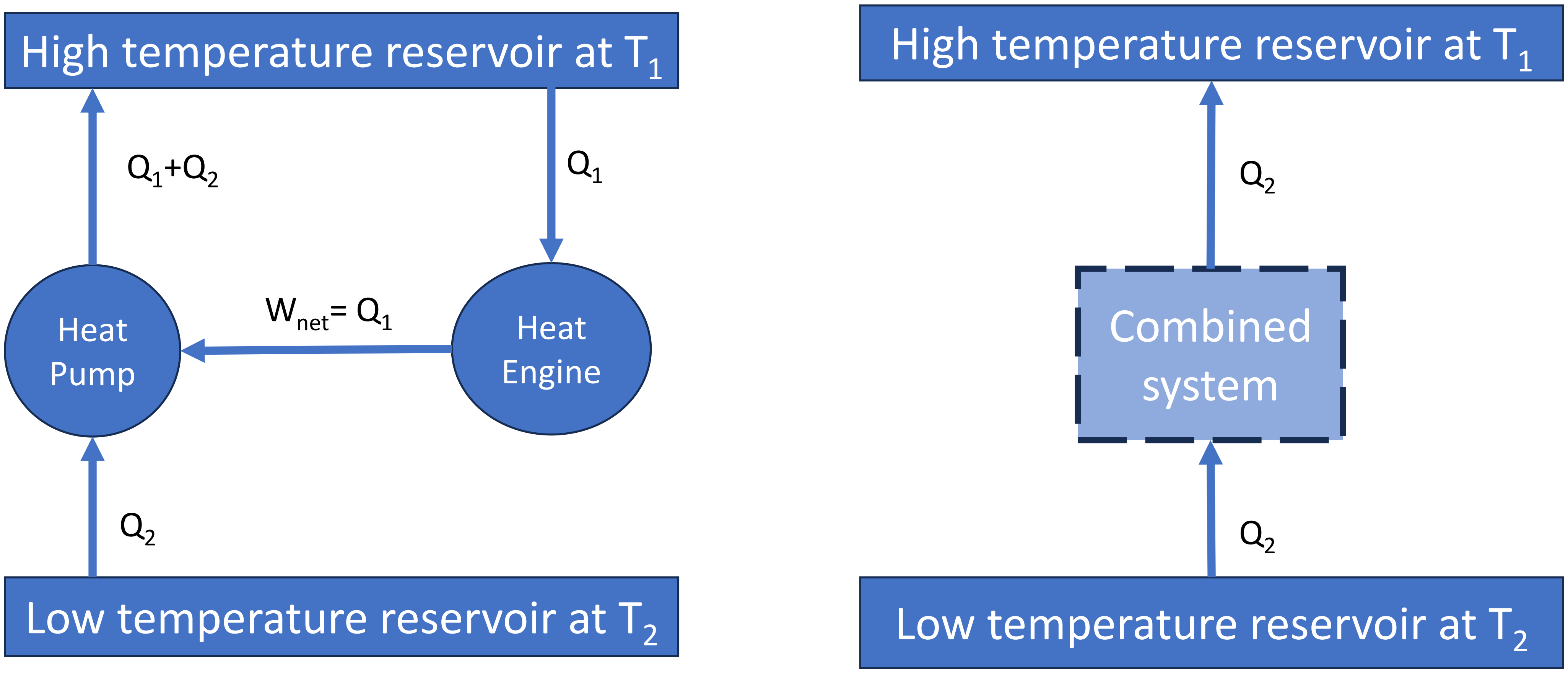
- The Kelvin-Plank and Clausius statement appear to be different, however they are interlinked and complementary to each other.
- It is impossible to have a device satisfying one statement and violating the other.
- Any device that violates Clausius statement leads to violation of Kelvin-Plank statement and vice-versa. These can be proved as under.

1)Violation of Kelvin-Plank statement leading to violation of Clausius statement

- Assume that the heat engine as shown in Fig , which operates from a single heat reservoir at temperature T_1. It receives Q_1 heat from this reservoir and converts it completely into an equivalent amount of work $W=Q_1$,without rejecting any heat to the low temperature reservoir at T_2.
- This is violating the Kelvin-Plank statement by absorbing heat from a single reservoir and producing an equal amount of work. The work output of the heat engine is used to derive a hest pump which absorb Q_2 heat from lower temperature T_2 reservoir and $(Q_1 + Q_2)$ amount of heat deliver to higher temperature T_1 reservoir.

1)Violation of Kelvin-Plank statement leading to violation of Clausius statement cont…

- So net heat interaction with high temperature reservoir is ($Q_1 + Q_2 - Q_1 = Q_2$).
- Hence, as shown in figure combined system of the heat engine and heat pump acts like a heat pump absorbing heat Q_2 from low temperature reservoir and delivering to high temperature reservoir without any external work.
- This is a violation of the Clausius statement.



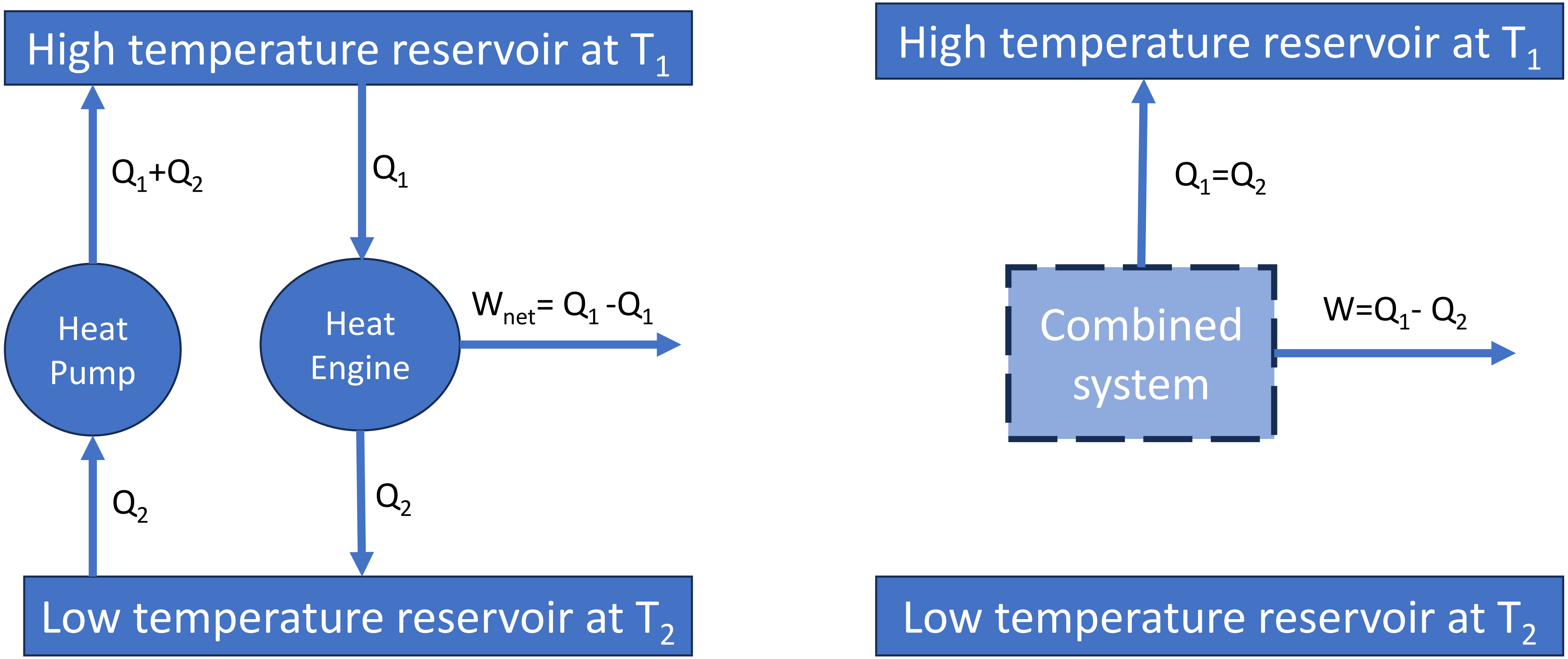
Equivalence of the Kelvin-Plank statement to the Clausius statement

2)Violation of Clausius statement leading to violation of Kelvin-Plank statement

- Assume that the heat pump as shown in Fig which transfers heat Q_2 from a low temperature to a high temperature reservoir without any external work is supplied.
- This is violating of Clausius statement, by absorbing heat from low temperature reservoir and delivering to high temperature reservoir without any external work supplied.
- The heat engine receives heat $Q_1 (Q_1 > Q_2)$ from high temperature reservoir, which develops a net work $W = Q_1 - Q_2$ and rejects Q_2 heat to low temperature reservoir.

2)Violation of Clausius statement leading to violation of Kelvin-Plank statement cont…

- Since there is heat engine rejects Q_2 heat to low temperature reservoir and heat pump absorbs same amount of heat from same low temperature reservoir.
- So net heat interaction with the low temperature reservoir is zero, it can be eliminated.
- As shown in Fig. below combined system of heat engine and heat pump act like a heat engine receives heat from single reservoir and produce same amount of work which is a violation of the Kelvin-Plank statement.



Equivalence of the Clausius to the Kelvin-Plank statement statement.

Perpetual motion

What is perpetual motion?

- Perpetual motion can be described as "motion that continues indefinitely without any external source of energy; impossible in practice because of friction. “It can also be described as "the motion of a hypothetical machine which, once activated, would run forever unless subject to an external force or to wear“. There is a scientific consensus that perpetual motion in an isolated system would violate the first and/or second law of thermodynamics.

Working principle

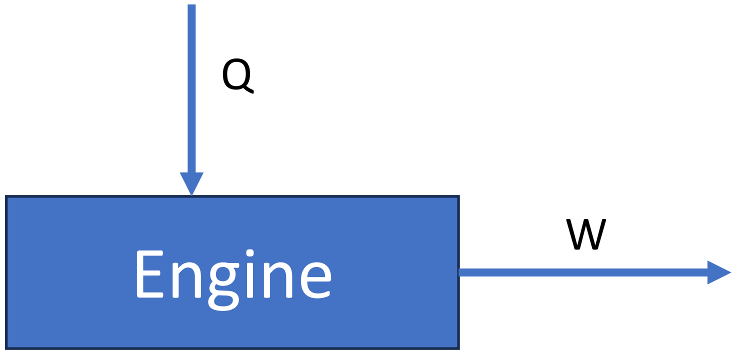
- There is a scientific consensus that perpetual motion in an isolated system violates either the first law of thermodynamics, the second law of thermodynamics, or both.
- The first law of thermodynamics is essentially a statement of conservation of energy.
- The second law can be phrased in several different ways, the most intuitive of which is that heat flows spontaneously from hotter to colder places and basically the above mentioned project follows the second law of thermodynamics and also works on the principle of centripetal force.

Perpetual motion machine of the first kind (PMM1):-

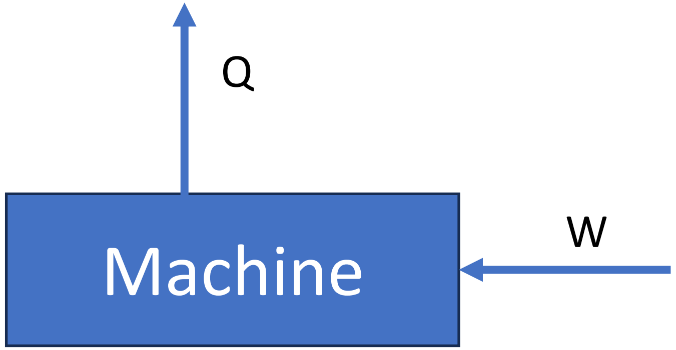
- The **first law of thermodynamics** states that energy can neither be created nor be destroyed. It can only get transformed from one form to another form.
- An imaginary device which would produce work continuously without absorbing any energy from its surroundings is called a Perpetual Motion Machine of the First kind,(PMM1).
- A PMM1 is a device which violates the first law of thermodynamics. It is impossible to devise a PMM1.

Perpetual motion machine of the first kind (PMM1):- cont…

- The converse of the above statement is also true, i.e., there can be no machine that would continuously consume work without some other form of energy appearing simultaneously.
- PMM1 violates the first law of thermodynamics.



PMM1



The converse of PMM1

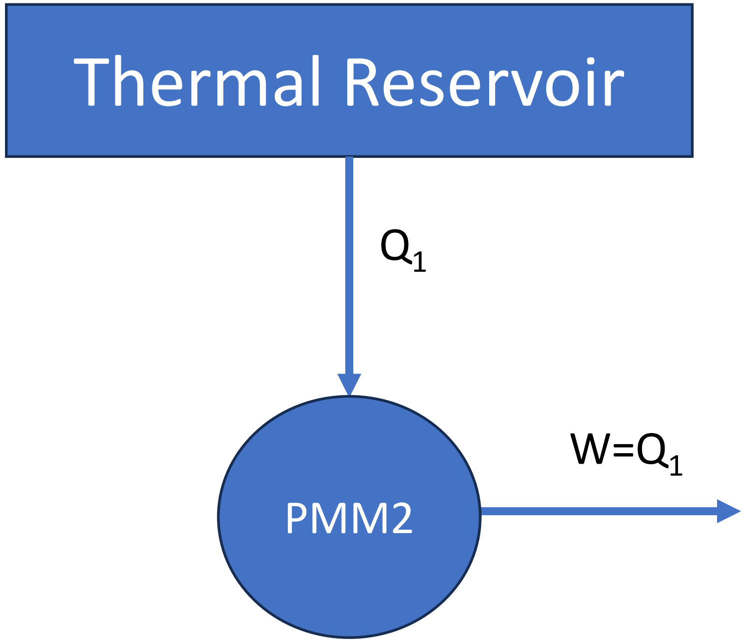
Perpetual Motion Machine of second kind (PMM2):-

- lf the engine exchanges heat only with single thermal reservoir, in which heat supplied is completely converted into an equivalent amount of work and efficiency of such engine becomes 100 %. This heat engine is called a perpetual motion machine of second kind, as PMM2 as shown in Fig. The PMM2 not violates first law, but it violates the Kelvin-Plank statement of second law. Practically this engine is not possible. We know that efficiency of heat engine as,

$$\eta_{th} = \frac{W_{net}}{Q_1} \times 100 = \frac{Q_1 - Q_2}{Q_1} \times 100$$

- For PMM2, Q2=0

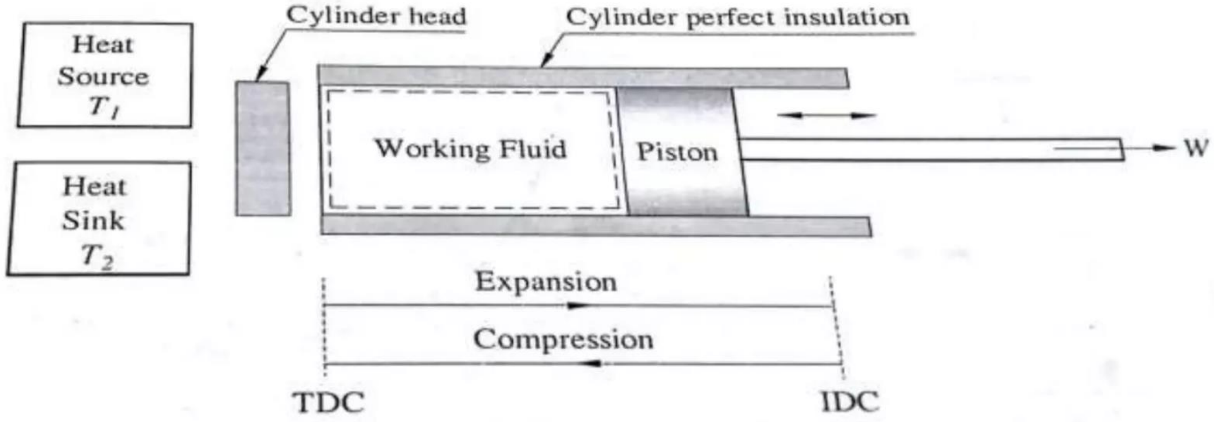
$$\eta_{th(PMM\,2)} = 100\%$$



PMM2, violates the second law of thermodynamics

Carnot cycle and Carnot heat engine

- A Carnot cycle is hypothetical cycle consists of four processes as two reversible isothermal processes and two reversible adiabatic processes.
- The cycle was proposed in 1824 by French engineer, Sadi Carnot.
- Since processes are individually reversible. Consider the piston cylinder arrangement to understand the working of an engine on Carnot cycle as Shown in Fig



Carnot cycle and Carnot heat engine cont…

- The cylinder head in Carnot engine behave alternatively perfect conductor or a perfect insulator of a heat. Heat is caused to flow into working fluid by the application of high temperature energy source during expansion, and flow out of fluid by the application of lower temp. energy sink during compression. There are some assumption made in Carnot cycle as follows:-

(i)The piston moving in a cylinder does not produce any friction during motion.

(ii) The cylinder head is arranged such a way that it can be perfect heat conductor or perfect heat insulator.

(iii) The walls of cylinder and piston are considered as perfect insulators of heat.

Carnot cycle and Carnot heat engine cont…

(iv)Heat transfer does not affect the temperature of source or sink.

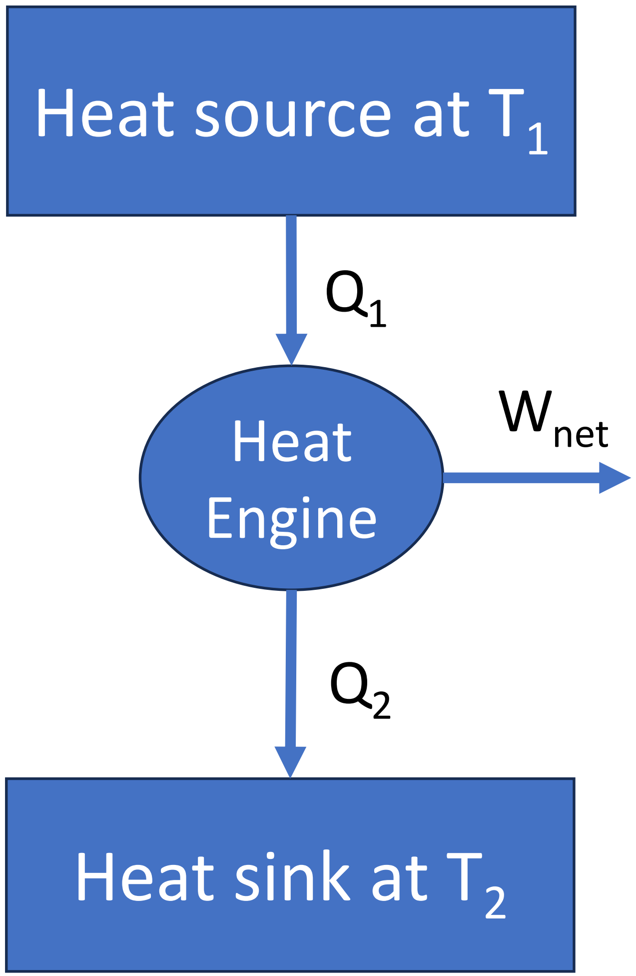
(v)Compression and expansion processes are reversible.

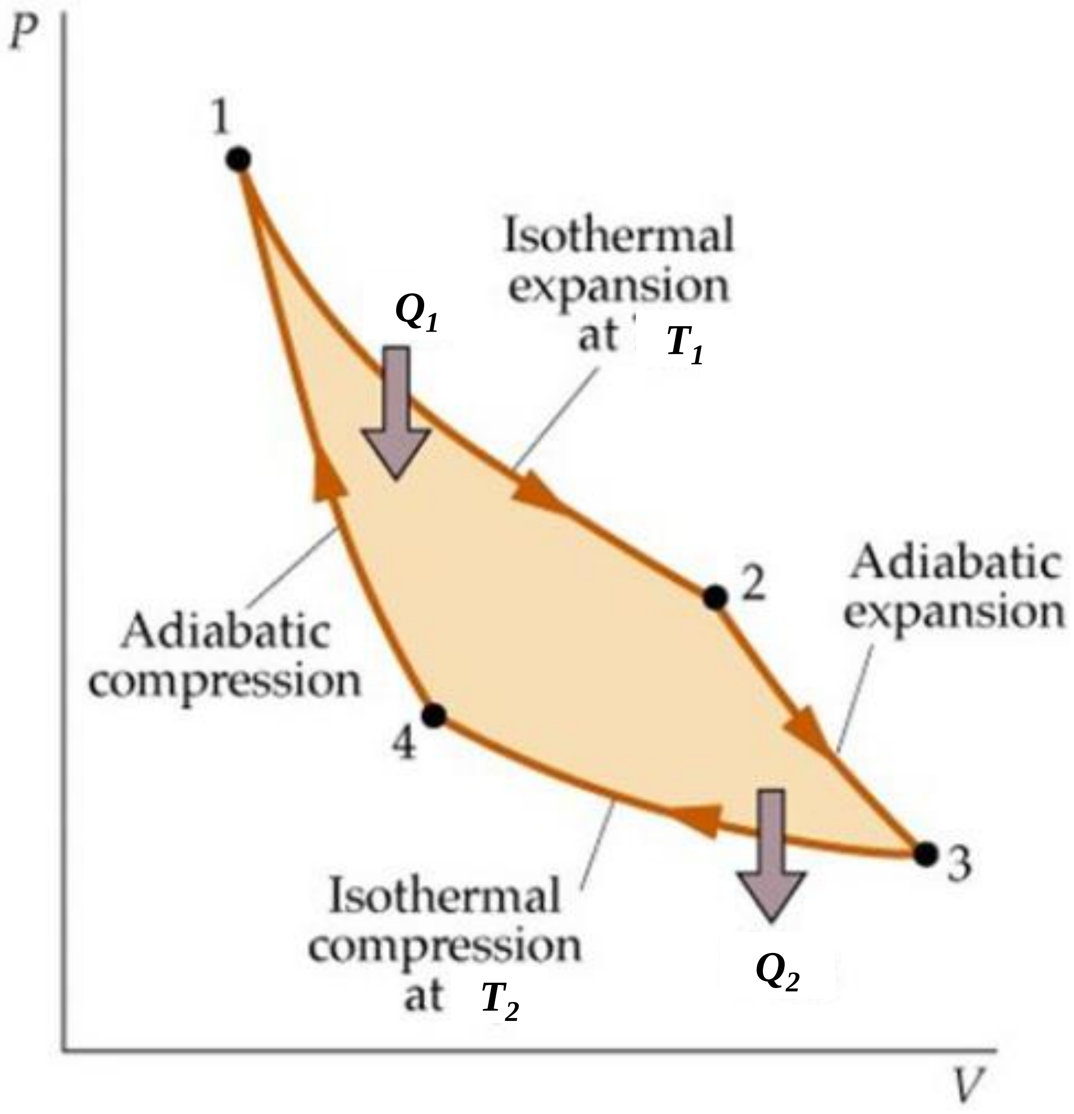
(vi) Working medium is a perfect gas and has constant specific heat.

The four processes are as shown in Fig. and explain as follows:

Process 1-2:Reversible isothermal expansion. During this process, the heat is supplied to the working fluid at constant temperature T_1. This is achieved by bringing the heat source in contact with the cylinder head. The fluid expands isothermally(at constant temperature)"Work done by system during process 1-2 or heat addition is given by

$$Q_1 = W_{1-2} = p_1 V_1 \ln \frac{V_2}{V_1} = mRT_1 \ln \frac{V_2}{V_1}$$





Carnot heat engine cycle

Carnot cycle and Carnot heat engine cont…

- **Process 2-3:Reversible adiabatic expansion**. The cylinder and cylinder head behaves like a perfect insulator so that no heat flow takes place. The fluid expands adiabatically, temperature is decreased from T_1 to T_2.
- Work done by system during process 2-3 is given by

$$W_{2-3} = \frac{p_2V_2 - p_3V_3}{\gamma - 1} = mC_v(T_1 - T_2)$$

Carnot cycle and Carnot heat engine cont…

- **Process 3-4 :Reversible isothermal compression.** The heat is rejected from the working fluid at constant temperature T_2. This is achieved by bringing the heatsink in contact with the cylinder head. The fluid compresses isothermally.
- Work done on the system during process 3-4 or heat rejection is given by

$$Q_2 = W_{3-4} = p_3 V_3 \ln \frac{V_3}{V_4} = mRT_2 \ln \frac{V_3}{V_4}$$

Carnot cycle and Carnot heat engine cont…

- **Process 4-1:Reversible adiabatic compression**. The cylinder and the cylinder head behave like a perfect insulator so that no heat flow takes place. The fluid compresses adiabatically, and temperature of fluid is increased from T_2 to T_1.
- Work done on system during process 4-1 is given by,

$$W_{4-1} = \frac{p_1V_1 - p_4V_4}{\gamma - 1} = mC_v(T_1 - T_2)$$

- Net work done per cycle = area 1-2-3-4

W_{net}= work done by system-work done on system

$$= [W_{12} + W_{23}] - [W_{34} + W_{41}]$$

$$= mRT_1 \ln\frac{V_2}{V_1} + mC_v(T_1 - T_2) - \left[mRT_2 \ln\frac{V_3}{V_4} + mC_v(T_1 - T_2) \right]$$

Carnot cycle and Carnot heat engine cont…

$$= mRT_1 \ln\frac{V_2}{V_1} - = mRT_2 \ln\frac{V_3}{V_4}$$

$$\therefore W_{net} = Q_1 - Q_2$$

- The thermal efficiency of Carnot heat engine is given by,

$$\eta_{th} = \frac{net\ work\ output}{heat\ input} = \frac{W_{net}}{Q_1}$$

$$\frac{mRT_1 \ln\frac{V_2}{V_1} - mRT_2 \ln\frac{V_3}{V_4}}{mRT_1 \ln\frac{V_2}{V_1}}$$

$$\frac{T_1 \ln\frac{V_2}{V_1} - T_2 \ln\frac{V_3}{V_4}}{T_1 \ln\frac{V_2}{V_1}}$$

Carnot cycle and Carnot heat engine cont…

- But during adiabatic process 2-3,

$$\frac{V_2}{V_3} = \left(\frac{T_2}{T_1}\right)^{\frac{1}{\gamma-1}}$$

- And during adiabatic process 4-1,

$$\frac{V_1}{V_4} = \left(\frac{T_2}{T_1}\right)^{\frac{1}{\gamma-1}}$$

- From above equations,

$$\frac{V_1}{V_4} = \frac{V_2}{V_3} \quad \left(\therefore \frac{V_2}{V_1} = \frac{V_3}{V_4}\right)$$

Carnot cycle and Carnot heat engine cont…

$$\eta_{th} = \frac{T_1 - T_2}{T_1} = 1 - \frac{T_2}{T_1}$$

- From above equation, following points observed with respect to efficiency of a Carnot engine.
- (1)η_{th} is independent of working fluid and depends upon the temperature of source and sink.
- (2)If T_2=0, η_{th}=100%, however that means there is no heatsink which is violation of Kelvin-Plank statement of the second law.
- (3) η_{th} directly proportional to temperature difference (T_1-T_2) between source and sink. Higher temperature difference (T_1-T_2) higher will be η_{th} .

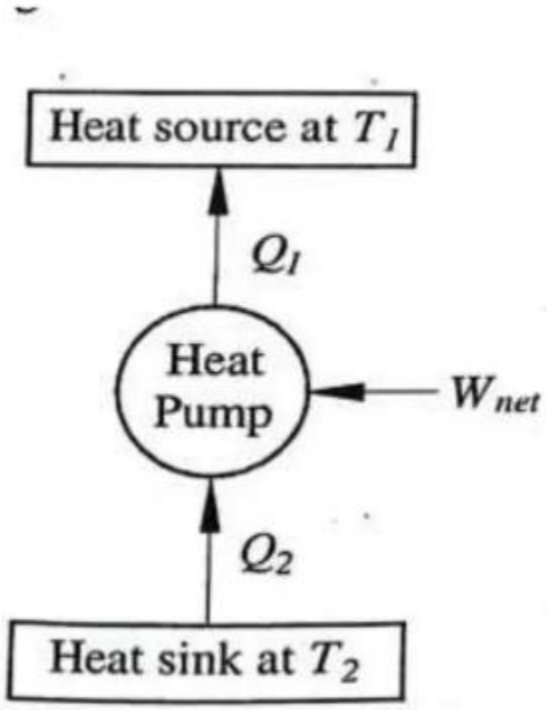
Carnot cycle and Carnot heat engine cont…

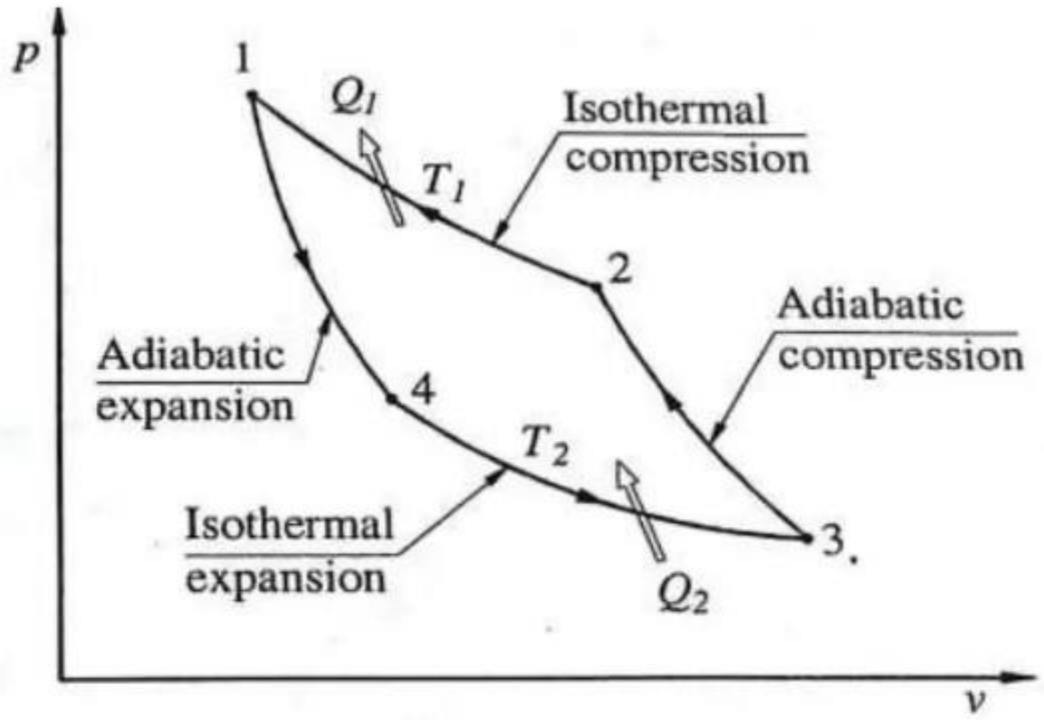
- (4) η_{th} increases with increase in temperature of source and decrease in temperature of sink . But T_1 limited against the metallurgical consideration and high cost of temperature resisting materials, and T_2 is limited by atmospheric or sink conditions.
- (5)If $T_1=T_2$ work done=0,and η_{th}=0.

Reversed and Irreversible Heat Engine or Carnot Heat Pump

(i)Reversed process

- The Carnot heat engine cycle explained in previous article is a totally reversible cycle, therefore all the processes can be reversed, and it is known as Carnot heat pump, as shown in figure





Reversed and Irreversible Heat Engine or Carnot Heat Pump cont…

- The various processes are as follows:

Process 1-4:Reversible adiabatic expansion temperature decreases from T_1 to T_2.

Process 4-3:Reversible isothermal expansion, heat is transferred from a low temperature sink to working fluid at constant temperature T_2.

$$Q_2 = mRT_2 \ln \frac{V_3}{V_4}$$

Process 3-2 :Reversible adiabatic compression, the temperature of working fluid increases from T_2 to T_1.

Reversed and Irreversible Heat Engine or Carnot Heat Pump cont…

- **Process 2-1**:Reversible isothermal compression heat is transferred from working fluid to high temperature source at constant temperature T_1.

$$Q_1 = mRT_1 \ln \frac{V_2}{V_1}$$

- The COP for heat pump;

$$(COP)_{HP} = \frac{Q_1}{Q_1 - Q_2} = \frac{mRT_1 \ln \frac{V_2}{V_1}}{mRT_1 \ln \frac{V_2}{V_1} - mRT_2 \ln \frac{V_3}{V_4}}$$

$$(COP)_{HP} = \frac{T_1}{T_1 - T_2} \qquad \text{Q}\left(\frac{V_2}{V_1} = \frac{V_3}{V_4}\right)$$

Reversed and Irreversible Heat Engine or Carnot Heat Pump cont…

- You may have observed that power cycles operate in the clockwise direction when plotted on a process diagram. The Carnot cycle may be reversed, in which it operates as a refrigerator.
- The refrigeration cycle operates in the counterclockwise direction.
- The COP for a refrigerator

$$(COP)_R = \frac{Q_2}{Q_1 - Q_2} = \frac{mRT_2 \ln \frac{V_3}{V_4}}{mRT_1 \ln \frac{V_2}{V_1} - mRT_2 \ln \frac{V_3}{V_4}}$$

$$(COP)_R = \frac{T_2}{T_1 - T_2} \qquad \text{Q}\left(\frac{V_2}{V_1} = \frac{V_3}{V_4}\right)$$

- The Carnot heat pumps and Carnot heat engine are not used in practice.

Reversed and Irreversible Heat Engine or Carnot Heat Pump cont…

(ii)Irreversible Process

- An irreversible process is a process that is not reversible.
- All real processes are irreversible. Irreversible processes occur because of the following:
  - Friction
  - Unrestrained expansion of gases
  - Heat transfer through a finite temperature difference
  - Mixing of two different substances
  - Hysteresis effects
  - I^2R losses in electrical circuits
  - Any deviation from a quasi-static process

Reversed and Irreversible Heat Engine or Carnot Heat Pump cont…

- Based on **Carnot Principles,** The second law of thermodynamics puts limits on the operation of cyclic devices as expressed by the Kelvin-Planck and Clausius statements. A heat engine cannot operate by exchanging heat with a single heat reservoir, and a refrigerator cannot operate without net work input from an external source.
- Consider heat engines operating between two fixed temperature reservoirs at $T_H > T_L$. We draw two conclusions about the thermal efficiency of reversible and irreversible heat engines, known as the Carnot principles.
  - (a)The efficiency of an irreversible heat engine is always less than the efficiency of a reversible one operating between the same two reservoirs.

$$\eta_{th} < \eta_{th,\ Carnot}$$

  - (b) The efficiencies of all reversible heat engines operating between the same two constant-temperature heat reservoirs have the same efficiency.

Reversed and Irreversible Heat Engine or Carnot Heat Pump cont…

- These statements form the basis for establishing an absolute temperature scale, also called the Kelvin scale, related to the heat transfers between a reversible device and the high- and low-temperature heat reservoirs by

$$\frac{Q_L}{Q_H} = \frac{T_L}{T_H}$$

- Then the Q_H/Q_L ratio can be replaced by T_H/T_L for reversible devices, where T_H and T_L are the absolute temperatures of the high- and low-temperature heat reservoirs, respectively. This result is only valid for heat exchange across a heat engine operating between two constant temperature heat reservoirs. These results do not apply when the heat exchange is occurring with heat sources and sinks that do not have constant temperature.

Reversed and Irreversible Heat Engine or Carnot Heat Pump cont…

- The thermal efficiencies of actual and reversible heat engines operating between the same temperature limits compare as follows:

$$\eta_{th} \begin{cases} < \eta_{th,\,rev} & \text{irreversible heat engine} \\ = \eta_{th,\,rev} & \text{reversible heat engine} \\ > \eta_{th,\,rev} & \text{impossible heat engine} \end{cases}$$

Example

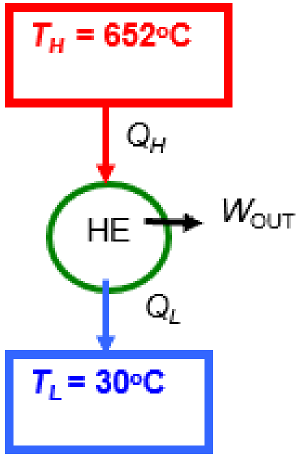
A Carnot heat engine receives 500 kJ of heat per cycle from a high-temperature heat reservoir at 652°C and rejects heat to a low-temperature heat reservoir at 30°C. Determine

(a) The thermal efficiency of this Carnot engine.

(b) The amount of heat rejected to the low-temperature heat reservoir

Solution

(a)



$$\eta_{th,\,rev} = 1 - \frac{T_L}{T_H}$$

$$= 1 - \frac{(30+273)K}{(652+273)K}$$

$$= 0.672 \quad or \quad 67.2\%$$

(b)

$$\frac{Q_L}{Q_H} = \frac{T_L}{T_H}$$

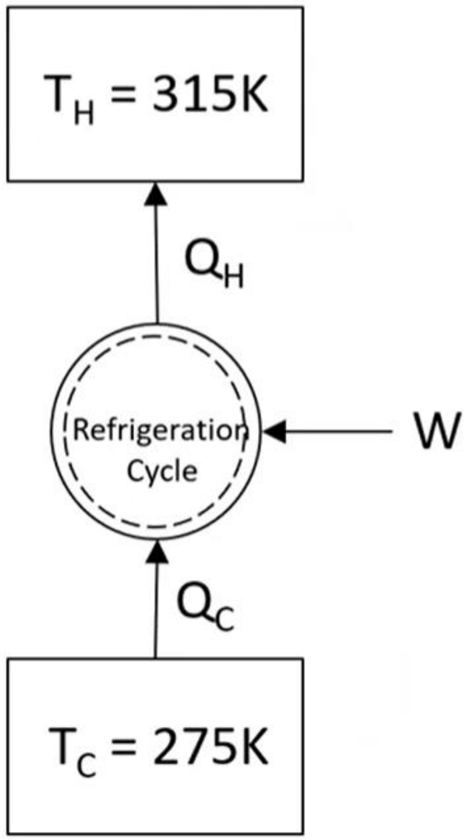
$$= \frac{(30+273)K}{(652+273)K} = 0.328$$

$$Q_L = 500\,kJ(0.328)$$

$$= 164\,kJ$$

Example

A refrigeration cycle operating between two reservoirs receives energy Q_c from a cold reservoir at T_C= 275K and rejects energy Q_H to a hot reservoir at T_H = 315K. For each of the following cases, determine whether the cycle operates reversibly, operates irreversibly, or is impossible: (a) Q_c= 1000 kJ; W_{cyle} = 80 kJ; (b) Q_c= 1200 kJ; Q_H= 2000 kJ; (c) Q_H=1575 kJ; W_{cycle}= 200kJ;(d)COP(β) = 6.



Solution Process: Compute β for each case and compare it to β_{max}

β is the Coefficient of Performance (COP) for a refrigeration cycle

$$\beta = \frac{Q_c}{W} = \frac{Q_c}{(Q_h - Q_c)}$$

$$\left(\frac{Q_c}{Q_h}\right)_{rev} = \frac{T_c}{T_h}$$

$$\beta_{max} = \frac{T_c}{(T_h - T_c)}$$

Where

$$\beta_{max} = \frac{T_c}{T_h - T_c} = \frac{275 \cdot K}{(315 \cdot K - 275 \cdot K)}$$

$$\underline{\beta_{max} = 6.875}$$

Case (a): Q_C = 1000 kJ; W_{cycle} = 80 kJ

$$\beta = \frac{Q_c}{W} = \frac{Q_c}{Q_h - Q_c} = \frac{1000 \cdot kJ}{80 \cdot kJ}$$

$$\beta = 12.5 \qquad \beta > \beta_{max}$$

Therefore, this process is ***impossible***.

Case (b): Q_C = 1200 kJ; Q_H = 2000 kJ

$$\beta = \frac{Q_c}{W} = \frac{Q_c}{Q_h - Q_c} = \frac{1200 \cdot kJ}{(2000 - 1200) \cdot kJ}$$

$$\beta = 1.5 \qquad \beta < \beta_{max}$$

Therefore, this process is possible.
All real processes are ***irreversible***.

Case (c): Q_H = 1575 kJ; W_{cycle} = 200kJ

$$\beta = \frac{Q_c}{W}$$ Energy Balance yields: $$W = Q_h - Q_c$$

$$Q_c = Q_h - W = 1575 \cdot kJ - 200 \cdot kJ$$

$$Q_c = 1375 \cdot kJ$$

$$\beta = \frac{1375 \cdot kJ}{200 \cdot kJ} \qquad \beta = 6.875 \cdot kJ$$

$\beta = \beta_{max}$ A ***Reversible*** process, which cannot actually be built.

Case (d): β = 6

$\beta < \beta_{max}$ → Possible, so it is an ***Irreversible*** process.