Chapter 2

Second Law of Thermodynamics

CHAPTER HIGHLIGHTS

- *Thermal Energy Reservoir*
- *Steam Power Plant as a Heat Engine*
- *Second Law of Thermodynamics*
- *Kelvin-plank Statement*
- *Perpetual Motion Machine of Second Kind*
- *Heat Engine and Cannot Heat Engine*
- *Thermodynamic Temperature Scale*
- *Refrigerator*
- *Entropy and Increase of Entropy Principle*
- *Entropy Balance of Control Volumes*
- *Third Law of Thermodynamics*
- *Availability and Irreversibility*
- *Thermodynamics Relations and Maxwell's Equations*
- *The Joule-Thomson Coefficients*

INTRODUCTION

The first law of thermodynamics states that heat and work are mutually convertible. That is, every process is possible, provided energy is neither created nor destroyed.

The first law places no restrictions on the direction of flow of heat and work. Thus according to first law, in every cyclic process work is completely converted in to heat or heat is completely converted into work.

Example:

1. Work $\rightleftharpoons$ heat
2. Potential energy $\rightleftharpoons$ kinetic energy
3. Heat flows from hot body to cold body and also cold body to hot body.
4. Gas expands from high pressure to low pressure and also from low pressure to high pressure.

In natural way, all the above processes are possible, but the reverse is not automatically true. That is,

1. Heat is not converted completely into work.
2. Kinetic energy is not converted completely in to potential energy.
3. Heat cannot flows from cold body to hot body automatically.
4. Gas never expands from low pressure to high pressure automatically.

So, the spontaneous process can be reversed but they will not be reversed automatically. They require some external energy source for reversing the process.

- From the Joule's experiment for cyclic process, $W \underset{\rightarrow}{=} Q$ and $Q \underset{\rightarrow}{>} W$. Where the arrow indicates the direction of energy transformation.
- Work is said to be high grade energy and heat is low grade energy.

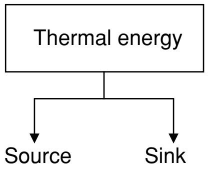
'The complete conversion of low grade energy into high grade energy in cycle is impossible.'

Limitations of first law

- First law does not speak whether a certain process is possible or not.
- First law does not give information regarding the direction of the process.
- The second law of thermodynamics is introduced to overcome the limitations of first law.
- Second law of thermodynamics gives the information regarding process possibility and the direction of the process.
- Hence first law is quantitative law and second law is qualitative law.

Thermal Energy Reservoir

It is a large body from which any amount of heat is withdrawn or any amount of heat is supplied to, without any change in its temperature.



Source It is a body from which if any amount of heat is withdrawn the temperature remains unchanged.

Example: Sun, furnace

Sink It is a body to which if any amount of heat is added, the temperature remains unchanged.

Example: atmosphere, river

Heat Engine

A heat engine is any continuously operating thermodynamic system in which heat and work flows across the boundaries.

The working fluid which is present in the system must undergo cyclic process and periodically return to its initial state. The primary purpose of heat engine is to convert heat into work.

Steam Power Plant as a Heat Engine

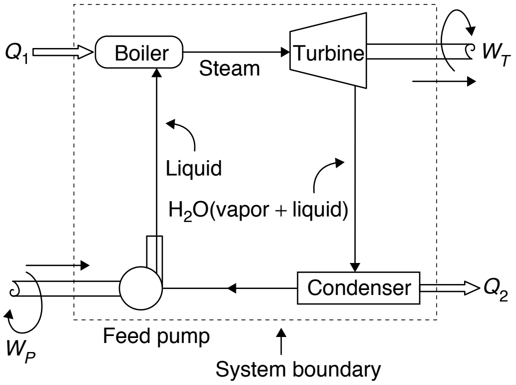
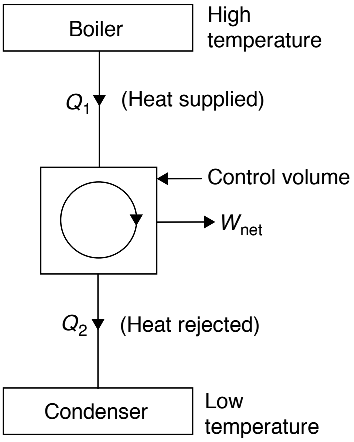


Figure 1 Steam power plant as heat engine

Heat is supplied in the boiler by burning fuel, to convert water into steam. This steam expands in the turbine and doing the external work W_T. steam from turbine is condensed in the condenser, there by releasing the heat and the water is pumped back by means of feed pump to which external work W_P is supplied.

As shown in figure heat flows into the control volume and produce work.



Thus steam power plant is heat engine.

Refrigeration and Air Condition Plant as a Reversed Heat Engine

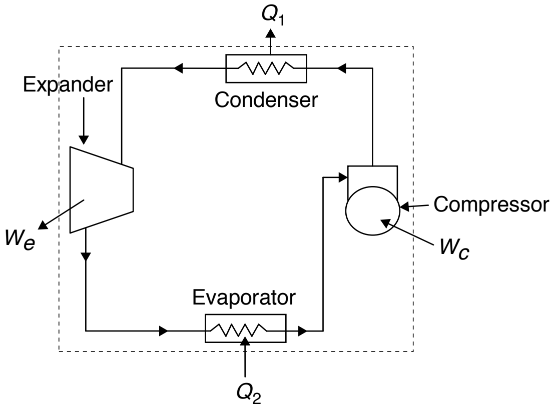
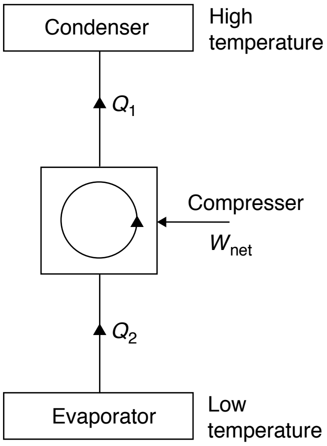


Figure 2 A cyclic refrigeration plant-reversed heat engine.

In this cycle a vapor known as refrigerant is compressed by supplying external work. This vapor is condensed in a condenser thereby rejecting heat. The condensed refrigerant expands in an expansion valve which supplies wet vapor to evaporator where the refrigerant picks up heat from the surrounding environment. It is further sucked by the compressor.



Thus *R* and *AC* plant is a reversed heat engine

SECOND LAW OF THERMODYNAMICS

Second law of thermodynamics follows two statements.

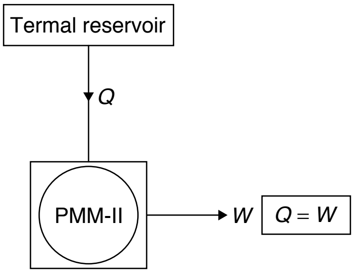
Kelvin–Plank Statement

‘It is impossible to develop a device operating on a cycle and which produce work by exchanging heat with single reservoir.’

Such a device is known as perpetual motion machine of second kind.

Perpetual Motion Machine of Second Kind

It is a machine which interacts with single thermal reservoir and produce work.



$$\text{Efficiency of PMM-II} = \frac{\text{output}}{\text{input}} = \frac{W}{Q}$$

$$= 100\% \; (\because W = Q)$$

$$\therefore \quad \eta_{\text{PMM-II}} = 100\%$$

Achieving 100% efficiency is impossible and hence PMM-II is impossible.

Heat Engine

Heat engine is a device which interacts with two Thermal reservoirs, converts part of heat into work and rejects remaining to sink or surrounding.

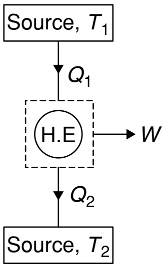


Figure 3 Heat engine operates on a cycle

$$\text{Efficiency} = \frac{\text{output}}{\text{input}} = \frac{W}{Q_1}$$

But

$$Q_1 = W + Q_2$$

$$W = Q_1 - Q_2$$

$$\eta_{\text{H.E}} = \frac{Q_1 - Q_2}{Q_1}$$

$$\eta_{\text{H.E}} = 1 - \frac{Q_2}{Q_1}$$

Where

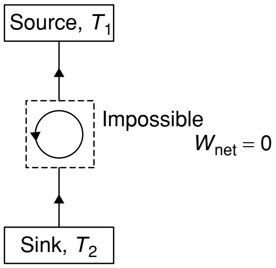
Q_1 = heat supplied (Q_s)
Q_2 = heat rejected (Q_R)

$$\eta_{\text{H.E}} = 1 - \frac{Q_R}{Q_S}$$

This equation is valid for any process (i.e., rev/irreversible process)

Clausius Statement

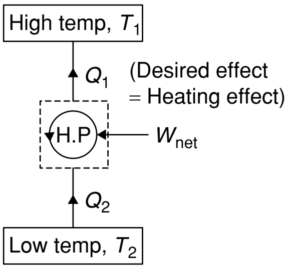
It is impossible to construct a device which transfers heat from low temperature reservoir to high temperature reservoir without any external input.



Heat Pump

It is a device which maintains higher temperature compared to surroundings.

$$\text{Co-efficient of performance (COP)} = \frac{\text{Desired effect}}{\text{Work input}}$$



$$= \frac{\text{heating effect}}{\text{work input}}$$

$$(\text{COP})_{\text{H.P}} = \frac{Q_1}{W_{\text{net}}} = \frac{Q_1}{Q_1 - Q_2}$$

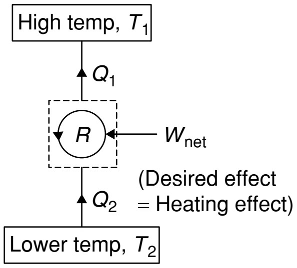
Valid for any cycle (i.e., rev/irrev).

Refrigerator

Refrigerator is a device which maintains lower temperature compared to surroundings

$$\text{Co-efficient of performance} = \frac{\text{Desired effect}}{\text{Work input}}$$

$$= \frac{\text{cooling effect}}{\text{work input}}$$



$$(\text{COP})_R = \frac{Q_2}{W_{\text{net}}} = \frac{Q_2}{Q_1 - Q_2}$$

Valid for any cycle (i.e., rev/irrev)

Relation between $(\text{COP})_{HP}$ and $(\text{COP})_R$ Operating Between Same temperature Limits

$$(\text{COP})_{\text{HP}} = \frac{Q_1}{Q_1 - Q_2}$$

$$(\text{COP})_R = \frac{Q_2}{Q_1 - Q_2}$$

$$(\text{COP})_{\text{HP}} = \frac{Q_1}{Q_1 - Q_2} = \frac{Q_1 - Q_2}{Q_1 - Q_2} + \frac{Q_2}{Q_1 - Q_2}$$

$$(\text{COP})_{\text{HP}} = 1 + (\text{C.O.P})_R$$

NOTES

1. $(\text{COP})_{\text{HP}} > 1$
2. $(\text{COP})_{\text{HP}} = \dfrac{1}{\eta_{\text{H.E}}}$; $(\text{COP})_R = \dfrac{1-\eta_{\text{HE}}}{\eta_{\text{HE}}}$
3. $\eta_{\text{H.E}} < 1$
4. In most of the machines COP varies from 3 to 4
5. (COP) of electrical heater (minimum) = 1
6. (COP) of Heat pump (minimum) = 3
7. COP increases when temperature difference between sink and source decreases.

Equivalence of Kelvin–Plank and the Clausius Statement

The Kelvin-plank and the Clausius statement of the second law of thermodynamics are equivalent.

It means that, when it is possible to have a refrigerator which does not consume any work, then it is also possible to have a heat engine which will receive heat from a single reservoir and convert it completely into work and vice versa.

CARNOT CYCLE

- It is reversible cycle and ideal cycle.
- A cycle is said to be reversible cycle only when each process in a cycle is a reversible process.
- Carnot cycle is not a practical cycle but this cycle is used for comparing other cycles.
- Carnot cycle consists of two Isothermal process and two adiabatic processes.
- Isothermal process is a slow process and adiabatic process is a fast process and hence these two combinations in a single stroke is not possible.
- Kelvin-plank and Clausius statements can be defined on the basis of the Carnot cycle.

Carnot Heat Engine

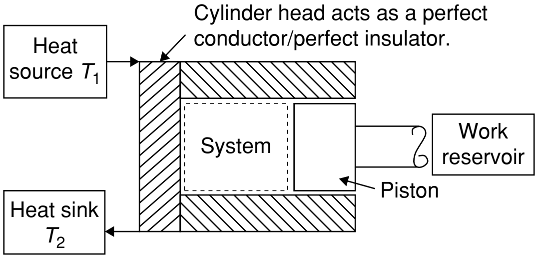


Figure 3 Working of a Carnot cycle

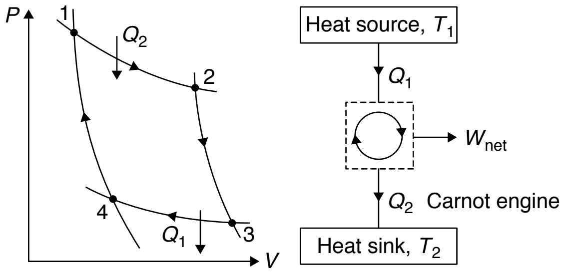


Figure 4 Carnot engine cycle

Processes

1 – 2: reversible Isothermal heat addition
2 – 3: reversible adiabatic expansion
3 – 4: reversible Isothermal heat rejection
4 – 1: reversible adiabatic compression

Efficiency of the Carnot heat engine:

$$\eta_{\text{carnot heat engine}} = \frac{\text{Work done}}{\text{Heat supplied}}$$

$$\eta_{CHE} = \frac{Q_1 - Q_2}{Q_1} = 1 - \frac{Q_2}{Q_1}$$

$$Q_1 = mRT_1 \ln\left(\frac{V_2}{V_1}\right)$$

$$Q_1 = mRT_2 \ln\left(\frac{V_3}{V_4}\right)$$

But $\left(\dfrac{V_2}{V_3}\right) = \left(\dfrac{T_2}{T_1}\right)^{\frac{1}{\gamma-1}}$ and $\dfrac{V_1}{V_4} = \left(\dfrac{T_2}{T_1}\right)^{\frac{1}{\gamma-1}}$

$$\therefore \frac{V_2}{V_3} = \frac{V_1}{V_4};\ \frac{V_2}{V_1} = \frac{V_3}{V_4}$$

$$\therefore \eta_{\text{Carnot engine}} = \frac{T_1 - T_2}{T_1}$$

NOTES

1. The efficiency of the engine does not depend on working substance
2. The efficiency only depends on temperature limits of source (T_1) and sink (T_2),

3. If $T_2 = 0$, $\eta_{CHE} = 100\%$ this is impossible according to second law.
4. For maximum efficiency T_2 should be low.
5. If $T_1 = T_2$, no work will done and efficiency will be zero.

Carnot Heat Pump and Refrigerator

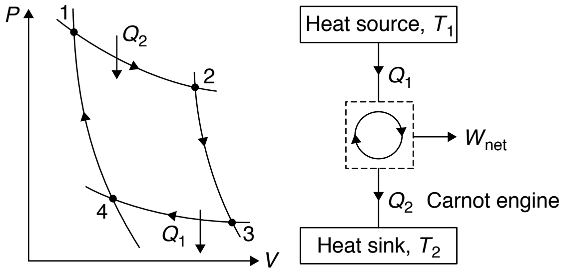


Figure 5 Carnot heat pump and refrigerator cycle

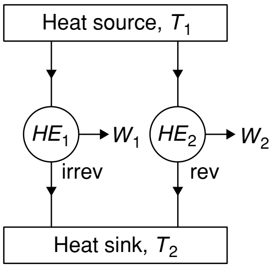
$$(\text{COP})_{\text{CHP}} = \frac{Q_1}{Q_1 - Q_2} = \frac{T_1}{T_1 - T_2}$$

$$(\text{COP})_{CR} = \frac{Q_2}{Q_1 - Q_2} = \frac{T_2}{T_1 - T_2}$$

CARNOT THEOREMS

Theorem I

'For different engines operating between same temperature limits no engine has efficiency greater than carnot cycle efficiency or reversible cycle efficiency.'

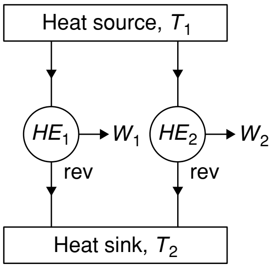


$$(W_2)_{rev} > (W_1)_{irrev}$$

$$\therefore \quad \eta_{rev} > \eta_{irrev}$$

Theorem 2

Efficiency of all reversible cycles operating between same temperature limits is same.



$$W_1 = W_2$$

$$\eta_{\text{rev1}} = \eta_{\text{rev2}}$$

$$\eta_{\text{rev 1}} = \eta_{\text{rev 2}} = \dots \eta_{\text{rev } n}$$

THERMODYNAMIC TEMPERATURE SCALE

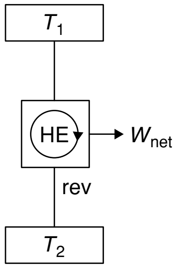
For reversible engines

$$\frac{Q_1}{T_1} = \frac{Q_2}{T_2} = \frac{Q_3}{T_2} = \cdots$$

Efficiency of a reversible heat engine

$$\eta = 1 - \frac{Q_2}{Q_1} \quad \text{(For any cycle i.e., rev/irrev)}$$

$$\frac{Q_1}{Q_2} = \frac{T_1}{T_2} \quad \text{For reversible engine}$$



$$\eta_{rev} = 1 - \frac{T_2}{T_1} = \frac{T_1 - T_2}{T_1} = \eta_c$$

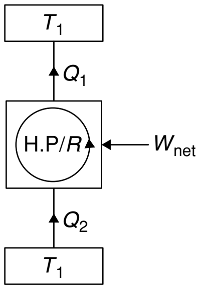
Valid only for reversible engine

COP of Reversible Heat Pump/Refrigerator

$$(\text{COP})_{\text{HP}} = \frac{Q_1}{Q_1 - Q_2} \quad \text{(For any rev/irrev cycle)}$$

$$(\text{COP})_{\text{revHP}} = \frac{T_1}{T_1 - T_2}$$

Valid only for rev cycle



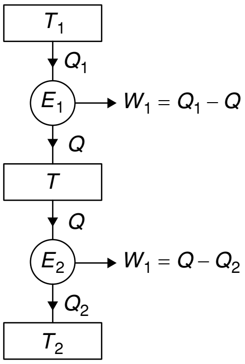
$$(\text{COP})_R = \frac{Q_2}{Q_1 - Q_2} \quad \text{(For any cycle, i.e., rev/irrev)}$$

$$(\text{COP})_{revR} = \frac{T_2}{T_1 - T_2}$$

Valid only for reversible cycle

Carnot Heat Engines in Series

Two Carnot engines E_1 and E_2 are connected in series.



1. For equal work output of these two engines, the intermediate temperature 'T' is equal to the arithmetic mean of the remaining two temperatures.

$$\boxed{T = \frac{T_1 + T_2}{2}}$$

Also $$\boxed{\frac{Q_1}{T_1} = \frac{Q}{T} = \frac{Q_2}{T_2}}$$

2. For equal efficiencies of these two engines.

$$\boxed{T = \sqrt{T_1 T_2}}$$

The intermediate temperature is equal to the geometric mean of other two temperatures.

Also $$\boxed{\frac{Q_1}{T_1} = \frac{Q}{T} = \frac{Q_2}{T_2}}$$

3. Overall efficiency of the coupled cycle,

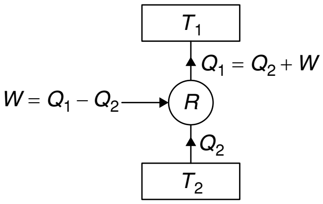
$$\eta_0 = \eta_1 + \eta_2 - \eta_1 \eta_2$$

NOTE

The overall efficiency of the coupled cycle is greater than the individual efficiency.

Refrigerator

Refrigerator is a device which maintains the temperature lower than the atmospheric temperature, continuously removing heat from it and doing work.



The efficiency of a refrigerator is expressed in terms of the coefficient of performance [COP].

$$\text{COP}_R = \frac{\text{Desired output}}{\text{Required input}} = \frac{Q_2}{W_{\text{net}}}$$

$$= \frac{\text{Net refrigerating effect}}{\text{Work done}}$$

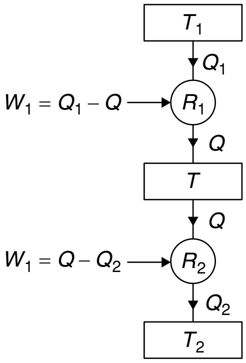
$$\boxed{\text{COP}_R = \frac{Q_2}{Q_1 - Q_2}}$$

NOTE

The value of COP_R can be greater than unity. That is the amount of heat removed from the refrigerated space can be greater than the amount of work input.

Coupled Refrigerator

Two refrigerators are connected in series here



1. For equal work inputs to the 2 coupled pumps the intermediate temperature 'T' is given by $\boxed{T = \frac{T_1 + T_2}{2}}$ which is the arithmetic mean of the other two temperatures.

Also $$\boxed{\frac{Q_1}{T_1} = \frac{Q}{T} = \frac{Q_2}{T_2}}$$

2. For equal COP_s of the two refrigerators, the intermediate temperature, 'T' is given by $T = \sqrt{T_1 T_2}$ which is the geometric mean of the remaining two temperatures.

Also $$\boxed{\frac{Q_1}{T_1} = \frac{Q}{T} = \frac{Q_2}{T_2}}$$

3. Overall COP of the coupled cycle

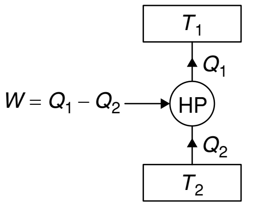
$$\boxed{\frac{1}{C_0} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}}$$

NOTE

The overall COP of the coupled refrigerator is less than the individual COP.

Heat Pump

Heat pump is a device which maintains the temperature of a body above that of the atmosphere by continuously supplying heat by doing external work.



COP of a heat pump is given by

$$\text{COP}_P = \frac{\text{Desired output}}{\text{Required input}} = \frac{Q_1}{W_{\text{net}}}$$

$$\boxed{\text{COP}_{\text{HP}} = \frac{Q_1}{Q_1 - Q_2}}$$

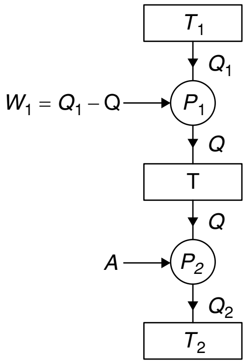
NOTE

$$(\text{COP})_R = \frac{1-\eta E}{\eta E}$$

$$(\text{COP})_P = \frac{1}{\eta E}$$

$$(\text{COP})_P = 1 + (\text{COP})_R$$

Heat Pumps in Series



1. For equal work inputs of two coupled heat pumps, the intermediate temperature 'T' is given by

$$\boxed{T = \frac{T_1 + T_2}{2}}$$

Also $$\boxed{\frac{Q_1}{T_1} = \frac{Q}{T} = \frac{Q_2}{T_2}}$$

2. For equal COPs of the two coupled heat pumps, the intermediate temperature 'T' is given by

$$\boxed{T = \sqrt{T_1 T_2}}$$

Also $$\boxed{\frac{Q_1}{T_1} = \frac{Q}{T} = \frac{Q_2}{T_2}}$$

3. Overall COP of the coupled heat pump is given by

$$\boxed{1 - \frac{1}{C_0} = \left(1 - \frac{1}{C_1}\right)\left(1 - \frac{1}{C_2}\right)}$$

Clausius Inequality

'When a system undergoes a complete cyclic process, the integral of $\frac{\delta Q}{T}$ around the cycle is less than zero or equal to zero.'

This is known as Clausius inequality

$$\therefore \oint \frac{\delta Q}{T} \leq 0$$

$$\oint \frac{\delta Q}{T} = 0 \quad \text{For reversible cycle}$$

$$\oint \frac{\delta Q}{T} < 0 \quad \text{For irreversible cycle.}$$

NOTES

1. Cluasius inequality speaks whether the cycle is reversible or irreversible.

2. The Clausius inequality for irreversible process may be written as $\oint \frac{\delta Q}{T} + I = 0$

Where I = amount by which the given cycle is irreversible

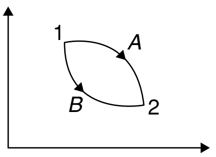
3. If $I = 0$, $\oint \frac{\delta Q}{T} = 0$, becomes irreversible process

Entropy

Entropy is the measure of molecular disorderness. More the disorderness is, more the probability of not predicting the position of the molecules and less the efficiency will be.

Example: Two libraries A and B. In Library A, books are not arranged in proper sequence and in library B, books are arranged in proper sequence. So we can say that in library A, to find a book it will take more time as compared to library B since library A has more entropy and hence efficiency in library A will be less.

- Suppose a system undergoes a cyclic process 1 – A – 2 – B – 1 as shown in figure.



If we apply Clausius inequality to this cyclic process, we get

$$\oint \frac{dQ}{T} = \int_{1A2} \frac{dQ}{T} + \int_{2B1} \frac{dQ}{T}$$

$$= \int_{1A_2} \frac{dQ}{T} - \int_{1B_2} \frac{dQ}{T}$$

That is, $$\int_{1A_2} \frac{dQ}{T} - \int_{1B_2} \frac{dQ}{T}$$

- The quantity $\int \frac{dQ}{T}$ is same for paths $1A_2$ and $1B_2$. That is $\int \frac{dQ}{T}$ is independent of the path and hence it is a property which is an exact differential. This property is known as entropy ‘*S*’.
- Entropy is defined by the relation $dS = \left(\frac{dQ}{T}\right)_R$ where ‘*R*’ denotes that this relation is true for reversible processes only.
- Entropy is a property.
- Entropy change of a system is determined by the initial and final states only, irrespective of how the system has changed its state.
- Entropy change associated with melting and vaporization can be obtained from

$$\boxed{\begin{aligned} S_{sf} &= \frac{h_f - h_s}{T} \\ S_{fg} &= \frac{h_g - h_s}{T} \end{aligned}}$$

- Entropy change associated with heating or cooling in constant pressure process is given as

$$\boxed{\Delta S = mC_p \ln \frac{T_2}{T_1}}$$

- Entropy change associated with heating or cooling in constant volume process is given as

$$\boxed{\Delta S = mC_v \ln \frac{T_2}{T_1}}$$

Adiabatic Mixing of Two Fluids

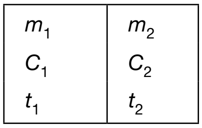


Figure shows a subsystem 1 consisting of a fluid of mass m_1, specific heat ‘C_1’; and temperature ‘t_1’. Subsystem 2 consisting of a fluid of mass ‘m_2’, specific heat ‘C_2’; and temperature ‘t_2’. The two subsystems together form a composite system in an adiabatic enclosure. The two subsystems are separated by a partition. When the partition is removed, the two fluids mix together and at equilibrium, let ‘t_f’ be the final temperature and $t_2 < t_f < t_1$.

As the energy interaction is exclusively combined to the two fluids, the system being isolated.

$$m_1C_1(t_1 - t_f) = m_2C_2(t_f - t_2)$$

$$\therefore \qquad \boxed{t_f = \frac{m_1C_1t_1 + m_2C_2t_2}{m_1C_1 + m_2C_2}}$$

Entropy change for the fluid in subsystem 1

$$dS_1 = m_1C_1 \ln \frac{t_f}{t_1}.$$

Entropy change for the fluid in subsystem 2,

$$dS_2 = m_2C_2 \ln \frac{t_f}{t_2}.$$

Entropy change of the total system,

$$\begin{aligned} (dS)_{\text{system}} &= dS_1 + dS_2 \\ &= m_1C_1 \ln \frac{t_f}{t_1} + m_2C_2 \ln \frac{t_f}{t_2} \end{aligned}$$

Since it is an insulated system,

$(dS)_{\text{surroundings}} = 0$ because heat transferred

$$Q = 0\left(ds = \frac{dQ}{T}\right)$$

Entropy of the universe

$$\begin{aligned} (dS)_{\text{universe}} &= (dS)_{\text{system}} + (dS)_{\text{surroundings}} \\ &= m_1C_1 \ln \frac{t_f}{t_1} + m_2C_2 \ln \frac{t_f}{t_2} \end{aligned}$$

$$\boxed{(dS)_{\text{universe}} = m_1C_1 \ln \frac{t_f}{t_1} + m_2C_2 \ln \frac{t_f}{t_2}}$$

NOTE

If the fluid is identical in all respects i.e., $m_1 = m_2 = m$ and $C_1 = C_2 = C$

$$\therefore \qquad t_f = \frac{t_1 + t_2}{2}$$

$$dS_1 = mC \ln \frac{t_f}{t_1}$$

$$dS_2 = mC \ln \frac{t_f}{t_2}$$

$$\begin{aligned} (dS)_{\text{system}} &= dS_1 + dS_2 \\ &= mC \ln \left(\frac{t_f^2}{t_1t_2}\right) \\ &= mC_2 \ln \frac{t_f}{\sqrt{t_1t_2}} = mC_2 \ln \frac{t_1t_2}{2\sqrt{t_1t_2}} \end{aligned}$$

NOTE

Mixing of fluid is an irreversible process.

Sl.No.	Process	$(dS)_{\text{system}}$	$(dS)_{\text{surroundings}}$	$(dS)_{\text{universe}}$
1.	Isothermal dissipation of work through a system into internal energy of the reservoir	0	$\frac{W}{T}$	$\frac{W}{T}$
2.	Adiabatic dissipation of work into internal energy of a system	$C_p \ln\left(\frac{T_2}{T_1}\right)$	0	$C_p \ln\left(\frac{T_2}{T_1}\right)$
3.	Free expansion of ideal gas	$nR \ln\left(\frac{V_2}{V_1}\right)$	0	$nR \ln\left(\frac{V_2}{V_1}\right)$
4.	Transfer of heat through a medium from a hot to cool medium	0	$\left(\frac{Q}{T_2}\right)-\left(\frac{Q}{T_1}\right)$	$\left(\frac{Q}{T_2}\right)-\left(\frac{Q}{T_1}\right)$

Entropy Changes of a Closed System

1. The entropy will decrease when heat is removed from the system, all processes being reversible ones.
2. The entropy will remain constant when reversible adiabatic processes occur within a system.
3. The entropy will increase when heat is added to the system, reversibly or irreversibly.
4. The entropy of an isolated system will increase when irreversible processes occur within it.

INCREASE OF ENTROPY PRINCIPLE

The entropy of any adiabatic closed system or isolated system during a process will always increases or remains constant. For any reversible process of isolated system, the entropy remains the same and for any irreversible process, the entropy of an isolated system will always increase. This is the increase of entropy principle.

$$(S_2 - S_1)_{\text{isolated}} \geq 0$$

NOTES

For an isolated system, $\Delta S > 0$ for an irreversible process. $\Delta S = 0$ for a reversible process. $\Delta S < 0$ for an impossible process.

1. Since $dS = \frac{dQ}{T}$ we get $dQ = TdS$. Therefore the area under the $T - S$ diagram gives the heat interaction for that process.

2. Entropy is an extensive property.

Entropy Generation

The entropy change is given $\boxed{dS \geq \frac{dQ}{T}}$ i.e., $S_2 - S_1 \geq \int_1^2 \frac{dQ}{T}$

where $(S_2 - S_1)$ represents the entropy change of a system and $\int_1^2 \frac{dQ}{T}$ represents the entropy transfer with heat. The inequality sign in the preceding relations shows that the entropy change of a closed system during an irreversible process is always greater than the entropy transfer i.e. some entropy is generated during an irreversible process and this generation is entirely due to the presence of irreversibilities. This entropy generated during a process is called entropy generation S_{gen}.

i.e., $$\boxed{(\Delta S)_{\text{system}} = S_2 - S_1 = \int_1^2 \frac{dQ}{T} + S_{\text{gen}}}$$

NOTE

S_{gen} is always a positive or zero quantity. Its value depends on the process and thus it is not a property of the system.

In the absence of any heat transfer, the entropy change of a system is equal to the entropy generation.

NOTE

For an isolated system, $dQ = 0$ entropy transfer, $\frac{dQ}{T} = 0$

$$\therefore\ S_2 - S_1 = S_{\text{gen}}$$

Since it is an isolated system, the entropy change $(S_2 - S_1)$ is taken as

$$(\Delta S)_{\text{system}} + (\Delta S)_{\text{surroundings}}$$

$$\therefore \quad \boxed{S_{\text{gen}} = (\Delta S)_{\text{total}} = (\Delta S)_{\text{sys}} + (\Delta S)_{\text{surroundings}}} \geq 0$$

NOTE

For a reversible process, due to lack of irreversibility, the entropy generated $S_{\text{gen}} = 0$

For an irreversible process the entropy generation is larger.

NOTES

1. The increase of entropy principle can also be summarized as

$$S_{\text{gen}} \begin{matrix} > 0 \\ = 0 \\ < 0 \end{matrix} \left\{ \begin{matrix} \text{irreversible process} \\ \text{reversible process} \\ \text{impossible process} \end{matrix} \right.$$

2. The entropy change of a system can be negative but entropy generated cannot be negative.

Entropy Balance

The entropy change of a system during a process is greater than the entropy transfer by an amount equal to the entropy generated during the process within the system, i.e.,

$$S_2 - S_1 = \int_1^2 \frac{dQ}{T} + S_{\text{gen}}$$

The increase of entropy principle for any system is expressed as,

(Total entropy entering) − (Total entropy leaving) + (Total entropy generated) = (change in total entropy of the system)

That is, $(S_{\text{in}} - S_{\text{out}}) + S_{\text{gen}} = (\Delta S)_{\text{system}}$

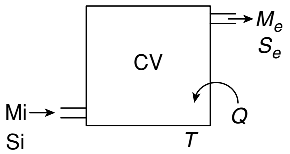
This relation is often referred to as the entropy balance and is applicable to any system undergoing any process.

The entropy balance relation given above can be stated as 'the entropy change of a system during a process is equal to the net entropy transfer through the system boundary and the entropy generated within the system'.

NOTES

1. The general entropy balance relation for a closed system is $\dfrac{\Sigma Q_k}{T_k} + S_{\text{gen}} = S_2 - S_1$.
2. The entropy balance relation for an adiabatic system can be written as $(Q = 0)$
$$(S_{\text{gen}} = (\Delta S)_{\text{adiabatic system}}$$
3. If system and surroundings are concerned, then
$$S_{\text{gen}} = \Sigma\Delta S = (\Delta S)_{\text{sys}} = (\Delta S)_{\text{surr}}$$

Entropy Balance of Control Volumes



The entropy balance for control volume involves the mass flow across the boundaries. It can be written as

$$\sum \frac{Q_k}{T_k} + \Sigma M_i S_i - \Sigma M_e S_e - S_{\text{gen}}$$

$$= \boxed{(S_2 - S_1)_{cv} \frac{kJ}{K}}$$

Or in the rate form,

$$\sum \frac{\dot{Q}_k}{T_k} + \sum \dot{M}_i S_i - \sum \dot{M}_e S_e + \dot{S}_{\text{gen}}$$

$$= \frac{dS_{cv}}{dt} \frac{kW}{K}$$

NOTES

1. For steady flow, $\dfrac{dS_{cv}}{dt} = 0$

We get $\dot{S}_{\text{gen}} = \sum \dot{M}_e S_e - \sum \dot{M}_i S_i - \sum \dfrac{\dot{Q}k}{T_k}$

2. For adiabatic system, $\dot{S}_{\text{gen}} = \Sigma M_e S_e - \Sigma M_i S_i$

1. A reversible adiabatic process is always isentropic but an isentropic process need not to be reversible adiabatic.

For example, $(ds) > \left(\dfrac{\delta Q}{T}\right)_{\text{irrev}}$

$$ds = \left(\frac{\delta Q}{T}\right)_{\text{irrev}} + (\delta S)_{\text{gen}} + ve \text{ quantity}$$

Let us assume $\left(\dfrac{\delta Q}{T}\right)_{\text{irrev}} = -5$ units

$$(\delta S)_{\text{gen}} = 5 \text{ units}$$

$\therefore ds = -5 + 5 = 0$, i.e., $S_1 = S_2$ is an isentropic process. But this process is not a reversible adiabatic process.

2. $(ds)_{\text{universe}} = (ds)_{\text{system}} + (ds)_{\text{surroundings}}$
$(ds)_{\text{surrounding}}$ is positive/negative/zero.
But $(ds)_{\text{surrounding}}$ is always positive.
hence $(ds)_{\text{universe}} \geq 0$

3. Relation between I-law and II-law:
$\delta Q = du + pdv$ valid for reversible process
$$\frac{\delta Q}{T} = ds;\ \delta Q = Tds$$
$Tds = du + pdv$ valid for any process.(i.e., rev/irrev)

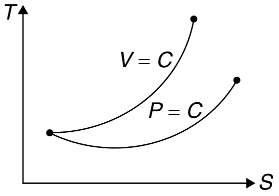
4. $h = u + pv$
$dh = du + pdv + Vdp$
$dh = \delta q + vdp$
$\delta q = dh - vdp$

5. Representation of constant volume and constant pressure line on T-s diagram
Constant volume process
$$Tds = du + pdv$$
$v = c,\ dv = 0$
$$Tds = du$$
$$du = C_v \,.\, dT$$
$$Tds = C_v \,.\, dT$$
$$\left(\frac{dT}{dS}\right) = \frac{T}{C_v}$$

Constant pressure process

$$Tds = dh - vdp$$
$$p = c$$
$$dp = 0$$
$$Tds = dh$$
$$= C_P\,dT$$
$$\left(\frac{dT}{dS}\right) = \frac{T}{C_P}$$

As $C_P > C_V$, constant volume line slope is greater than constant pressure line slope.



The slopes of the curves in T-s diagram is always positive

Entropy Change of Ideal Gases

$$TdS = dU + PdV$$

or $dS = \frac{dU}{T} + \frac{P}{T}dV \quad \left\{PV = mRT \text{ for ideal gas, } \frac{P}{T} = \frac{mR}{V}\right\}$

Now $dU = C_V\,dT$

$$\therefore \quad \int_1^2 dS = \int_1^2 \frac{C_V dT}{T} + \int_1^2 \frac{R}{V}dV \quad \{\text{From state 1 to 2}\}$$

$$S_2 - S_1 = C_V \ln\frac{T_2}{T_1} + R\ln\frac{V_2}{V_1}$$

Or $\quad TdS = dh - VdP$

Or $\quad dS = \frac{dh}{T} - \frac{V}{T}dP \Rightarrow \int_1^2 dS = \int_1^2 \frac{C_P dT}{T} - \int_1^2 \frac{R}{P}dP$

$$\left\{\because \quad PV = mRT \Rightarrow \frac{V}{T} = \frac{mR}{P} \text{ and } dh = C_p dT\right\}$$

$$S_2 - S_1 = C_P \ln\frac{T_2}{T_1} - R\ln\frac{P_2}{P_1}$$

Or $\quad S_2 - S_1 = C_V \ln\frac{T_2}{T_1} + R\ln\frac{V_2}{V_1}$

$$\Rightarrow \quad S_2 - S_1 = C_V \ln\frac{T_2}{T_1} + (C_P - C_V)\ln\frac{V_2}{V_1}\{\because \quad C_P - C_V = R\}$$

$$S_2 - S_1 = C_v\left[\ln\frac{T_2}{T_1} - In\frac{V_2}{V_1}\right] + C_p \ln\frac{V_2}{V_1}$$

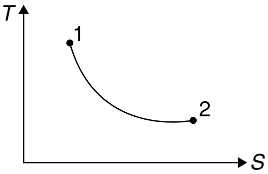
$$\Rightarrow \quad S_2 - S_1 = C_V \ln\left[\frac{T_2/T_1}{V_2/V_1}\right] + C_P \ln\frac{V_2}{V_1}$$

$$\left\{\because \quad \frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2} \Rightarrow \frac{T_2/T_1}{V_2/V_1} = \frac{P_2}{P_1}\right\}$$

$$\therefore \quad S_2 - S_1 = C_V \ln\frac{P_2}{P_1} + C_P \ln\frac{V_2}{V_1}$$

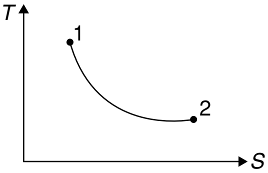
1. **Isochoric process ($V = C$)**

$V = C$
$dV = 0$
$TdS = C_v dT$
$dS = \frac{C_v dT}{T}$



2. **Isobaric process**

$P = C$
$dP = 0$
$TdS = CpdT$
$\boxed{dS = \frac{C_p dT}{T}}$

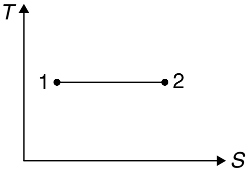


3. **Isothermal process ($T = C$)**

$T = C$
$dT = 0$

$\boxed{dS = mR\ln\frac{V_2}{V_1}}$

Also $\boxed{dS = mR\ln\frac{P_1}{P_2}}$



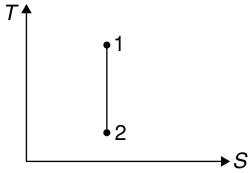
4. **Adiabatic process ($dQ = 0$)**

$dS = \frac{dQ}{T} = 0$

i.e., $S_1 = S_2$

NOTE

Adiabatic process is also known as isoentropic process.



5. **Polytropic process**

$PV^n = C$

$$S_2 - S_1 = R\ln\left(\frac{T_2}{T_1}\right)\left[\frac{(r-n)}{(r-1)(1-n)}\right]$$

$$= R\ln\left(\frac{V_2}{V_1}\right)\left[\frac{r-n}{r-1}\right] = R\ln\left(\frac{P_2}{P_1}\right)\left[\frac{r-n}{n(1-r)}\right]$$

THIRD LAW OF THERMODYNAMICS

Definition: It is impossible by any procedure, no matter how idealized, to reduce any system to the absolute zero of temperature in a finite number of operation.

The 'entropy of a pure crystalline substance at absolute zero temperature is zero' since there is no uncertainty about the state of the molecules at that instant. This statement is known as the third law of thermodynamics.

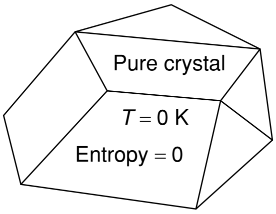


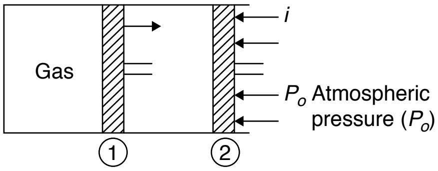
Figure 6 A pure substance at absolute zero temperature is in perfect order and its entropy is zero.

NOTES

1. The third law of thermodynamics provides an absolute reference point for the determination of entropy. The entropy determined relative to this point is called absolute entropy.
2. There is no entropy transfer associated with energy transfer as work.

AVAILABILITY AND IRREVERSIBILITY

1. **Useful work**



When the piston moves from initial position (1) to final position (2) i.e., the gas is expanding, work has been done by the system, but some work is used to push the piston from (1) to (2) against atmospheric pressure and this work is not useful or not utilized for any useful purpose. This work is termed as surrounding work and is given by

$$W = P_0(V_2 - V_1)$$

That is, $$W_{\text{surs}} = P_0(V_2 - V_1)$$

The difference between the actual work 'W' and the surroundings work W_{surs} is called the useful work 'W_u'.

$$W_u = W - W_{\text{surs}} = W - P_0\,(V_2 - V_1)$$

NOTE

When a system is expanding and doing work, part of the work done is used to overcome the atmospheric pressure and thus W_{surs} represents a loss.

When a system is compressed, the atmospheric pressure helps the compression process, thus W_{surs} represents a gain.

2. **Reversible work:** It is defined as the maximum amount of useful work that can be produced or the minimum amount of work that needs to be supplied as a system undergoes a process between the specified initial and final states.
3. **Irreversibility:** Any difference between the reversible work W_{rev} and the useful work W_U is due to irreversibilities present during the process and the difference is called irreversibility 'I'.

$$I = W_{\text{rev}} - W_u$$

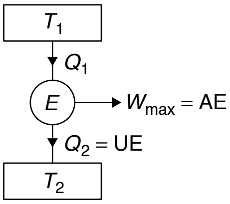
NOTE

For a totally reversible process, irreversibility, $I = 0$ since totally reversible processes generate no entropy.

The performance of a system can be improved by minimizing the irreversibility associated with it.

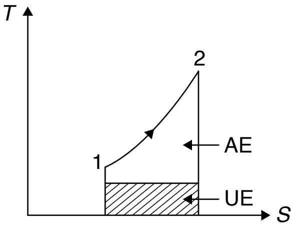
4. **Available energy and unavailable energy:** The maximum work output obtainable from a certain heat input in a cyclic heat engine is called available energy (AE) or the available part of the energy supplied.

   The minimum energy that has to be rejected to the sink by the second law is called the unavailable energy (UE).



$$\therefore \quad Q_1 = AE + UE$$

$$W_{\text{max}} = AE = Q_1 - UE$$



NOTE

The available energy is known as the 'energy' and the unavailable energy is known as the 'a energy'.

5. **Dead state**: A system is said to be in dead state when it is in thermodynamic equilibrium with the environment. At the dead state, a system is at the temperature and pressure of its environment.

6. **Availability of a closed system:** As per first law,

$$Q - W = U_2 - U_1$$

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

Also, $S_{\text{gen}} = (S_2 - S_1) - \dfrac{Q}{T_0}$ where

T_0 – dead state temperature

$$T_0\, S_{\text{gen}} = T_0(S_2 - S_1) - Q$$

$$Q = T_0\,(S_2 - S_1) - T_0\, S_{\text{gen}}$$

From first law,

$$W = Q + (U_1 - U_2) = T_0\,(S_2 - S_1) - T_0\, S_{\text{gen}} + (U_1 - U_2)$$

$$W_{\text{useful}} = W - W_{\text{surs}}$$

$$= (U_1 - U_2) + T_0\,(S_2 - S_1) - T_0\, S_{\text{gen}} - P_0(V_2 - V_1)$$

$$W_U = (U_1 - U_2) + P_0(V_1 - V_2) - T_0\,(S_1 - S_2) - T_0\, S_{\text{gen}}$$

For a reversible process, $S_{\text{gen}} = 0$

$$\boxed{(W_U)_{rev} = (U_1 - U_2) + P_0(V_1 - V_2) - T_0(S_1 - S_2)}$$

– Availability of the system

7. **Availability function (ϕ):** Availability function, ϕ is given as

$$\boxed{\phi = U + P_0V - T_0S}$$

NOTE

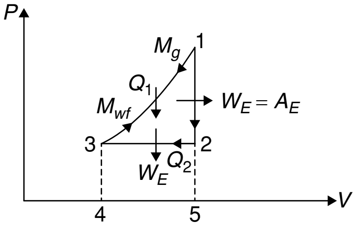
If a system changes from state 1 to state 2 then the change in availability is $\phi_1 - \phi_2$.

8. **Second law efficiency**

- The whole energy absorbed as heat by an engine cannot be converted into work and only the available energy is converted to work. Thus work is the highest quality energy. When the energy is transferred from one system to another, it is necessary to maintain the quality of energy.
- The ratio of net work done to the energy absorbed as heat is called the thermal efficiency of an engine. This efficiency deals with the conversion of energy from one form to another and is usually referred to as first law efficiency. But this efficiency does not take into account the quality of energy.
- In order to measure the performance of a device relative to its performance under reversible conditions, we use second law efficiency. The second law efficiency is the ratio of actual thermal efficiency to the maximum possible (reversible) thermal efficiency under the same conditions.

$$\boxed{\eta_{II} = \frac{\eta_{\text{th}}}{\eta_{\text{th}_{\text{rev}}}}}$$

9. **Available energy from a finite energy source**



A hot gas of mass 'm_g' is at a temperature 'T' when the environmental temperature is T_0. This gas is cooled at constant pressure from state 1 at temperature T to state 3 at temperature T_0 and the heat is given up by the gas, 'Q_1' be utilized in heating up reversibly a working fluid of mass 'W_f' from state 3 to state 1 along the same path so that the temperature difference between the gas and the working fluid at any instant is zero and hence the entropy increase of the universe is also zero. The working fluid expands reversibly and adiabatically in an engine or turbine from state 1 to state 2 doing work W$_E$ and then rejects heat Q_2 reversibly and isothermally to return to the initial state 3 to complete a heat engine cycle.

$$Q_1 = m_gC_{pg}(T - T_0) = m_{wf}C_{pwf}\,(T - T_0) = \text{Area } 134521$$

$$\therefore\quad m_gC_{pg} = m_{wf}C_{pwf}$$

$$\Delta S_{\text{gas}} = \int_T^{T_0} m_gC_{pg}\,\frac{dT}{T} = m_gC_{pg}\ln\frac{T_0}{T}\,\text{(negative)}$$

$$(\Delta S)_{wf} = \int_T^{T_0} m_{wf}C_{pwf}\,\frac{dT}{T} = m_{wf}C_{pwf}\ln\frac{T_0}{T}\,\text{(positive)}$$

$$(DS)_U = (DS)_{\text{gas}} + (DS)_{wf} = 0$$

$$Q_2 = T_0(DS)_{wf} = T_0m_{wf}C_{pwf}\ln\frac{T_0}{T}$$

$$\therefore\ \text{Available energy} = W_{\max} = Q_1 - Q_2$$

$$= m_gC_{pg}(T - T_0) - T_0m_gC_{pg}\ln\frac{T}{T_0} = \text{Area } 1231$$

NOTE

The available energy or exergy of a gas of mass m_g at temperature 'T' is given by

$$AE = m_gC_{pg}\left[(T - T_0) - T_0\ln\frac{T}{T_0}\right]$$

Useful tip: Whenever heat is transferred through a finite temperature difference, there is a decrease in available energy.

10. **Availability in steady flow systems:** The availability of a steady flow system is the maximum work that can be delivered by the system to something other than the surroundings as the state changes from that at entry to the control volume to the dead state at the exit boundary, at the same time exchanging only with the surroundings.

The availability for a non–flow process is given as $f = U + P_0V - T_0S$.

This can also be applied to flow systems. In this case, the availability of each unit mass of fluid at a specified state with respect to an environment at pressure 'P' and temperature 'T_0' is increased by the amount of work that can be delivered by virtue of flow.

This work is given by $(P_1V_1 - P_0V_1)$

Therefore the useful work

$$W_{\text{useful}} \le (U_1 - U_0) - T_0(S_1 - S_0) - P_0(V_0 - V_1) + (P_1V_1 - P_0V_1)$$

$$W_U \le (U_1 + P_1V_1 - T_0S_1) - (U_0 + P_0V_0 - T_0S_0)$$

$$\le (B_1 - B_0) \text{ where}$$

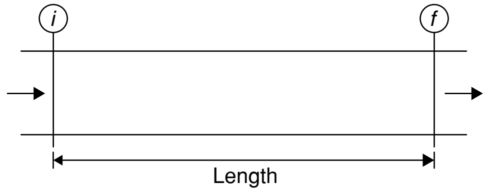
$$B = U + PV - T_0S$$

$$= H - T_0S$$

$W_U \le (B_1 - B_0)$ is known as the availability function for steady flow.

11. **Law of degradation of energy:** This law tells about the quality and quantity of energy and states that 'energy is always conserved but its quality always degraded'.

Let us take an example of hot gas flowing through a pipe at a reversible constant pressure condition from inlet condition (i) to the final condition (f) as shown in the figure.



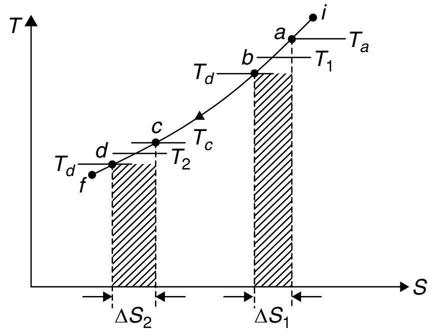
Throughout the length of the pipe the heat loss will take place from the pipe to the atmosphere.

For reversible constant pressure process

$$Tds = dh - Vdp$$

$$\boxed{\begin{aligned} \text{or } Tds &= m\,C_P dT \\ \text{Or } \frac{dT}{ds} &= \frac{T}{mC_P} \end{aligned}}$$

So, $\frac{dT}{ds}$ gives the slope of the curve on T-S plot.



When temperature (T) increases, the slope of the curve increases and vice verse.

Now let us take four points on the curve a, b, c, d and Q units of heat is lost from the pipe to the surroundings as the temperature decreases from T_a to T_b, T_1 being the average of the two. Then,

Heat loss will be, $Q = mC_P(T_a - T_b) = T_1\,\Delta S_1$

Similarly for c to d, as temperature decreases from T_c to T_d, the same amount Q has lost, T_2 being the average of it.

Heat lost, $Q = mC_P(T_c - T_d) = T_2\,\Delta S_2$

Available energy lost with this heat loss at temperature at T_1, $W_1 = Q - T_1\,\Delta S_1$

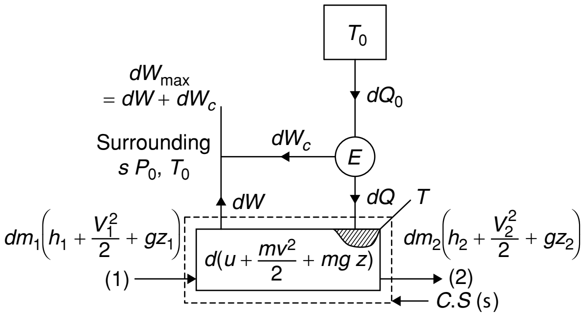
and at T_2, $W_2 = Q - T_2\,\Delta S_2$

$\because T_1 > T_2$, $\Delta S_2 > \Delta S_1$

$\therefore\ W_1 > W_2$

Hence loss of available energy is less when the loss of heat occurs at lower temperature T_2 as compared to the loss at higher temperature T_1. The quantity of loss (Q) is same but at higher temperature the loss of available energy is more and this shows the degradation of energy quality wise. Quantity wise the energy loss (Q) is same but quality wise (W), the losses are different.

12. **Reversible work by an open system exchanging heat only with the surroundings**



Let us consider an open system exchanging energy only with the surroundings at constant temperature T_0 and at constant pressure P_0. A mass dm_1 enters the system at state 1, a mass of dm_2 leaves the system at state 2, an amount of heat dQ is absorbed by the system, an amount of work dW is delivered by the system, and the energy of the system (control volume) changes by an amount $(dE)_\sigma$.

Applying the first law, we have

$$dQ + dm_1\left(h_1 + \frac{V_1^2}{2} + gZ_1\right)$$

$$-dm_2\left(h_2 + \frac{V_2^2}{2} + gZ_2\right) - dW = (dE)_\sigma$$

$$= \left(dU + \frac{mV^2}{2} + mgZ\right)_\sigma$$

$$\therefore \quad dW_{\max} = dm_1\left(h_1 - T_0S_1 + \frac{V_1^2}{2} + gZ_1\right)$$

$$-dm_2\left(h_2 + T_0S_2 + \frac{V_2^2}{2} + gZ_2\right)$$

$$-d\left[U - T_0S + \frac{mV^2}{2} + mgZ\right]_\sigma \qquad (1)$$

13. **Reversible work in a steady flow process:** For a steady flow process, $dm_1 = dm_2 = dm$
and

$$d\left[U - T_0S + \frac{mV^2}{2} + mgZ\right]_\sigma = 0$$

Equation (1) for $dW_{\max}$ reduces to

$$\therefore \quad dW_{\max} = dm\left(h_1 - T_0S_1 + \frac{V_1^2}{2} + gZ_1\right)$$

$$-\left(h_2 + T_0S_2 + \frac{V_2^2}{2} + gZ_2\right) \qquad (2)$$

For total mass flow, the integral form of equation (2) becomes

$$W_{\max} = \left(H_1 - T_0S_1 + \frac{mV_1^2}{2} + mgZ_1\right)$$

$$-\left(H_2 - T_0S_2 + \frac{mV_2^2}{2} + mgZ_2\right)$$

Useful tip: The expression $(H - T_0S)$ is called the Keenan function 'B'.

$$\therefore \; W_{\max} = \left(B_1 + \frac{mV_1^2}{2} + mgZ_1\right) - \left(B_2 + \frac{mV_2^2}{2} + mgZ_2\right)$$

$$= \Psi_1 - \Psi_2$$

Where Ψ is called the availability function of a steady flow process which is given by

$$\Psi = B + \frac{mV^2}{2} + mgZ$$

On a unit mass basis,

$$W_{\max} = \left(h_1 - T_0S_1 + \frac{V_1^2}{2} + gZ_1\right)$$

$$-\left(h_1 - T_0S_2 + \frac{V_2^2}{2} + gZ_2\right)$$

$$= \left(b_1 + \frac{V_1^2}{2} + gZ_1\right) - \left(b_2 + \frac{V_2^2}{2} + gZ_2\right)$$

If KE and PE changes are neglected, then

$$W_{\max} = B_1 - B_2$$

$$= (H_1 - T_0S_1) - (H_2 - T_0S_2)$$

$$= (H_1 - H_2) - T_0(S_1 - S_2)$$

and per unit mass

$$W_{\max} = b_1 - b_2$$

$$= (h_1 - h_2) - T_0(S_1 - S_2)$$

14. **Reversible work in a closed system:** For a closed system, $dm_1 = dm_2 = 0$
∴ Eqn (1) becomes

$$dW_{\max} = -\left[U - T_0S + \frac{mV^2}{2} + mgZ\right]_\sigma = -d[E - T_0S]_s$$

Where $E = U + \dfrac{mV^2}{2} + mgZ$

For a change of state of a system, from the initial state 1 to the final state 2,

$$W_{\max} = [E_1 - E_2] - T_0(S_1 - S_2)$$

$$= [E_1 - T_0S_1] - [E_2 - T_0S_2]$$

If KE and PE changes are neglected, the above equation reduces to

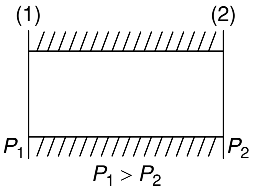
$$W_{\max} = (U_1 - T_0S_1) - (U_2 - T_0S_2)$$

For unit mass of fluid,

$$W_{\max} = (U_1 - U_2) - T_0(S_1 - S_2)$$

$$= (U_1 - T_0S_1) - (U_2 - T_0S_2)$$

15. **Flow with friction:** If we consider the steady and adiabatic flow of an ideal gas through the segment of a pipe,



Then, entropy generation is given by

$$\boxed{S_{\text{gen}} = \frac{mR\Delta P}{P_1}}$$

Irreversibility is given by

$$\boxed{\begin{aligned} I &= T_0S_{\text{gen}} \\ &= \frac{mR\Delta P}{P_1} \end{aligned}}$$

Useful tip: With pressure loss, we will loose available energy which leads to irreversibility of the system.

16. **Reversible work expressions**

(a) Cyclic devices

$$W_{\text{rev}} = \eta_{\text{rev}}\, Q_1 \text{ (Heat engines)}$$

$$-W_{\text{rev}} = \frac{Q_2}{(\text{COP})_{\text{rev}}} \text{ of refrigerators}$$

$$-W_{\text{rev}} = \frac{Q_2}{(\text{COP})_{\text{rev}}} \text{ of heat pumps}$$

NOTES

1. **Guoy stodola theorem:** ‘It states that irreversibility is directly proportional to entropy change of universe.’

$$I \propto (ds)_{\text{universe}}$$

$$\because \quad (ds)_{\text{universe}} \geq 0$$

$$\therefore \quad I \geq 0$$

2. Gibbs function $(G) = H - TS$
3. Helmoltz function $(F) = U - TS$

THERMODYNAMICS RELATIONS

Theorem I

$$dz = Mdx + Ndy$$

Is an exact differential equation when

$$\left(\frac{\partial M}{\partial y}\right)_x = \left(\frac{\partial N}{\partial x}\right)_y$$

Theorem 2

$$f = \phi(x, y, z)$$

$$\left(\frac{\partial x}{\partial y}\right)_f \cdot \left(\frac{\partial y}{\partial z}\right)_f \cdot \left(\frac{\partial z}{\partial x}\right)_f = 1$$

Theorem 3

$$z = \phi(x.\ y)$$

$$\left(\frac{\partial x}{\partial y}\right)_z \cdot \left(\frac{\partial y}{\partial z}\right)_x \cdot \left(\frac{\partial z}{\partial x}\right)_y = -1$$

MAXWELL’S EQUATIONS

1. $Tds = du + pdv$

   $du = Tds - pdv$; but exact differential equations are of the form

   $dz = Mdx + Ndy$

   Where $M = T, x = s, N = -P, dx = ds, dy = dv$

$$\left(\frac{\partial M}{\partial y}\right)_x = \left(\frac{\partial N}{\partial x}\right)_y$$

$$\left(\frac{\partial T}{\partial v}\right)_S = -\left(\frac{\partial P}{\partial S}\right)_V \qquad (1)$$

2. $Tds = dh - Vdp$

   $dh = Tds + Vdp$, But exact differential equations are of the form

   $dz = Mdx + Ndy$

   $Z = h, M = T, x = S, N = V, dx = ds, dy = dv$

$$\left(\frac{\partial T}{\partial P}\right)_S = \left(\frac{\partial V}{\partial S}\right)_P \qquad (2)$$

3. $G = H - TS$

   $dG = dH - [Tds + sdT]$

   $dG = dH - Tds - sdT$

   But $Tds = dH - vdp$

   $dH = Tds + vdp$

   $\therefore\ dG = vdp - sdT$ (Exact equation)

   $dz = Mdx + Mdy$

   $z = G, M = v, x = P, N = -S, dy = dT, dx = dp$

$$\therefore \quad \left(\frac{\partial M}{\partial y}\right)_x = \left(\frac{\partial N}{\partial x}\right)_y$$

$$\left(\frac{\partial V}{\partial T}\right)_P = -\left(\frac{\partial S}{\partial P}\right)_T \qquad (3)$$

4. $F = U - TS$

   $dF = du - (Tds + sdT)$

   $dF = du - Tds - sdT$ (Exact equation)

   $dF = -pdv - sdT$

   $dz = Mdx + Ndy$

$$\left(\frac{\partial M}{\partial y}\right)_x = \left(\frac{\partial N}{\partial x}\right)_y$$

$$-\left(\frac{\partial P}{\partial T}\right)_V = \left(\frac{\partial S}{\partial V}\right)_T$$

$$\left(\frac{\partial P}{\partial T}\right)_V = \left(\frac{\partial S}{\partial v}\right)_T \qquad (4)$$

   $Tds = dut + pdv$

   $-pdv = du - Tds$

Deduction of Maxwell’s Equations

1. $\left(\frac{\partial T}{\partial V}\right)_S = -\left(\frac{\partial P}{\partial S}\right)_V$
2. $\left(\frac{\partial V}{\partial T}\right)_P = -\left(\frac{\partial S}{\partial P}\right)_T$
3. $\left(\frac{\partial T}{\partial P}\right)_S = \left(\frac{\partial V}{\partial S}\right)_P$
4. $\left(\frac{\partial P}{\partial T}\right)_V = \left(\frac{\partial S}{\partial V}\right)_T$

are called Maxwell equations.

Tds Equations

$$Tds = C_v dT + T \cdot \left(\frac{\partial P}{\partial T}\right)_v dv \qquad (5)$$

$$Tds = C_P dT - T\left(\frac{\partial V}{\partial T}\right)_P dp \qquad (6)$$

$$\left(\frac{\partial T}{\partial P}\right)_V = \frac{T}{C_P - C_V}\left(\frac{\partial V}{\partial T}\right)_P$$

$$C_P - C_V = T \cdot \left(\frac{\partial V}{\partial T}\right)_P \left(\frac{\partial P}{\partial T}\right)_V$$

$$T = f(P, V)$$

$$\left(\frac{\partial P}{\partial V}\right)_T \left(\frac{\partial V}{\partial T}\right)_P \left(\frac{\partial T}{\partial P}\right)_V = -1$$

$$-\left(\frac{\partial P}{\partial V}\right)_T \left(\frac{\partial V}{\partial T}\right)_P = \left(\frac{\partial P}{\partial T}\right)_V$$

$$\therefore \qquad C_P - C_V = T\left(\frac{\partial V}{\partial T}\right)_P \left(\frac{\partial P}{\partial T}\right)_V$$

$$= -T\left(\frac{\partial P}{\partial V}\right)\left(\frac{\partial V}{\partial T}\right)_P \left(\frac{\partial V}{\partial T}\right)_P$$

$$C_P - C_V = -T\left[\left(\frac{\partial V}{\partial T}\right)_P\right]^2 \left(\frac{\partial P}{\partial V}\right)_T$$

NOTES

1. $\left(\frac{\partial V}{\partial T}\right)_P^2 \rightarrow$ Is always '+ve'

   $\left(\frac{\partial P}{\partial V}\right)_T \rightarrow$ Is always –ve

   $\therefore C_P - C_V = +\text{ve}$

   i.e., $C_P > C_V$
2. As $T \rightarrow 0$ K, $C_P \rightarrow C_V$ or at absolute zero temperature $C_P = C_V$
3. $\left(\frac{\partial V}{\partial T}\right)_P = 0$: e.g., for water at 4°C, when density is maximum or specific volume is minimum).

   $$\therefore \qquad C_P = C_V$$
4. For an ideal gas, $pv = mRT$

   $$\left(\frac{\partial V}{\partial T}\right)_P = \frac{mR}{P} = \frac{V}{T}$$

   $$\left(\frac{\partial P}{\partial V}\right)_T = \frac{-mRT}{V^2}$$

   $$C_P - C_V = -T\frac{V^2}{T^2} \times \frac{-mRT}{V^2}$$

   $$C_P - C_V = mR$$

   $$C_P - C_V = R.$$

Co-efficient of Volume Expansion or Volume Expansivity (β)

$$\beta = \frac{1}{V}\left(\frac{\partial V}{\partial T}\right)_P \quad \therefore \quad \beta V = \left(\frac{\partial V}{\partial T}\right)_P$$

It shows variation of volume with respect to temperature under isobaric condition.

Isothermal Compressibility (K_T)

$$K_T = -\frac{1}{V}\left(\frac{\partial V}{\partial P}\right)_T \quad K_T V = -\left(\frac{\partial V}{\partial P}\right)$$

It shows variation of volume with respect to pressure under isothermal conditions.

NOTE

$$C_P - C_V = -T\left(\frac{\partial V}{\partial T}\right)_P^2 \left(\frac{\partial P}{\partial V}\right)_T \quad s$$

$$\left(\frac{\partial V}{\partial T}\right)_P = \beta V; \quad \left(\frac{\partial P}{\partial V}\right)_T = \frac{-1}{K_T V}$$

$$C_P - C_V = -T(\beta V)^2 - \frac{1}{K_T \cdot V}$$

$$C_P - C_V = \frac{TV\beta^2}{K_T}$$

THE JOULE–THOMSON CO-EFFICIENTS

When a fluid passes through restriction such as a porous plug, a capillary tube, or an ordinary valve the pressure decreases. This is called throttling process.

The enthalpy of the fluid remains constant during throttling process.

During throttling process fluid may experience a large temperature drop, which forms the basis of operation for refrigerators and air conditions.

However, the above condition is not always true; the fluid temperature may remain constant or may increase during throttling process:

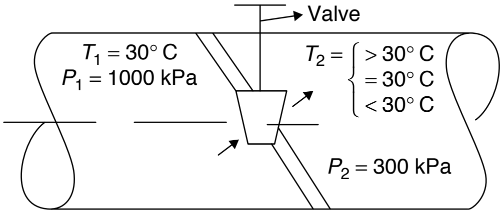


Figure 7 The temperature of Fluid may increase, decrease, or remains unchanged during throttling but pressure drop takes place

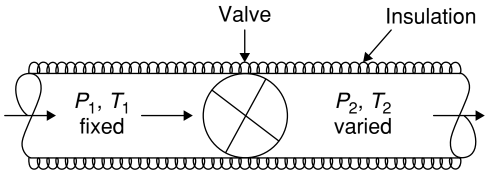
'The temperature behavior of fluid during throttling process (h = constant) is described by the Joule–Thomson coefficient.'

It is defined as $\mu = \left(\frac{\partial T}{\partial P}\right)_h$

The Joule–Thomson coefficient is measure of the change in temperature with pressure during a constant enthalpy process.

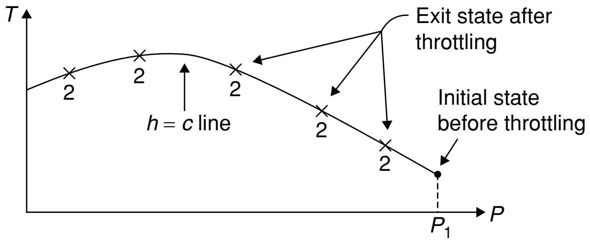
$$\mu_{JT} \begin{cases} < 0 \text{ temperature increases} \\ = 0 \text{ temperature remains constant} \\ > 0 \text{ temperature decreases} \end{cases}$$

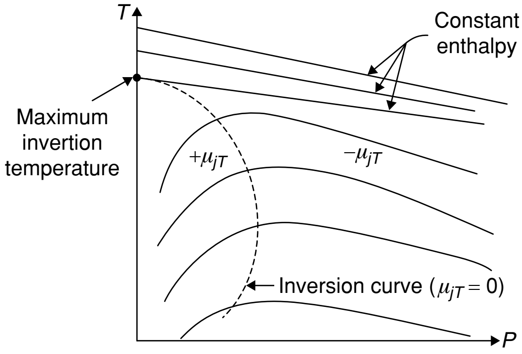
Porous Plug-experiment



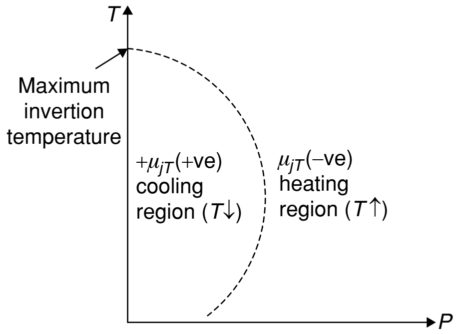
Figue 8 Porous plug-experiment

- A fluid is passing through restricted passage or porous plug with an initial fixed temperature T_1 and pressure P_1 and after passing the plug; the final temperature T_2 and pressure P_2 are measured.
- The above step is repeated for different passage openings or different size of porous plug, each experiment will give different set of final temperature T_2 and final pressure P_2.
- Since the above experiment is constant enthalpy process, when plotting on T–P diagram, a constant enthalpy line will come with different sets of final temperature (T_2) and pressure (P_2)
- Repeating the experiment for different sets of inlet pressure and temperature and plotting the results, the following diagram can be constructed on T-P co-ordinates.





- Some $h = c$ lines on T-P diagram pass through a point of zero slope or zero Joule-Thomson coefficient.
- 'The line passing through these points is called the inversion line.'
- The temperature at a point where the inversion curve intersects the constant enthalpy line is called inversion temperature.
- 'The temperature, at the intersection of the $P = 0$ line and inversion line is called the maximum inversion temperature'.



- The slope of the curve on T-P diagram is called the Joule Thomson co-efficient. i.e., ($\mu_J T$)

Observations:

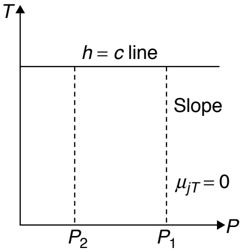
1. Slope (μ_{JT}) is –ve on right side of inversion curve, temperature increases.
2. Slope (μ_{JT}) is +ve on left side of inversion curve, temperature decreases.
3. Slope (μ_{JT}) is zero on the Inversion curve Temperature is constant.

General Relation for Joule–Thomson Co-efficient

$$\mu_J = \left(\frac{\partial T}{\partial P}\right)_h = \frac{1}{C_P}\left[T\left(\frac{\partial V}{\partial T}\right)_P - v\right]$$

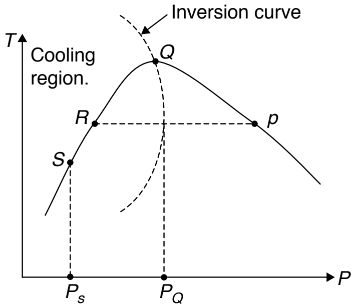
NOTES

1. For an ideal gas $\mu_{JT} = 0$



The temperature of an ideal gas remains constant during throttling process since $h = c$ and $T = c$ lines on a T–P diagram coincides.

2. Maximum cooling (temperature drop) by Joule–Kelvin expansion is achieved when the initial state lies on the inversion curve (i.e., ($T_Q - T_S$)).



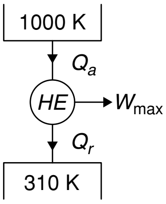
3. For Hydrogen and helium the maximum inversion temperature is less than room temperature hence no cooling effect is achieved by Joule-kelvin expansion. That is, μ_J is always negative.

Solved Examples

Example 1: A cyclic heat engine operates between a source temperature of 1000 K and a sink temperature of 37°C. What is the least rate of heat rejection per kW net output of the engine?

(A) 0.85 kW (B) 0.65 kW
(C) 0.45 kW (D) 1.45 kW

Solution:
For minimum heat rejection, the engine should be reversible.



$$\eta = 1 - \frac{310}{1000} = \frac{W_{\max}}{Q_a}$$

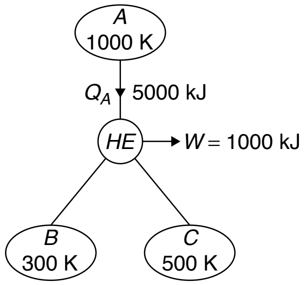
$$\Rightarrow \quad \frac{W_{\max}}{Q_a} = 0.69$$

or
$$\frac{Q_a}{W_{\max}} = 1.45$$

Now $Q_r = Q_a - W_{\max}$ $\Rightarrow \dfrac{Q_r}{W_{\max}} = \dfrac{Q_a}{W_{\max}} - 1$

$$\Rightarrow \quad \frac{Q_r}{W_{\max}} = 1.45 - 1 = 0.45 \text{ kW}$$

Example 2: The figure shows a system undergoing a reversible cycle during which it exchanges heat with three thermal reservoirs and develops 1000 kJ of work. Find the heat exchanged at *B* and *C* respectively.



(A) 1950 and 7250 (B) 2250 and 6250
(C) 2500 and 6000 (D) 3000 and 6000

Solution:

$$W = Q_A + Q_B + Q_C$$

[let us assume the direction of Q_B and Q_C be into the system]

or
$$Q_B + Q_C = 1000 - 5000 = -4000 \tag{1}$$

Now for reversible cycle,

$$\oint \frac{dQ}{T} = 0 \quad \Rightarrow \quad \frac{Q_A}{T_A} + \frac{Q_B}{T_B} + \frac{Q_C}{T_C} = 0$$

$$\frac{5000}{1000} + \frac{Q_B}{300} + \frac{Q_C}{500} = 0$$

$$\Rightarrow \quad \frac{Q_B}{300} + \frac{Q_C}{500} = -5 \tag{2}$$

From equation (1) and (2) we get
$Q_B = 2250$ kJ, $Q_C = -6250$ kJ
∴ Q_B towards the engine and Q_C from the engine.

Example 3: Two Cannot engines *A* and *B* are connected in series between two thermal reservoirs maintained at 1200 K and 200 K respectively. Engine *A* receives 2000 kJ of heat from the high temperature reservoir and rejects heat to the Cannot engine *B*. Engine *B* receives heat rejected by engine *A* and rejects heat to the low temperature reservoir.

i. If engine *A* and *B* have equal thermal efficiencies, then the work done during the process by engines *A* and *B* respectively are
(A) 1013.3 and 412.69 (B) 1183.5 and 483.164
(C) 1123.6 and 384.64 (D) 1238.5 and 384.64

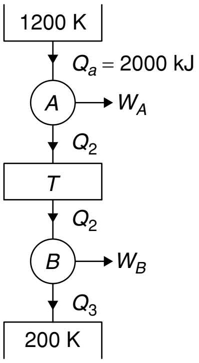
ii. If engine *A* and *B* deliver equal work, determine the amount of heat rejected by engine *B* (in kJ)
(A) 383.4 (B) 234.3
(C) 353.3 (D) 333.3

Solution:

i. (B)

$$\eta_A = \eta_B$$

$$T = \sqrt{T_1 T_2}$$



$$= \sqrt{1200 \times 200}$$

$$T = 489.9 \text{ K}$$

$$\eta_A = 1 - \frac{489.9}{1200} = 0.59175 = \frac{W_A}{Q_1}$$

$$\Rightarrow \quad W_A = 0.59175 \times 2000 = 1183.5 \text{ kJ}$$

Now $W_A = Q_1 - Q_2$ $\Rightarrow$ $Q_2 = -1183.5 + 2000$

$$\Rightarrow \quad Q_2 = 816.5 \text{ kJ}$$

$$\eta_B = 0.59175 = \frac{W_B}{Q_2}$$

$$\Rightarrow \quad W_B = 483.164 \text{ kJ}$$

ii. (D)

If $W_A = W_B$ then $T = \dfrac{T_1 + T_2}{2}$

$$T = \frac{1200 + 200}{2} = 700 \text{ K}$$

$$\eta_A = 1 - \frac{700}{1200} = 0.4167$$

and $\eta_B = 1 - \dfrac{200}{700} = 0.7143$

Now $\eta_A = 0.4167 = \dfrac{W_A}{Q_1} \Rightarrow W_A = 0.4167 \times 2000$

$$\Rightarrow W_A = 833.4 \text{ kJ} = Q_1 - Q_2$$

$$\Rightarrow Q_2 = 1166.6 \text{ kJ}$$

$\because \quad \eta_B = 0.7143 = 1 - \dfrac{Q_3}{Q_2}$

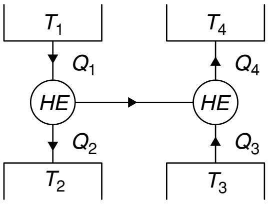
$\therefore \quad Q_3 = 333.297 \text{ kJ} \sim 333.3 \text{ kJ}$

Example 4: A heat engine is used to drive a heat pump. The heat transfers from the heat pump and heat engine are used to heat the water circulating through the radiator of the building. If the efficiency of the heat engine is 30% and the COP of the heat pump is 6 then the ratio of the heat transfer to the circulating water to the heat transfer to the heat engine will be

(A) 2.25 (B) 1.8

(C) 2.5 (D) 2.0

Solution:



Given:

$$1 - \frac{Q_2}{Q_1} = 0.30 \Rightarrow Q_2 = 0.7\, Q_1 \tag{1}$$

and
$$\frac{Q_4}{Q_4 - Q_3} = 6 \Rightarrow Q_4 = 6Q_4 - 6Q_3$$

$$\Rightarrow Q_3 = 0.834\, Q_4 \tag{2}$$

Now $W = Q_1 - Q_2 = Q_4 - Q_3$ (3)

From equation (1), $Q_2 + Q_4 = 0.7Q_1 + Q_4$ (4)

From equation (3), $Q_4 = Q_1 - Q_2 + Q_3$

$\Rightarrow \quad Q_4 = Q_1 - 0.7Q_1 + 0.834Q_4$

$\Rightarrow \quad 0.166Q_4 = 0.3Q_1$

$\Rightarrow \quad Q_4 = 1.8Q_1$ (5)

Putting value of Q_4 from equation (5) to equation (4)

$\therefore \qquad Q_2 + Q_4 = 0.7Q_1 + 1.8Q_1$

$$\Rightarrow \frac{Q_2 + Q_4}{Q_1} = 2.5$$

Example 5: An ideal gas is flowing in an insulated pipe. The pressure and temperature measurements of the air at two stations are given below. Assume specific heat C_P = 1.005 kJ/kg-K and C_V = 0.718 kJ/kg-K

	Station A	Station B
Pressure	150 kPa	100 kPa
Temperature	60°C	20°C

The directions of the flow will be

(A) A to B (B) Flow is not possible

(C) None of these (D) B to A

Solution:

Let us assume the flow is from station A to B

$$Tds = dh - VdP$$

$$\Rightarrow \int_A^B dS = \int_A^B C_p \frac{dT}{T} - \int_A^B \frac{V}{T} dP$$

$$\Rightarrow (S_A - S_B) = C_p \ln \frac{T_B}{T_A} - R \ln \frac{P_B}{P_A}$$

$$\Rightarrow (S_A - S_B) = 1.005 \times \ln\left(\frac{20 + 273}{60 + 273}\right) - 0.287 \times \ln\left(\frac{100}{150}\right)$$

$\because S_A - S_B = -0.0122 = (\Delta S)_{\text{system}}$

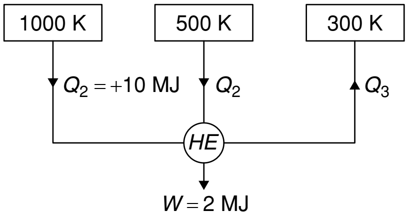
Now $(\Delta S)_{\text{universe}} = (\Delta S)_{\text{system}} + (\Delta S)_{\text{surrounding}}$

But $(\Delta S)_{\text{surrounding}} = 0 \quad \{\because \text{Insulated}\}$

$\because (\Delta S)_{\text{universe}} = (\Delta S)_{\text{system}} = -0.0122$ kJ/kg-K

This is impossible and hence the flow is from station B to A.

Example 6: A reversible engine is shown in figure. If $Q_1 = +10$ MJ then the amount and magnitude of Q_2 and Q_3 will be



(A) +12.5 MJ and –4.5 kJ

(B) –12.5 MJ and +4.5 MJ

(C) –12.5 MJ and –4.5 MJ

(D) +12.5 MJ and +4.5 MJ

Solution:

We know that, $W = Q_1 + Q_2 - Q_3$

$$\Rightarrow Q_1 + Q_2 - Q_3 = 2 \text{ MJ}$$

$$\Rightarrow Q_2 - Q_3 = 2 - 10 = -8 \text{ MJ} \tag{1}$$

Now $(\Delta S)_{\text{univ}} = (\Delta S)_{\text{sys}} + (\Delta s)_{\text{surr}} = 0$ [reversible]

But $(\Delta S)_{\text{sys}} = 0$ [cycle]

$\therefore (\Delta S)_{\text{surr}} = 0$

$$\Rightarrow -\frac{Q_1}{1000} - \frac{Q_2}{500} + \frac{Q_3}{300} = 0 \Rightarrow -\frac{10}{1000} - \frac{Q_2}{500} + \frac{Q_3}{300} = 0$$

$$\Rightarrow \frac{Q_3}{300} - \frac{Q_2}{500} = 0.01$$

$$\Rightarrow 5Q_3 - 3Q_2 = 15 \tag{2}$$

From equation (1) and (2) we get

$$Q_2 = -12.5 \text{ MJ} \quad \text{and} \quad Q_3 = -4.5 \text{ MJ}$$

Example 7: A mass of 5 kg of water at 90°C mixed adiabatically with another mass of 10 kg water which is at 15°C. Mixing process is held in atmospheric pressure. The change in entropy of the universe (in kJ/K) due to mixing will be

(A) 0.416
(B) 0.383
(C) 0.263
(D) Process is not possible

Solution:

$$(\Delta S)_{\text{univ}} = (\Delta S)_{\text{sys}} + (\Delta S)_{\text{surr}}$$

∵ $(\Delta S)_{\text{surr}} = 0$ [Adiabatic process]

∴ $(\Delta S)_{\text{univ}} = (\Delta S)_{\text{sys}}$

Now, $Tds = dh - vdp \Rightarrow Tds = dh$ [∵ $p = \text{const}$]

Or $(S_2 - S_1) = (\Delta S)_{sys} = m_1 C \ln \frac{T_f}{T_1} + m_2 C \ln \frac{T_f}{T_2}$

Now $m_1 C\,(T_1 - T_f) = m_2 C (T_f - T_2)$

$\Rightarrow$ $5 \times 4.187 \times [90 - T_f] = 10 \times 4.187 \times [T_f - 15]$

$\Rightarrow$ $T_f = 40°\text{C}$

$$\therefore \quad (\Delta S)_{sys} = 5 \times 4.187 \times \ln\left[\frac{40+273}{90+273}\right] + 10 \times 4.187 \times \ln\left[\frac{40+273}{15+273}\right]$$

∴ $(\Delta S)_{\text{sys}} = (\Delta S)_{\text{univ}} = +0.383$ kJ/K

Example 8: An insulated container contains 5 kg of water at 27°C. By paddle-wheel work transfer, the temperature of water is increased to 47°C. The entropy change of the universe (in kJ/K) will be

(A) 11.6 (B) 2.631
(C) 0.352 (D) 1.3511

Solution:

$$(\Delta S)_{\text{univ}} = (\Delta S)_{\text{sys}} = mC \ln \frac{T_f}{T}$$

[∵ $(\Delta S)_{\text{surr}} = 0$]

$$\therefore \quad (\Delta S)_{\text{univ}} = 5 \times 4.187 \times \ln\left[\frac{47+273}{27+273}\right]$$

$$\Rightarrow \quad (\Delta S)_{\text{univ}} = 1.3511 \text{ kJ/K}$$

Example 9: Air expands through a turbine from 600 kPa, 527°C to 100 kPa, 327°C. Dead state is at 97 kPa, 27°C. During expansion 12 kJ/kg of heat is lost to the surrounding. Neglect the K.E and P.E changes. Determine per kg of air

i. Change in availability (in kJ/kg)
(A) 212.3 (B) 301.2
(C) 268.5 (D) 371.6

ii. Irreversibility of the process (in kJ/kg)
(A) 67.5 (B) 83.4
(C) 63.6 (D) 79.5

Solution:

i. (C)

Change in availability, $A_1 - A_2 = (h_1 - T_o S_1) - (h_2 - T_o S_2)$

or $A_1 - A_2 = (h_1 - h_2) - T_o(S_1 - S_2)$

$$\Rightarrow \quad A_1 - A_2 = C_p(T_1 - T_2) - T_o\left[R \ln \frac{P_2}{P_1} - C_p \ln \frac{T_2}{T_1}\right]$$

$$\Rightarrow \quad A_1 - A_2 = 1.005(527 - 327) - 300\left[0.287 \times \ln\left(\frac{1}{6}\right) - 1.005 \times \ln\left(\frac{600}{800}\right)\right]$$

$\Rightarrow$ $A_1 - A_2 = 268.534$ kJ/kg

ii. (D)

$$I = T_o(\Delta S)_{\text{univ}} = T_o[(\Delta S)_{\text{sys}} + (\Delta S)_{\text{surr}}]$$

$$\Rightarrow I = 300\left[\left\{1.005 \times \ln\left(\frac{600}{800}\right)\right\} - \left\{0.287 \times \ln\left(\frac{1}{6}\right)\right\} + \frac{12}{300}\right]$$

$\Rightarrow$ $I = 79.534$ kJ/kg

Example 10: 5 kg of air at 600 kPa, 80°C expands in a closed insulated system until its volume is doubled and its temperature becomes 7°C. Surrounding pressure and temperature are 100 kPa and 7°C respectively.

i. Determine the change in availability (in kJ).
(A) 315.5 (B) 420.1
(C) 273.4 (D) 377.7

ii. Determine the irreversibility (in kJ).
(A) 19.24 (B) 27.36
(C) 17.54 (D) 14.39

Solution:

i. (A)

$$(\Delta S)_{\text{sys}} = mC_V \ln \frac{T_2}{T_1} + mR \ln \frac{V_2}{V_1}$$

$$\Rightarrow \quad (\Delta S)_{\text{sys}} = 5\left[0.718 \times \ln\left(\frac{280}{363}\right) + 0.287 \times \ln(2)\right]$$

$\Rightarrow$ $(\Delta S)_{\text{sys}} = 0.062655$ kJ/K

Change in availability, $A_1 - A_2 = (U_1 - U_2) - T_o(S_1 - S_2)$

$\Rightarrow$ $A_1 - A_2 = m\,C_v(T_1 - T_2) + T_o(\Delta S)_{\text{sys}}$

$\Rightarrow$ $A_1 - A_2 = [5 \times 0.718 \times (90 - 7)] + (280 \times 0.062655)$

$\Rightarrow$ $A_1 - A_2 = 315.5$ kJ

ii. (C)

$I = T_o(\Delta S)_{\text{univ}} = T_o[(\Delta S)_{\text{sys}} + (\Delta S)_{\text{surr}}]$

$\Rightarrow$ $I = 280[(\Delta S)_{\text{sys}} + 0]$

$\Rightarrow$ $I = 200 \times 0.062655$

$\Rightarrow I = 17.54$ kJ

Example 11: A heat engine is working between temperature limit of 1000 K and 300 K. Dead state is at 300 K. If the amount of heat added to the engine is 1200 kJ then the maximum useful work we can get from the engine will be (in kJ)

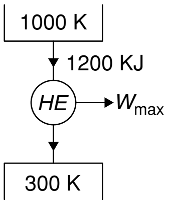
(A) 840 (B) 1000

C) 960 (D) 820

Solution:

$$\eta_{\max} = 1 - \frac{300}{1000} = \frac{W_{\max}}{1200}$$

$$\Rightarrow \quad W_{\max} = 840 \text{ kJ}$$



EXERCISES

Practice Problems I

Direction for questions 1 to 23: Select the correct alternative from the given choices.

1. The minimum amount of work input necessary to a refrigerator which will convert 2kg of water at 25°C into ice at −5°C is take C_p office = 2.09 kJ/kg.K

(A) 100.77 (B) 75.25

(C) 87.25 (D) 150.77

2. A heat engine receives heat from a solar collector plate. Solar radiation of amount 2000 kJ/m^2 h falls on the solar collector plate end raises its temperature to 100°C. The engine rejects heat to the atmosphere where temperature is assumed to be 20°C. The minimum area required for solar collector to produce 1 kW of useful shaft power in m^2 is

(A) 10 (B) 9.5 (C) 8.4 (D) 5

3. The data given in the table refers to an engine based on Cannot cycle

Where Q_1 = Heat supplied (kJ/min)

Q_2 = Heat rejected (kJ/s)

W = work output (kW)

S.NO	Q_1	Q_2	W
1.	1500	16.80	8.20
2.	1600	17.92	8.75
3.	1700	19.03	9.30
4.	1800	20.15	9.85

If heat received by the engine is 2000 kJ/min the work output will be nearly

(A) 20.53 (B) 10.93

(C) 5.45 (D) zero

4. A reversible heat engine receives 8 kJ of heat from thermal reservoir at temperature 600 k, and 7 kJ of heat from another thermal reservoir at temperature of 800 K. If it rejects heat to a third thermal reservoir at temperature 200 K, then the thermal efficiency of the engine is approximately equal to

(A) 80% (B) 70%

(C) 60% (D) 50%

5. An engine working on Cannot cycle rejects 40% of absorbed heat from the source, while the sink temperature is maintained at 27°C, then the source temperature is

(A) 750°X (B) 477°X

(C) 203°C (D) 67.5°X

6. A series combination of two Cannot engines operates between the temperatures of 190°C and 25°C. If the engine produce equal amount of work, then the intermediate temperature is

(A) 100°C (B) 107°C

(C) 109°C (D) 110°C

7. In a heat engine operating in a cycle between a source temperature of 610°C and sink temp of 20°C, then the least rate of heat rejection per kW net output of the engine is

(A) 0.476 kW (B) 0.486 kW

(C) 0.496 kW (D) 0.5 kW

8. A reversible cycle is used to drive a reversible heat pump cycle. The power cycle takes in Q_1 heat units at T_1 and rejects Q_2 at T_2 the heat pump abstracts Q_4 from the sink at T_4 and discharges Q_3 at T_3. The ratio of Q_4/Q_1 is

(A) $\frac{T_1}{T_3}\left(\frac{T_3 - T_4}{T_1 - T_2}\right)$ (B) $\frac{T_4}{T_3}\left(\frac{T_1 - T_2}{T_3 - T_2}\right)$

(C) $\frac{T_4}{T_1}\left(\frac{T_1 - T_2}{T_3 - T_4}\right)$ (D) $\frac{T_4}{T_1}\left(\frac{T_1 - T_2}{T_3 - T_2}\right)$

9. An irreversible heat engine extracts heat from a high temperature source at a rate of 100 kW and rejects heat to a sink at rate of 50 kW. The entire work output of heat engine is used to drive a reversible heat pump operating between a set of independent isothermal heat reservoirs at 17°C and 75°C. The rate (in kW) at which the heat pump delivers heat to its high temperature sink is

(A) 50 (B) 250

(C) 300 (D) 360

Direction for questions 10 and 11: A reversible heat engine receives heat from a reservoir at 700°C and rejects heat to another reservoir at temperature T_2, A second heat engine receives the heat rejected by the first engine and rejects heat to a sink at 37°C calculate the temperature T_2 for

10. Equal efficiency for both engines

(A) 540 K (B) 600 K

(C) 700 K (D) 800 K

11. Equal work of both engines.
(A) 530 K (B) 636 K
(C) 750 K (D) 800 K.

12. An engine is supplied with 1130 kcal/mt of heat, the heat source and sink being maintained at 565°K and 315°K respectively. If heat rejected is 630kcal/mt, then applying Clausius inequality, determine, whether the process is
(A) Reversible (B) Irreversible
(C) Impossible (D) Unstable

13. During the brake test of an electric motor of 10 kW for one hour, the heat generated by friction was found to be transferred to surroundings at 25°C. The resulting entropy in kJ/K is
(A) 200.2 (B) 120.8
(C) 89.9 (D) 50.2

Direction for questions 14 and 15: 4 kg of air at 1.2 bar and 25°C is compressed to 22 bar pressure according to the law $Pv^{1.33} = C$; after compression air is cooled at constant volume at 30°C

14. The volume and temperature at the end of compression are
(A) 0.32 m^3, 300°C (B) 0.29 m^3, 340°C
(C) 0.29 m^3, 300°C (D) 0.32 m^3, 340°C

15. Change of entropy during compression is
(A) 0.4393 kJ/K (B) 0.6245 kJ/K
(C) – 0.4393 kJ/K (D) – 0.6245 kJ/K

16. Change of entropy during constant volume cooling is
(A) 2.023 kJ/K (B) – 2.023 kJ/K
(C) 4.023 kJ/K (D) – 4.023 kJ/K.

Direction for questions 17 and 18: In an experimental set up, air flows between two stations *P* and *Q* adiabatically. The direction of flow depends on the pressure and the temperature conditions maintained at *P* and *Q*. The conditions at station *P* are 150 kPa and 350 K. The temperature at station *Q* is 300 K. The following are the properties and relations pertaining to air; specific heat at constant pressure, C_P = 1.005 kJ/kg.K specific heat at constant volume C_v = 0.718 kJ/kg.K characteristic gas constant, R = 0.287 kJ/kg.K enthalpy, $h = C_p.T$

17. If the air has to flow form station *P* to station *Q*, the maximum possible value of pressure in KP_a at station *Q* is close to
(A) 50 (B) 87
(C) 128 (D) 150

18. If the pressure at station *Q* is 50 KP_a, The change in entropy ($S_Q - S_P$) in kJ/kg is
(A) –0.155 (B) 0
(C) 0.160 (D) 0.355

19. The entropy change in kJ/K for 4.5 kg of a perfect gas whose specific heat is (0.45 + 0.009T) kJ/kg K during a constant volume process from 150°C to 200°C is
(A) 3.451 (B) 2.251
(C) 5.0 (D) 7.85

Direction for questions 20 and 21: In a certain flow process, the fluid is taken in from 10 bar and 500°C to 2 bar and 250°C while 200 kJ/kg of useful work is realized. The properties of fluid are given below.

Pressure P (bar)	Temperature t (°c)	Enthalpy h (kJ/kg K)	Entropy s (kJ/kg K)
10	500	2818	12.15
2	250	2030	10.50

If the ambient conditions are 1 bar and 15°C, determine.

20. The Degree of effectiveness of the process
(A) 63.9% (B) 73.9%
(C) 85% (D) 90%

21. The irreversibility per unit mass of fluid is
(A) 112.8 kJ/kg (B) 115.8 kJ/kg
(C) 120.2 kJ/kg (D) 122.5 kJ/kg

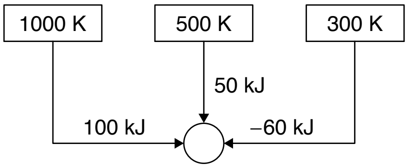
22. A steel billet of 2000 kg mass is to be cooled from 1250 k to 450 k. The heat released during this process is to be used as source of energy. The ambient temperature is 303K and specific heat of steel is 0.5 kJ/kg.K The available energy of this billet is
(A) 490.44 MJ (B) 30.95 MJ
(C) 10.35 MJ (D) 0.10 MJ

23. The gas expands through a very small opening in a pipe from pressure and temperature of 8 bar and 600 K to a pressure of 1.2 bar. Assume gas to be an ideal gas and take temperature of surrounding 298 K. The irreversibility associated with this process is
(A) 163 (B) 173
(C) 150 (D) 153

Practice Problems 2

Direction for questions 1 to 35: Select the correct alternative from the given choices.

1. A cyclic device operates between three thermal reservoirs, as shown in the figure. Heat is transferred to/from the cycle device. It is assumed that heat transfer between each thermal reservoir and the cyclic device takes place across negligible temperature difference. Interactions between the cyclic device and the respective thermal reservoirs that are shown in the figure are all in the form of heat transfer



The cycle device can be

(A) A reversible heat engine
(B) A reversible heat pump or a reversible refrigerator
(C) An irreversible heat engine
(D) An irreversible heat pump or an irreversible refrigerator.

2. A heat pump is used in place of a furnace for heating a house in winter. The heat lost from the house is 50,000 kJ/hr when the outside air temperature is −20°C, and the inside temperature is 20°C the minimum electric power required to operate the heat pump is

(A) 1.9 kW (B) 2.9 kW
(C) 5 kW (D) 3.5 kW

3. A Carnot cycle absorbs 210 kJ of heat from a reservoir at the temperature of normal boiling point of water and rejects heat to reservoir at the temperature of the triple point of water. The thermal efficiency is ____

(A) 40% (B) 27%
(C) 43% (D) 57%

4. A heat engine receives reversibly 420 kJ/cycle of heat from a source at 327°C and rejects heat reversibly to a sink at 27°C. There is no other heat transfer: For each of the three hypothetically amounts of heat rejected, In the following cases 1, 2, 3 compute the cyclic integral of $\frac{\delta Q}{T}$

1. 210 kJ/cycle rejected
2. 105 kJ/cycle rejected
3. 315 kJ/cycle rejected

(A) 0, −0.35, 0.35 (B) 0, 0.35, −0.35
(C) 0.35, 0, −0.35 (D) −0.35, 0, 0.35

5. The Carnot efficiency of the engine working at temperature limits of 730°C and 27°C is

(A) 60% (B) 70%
(C) 65% (D) 75%

6. Consider the following two process

I. A heat source at 1200 K losses 2500 kJ of heat to a sink at 800K
II. A heat source at 800 K losses 200 kJ of heat to a sink at 500 K.

Which of the following statement is true

(A) Process I is more irreversible than process II
(B) Process II is more irreversible than process I
(C) Irreversibility associated in both the process are equal
(D) Both the process are reversible

7. A reversible heat engine operates between 600°C and 40°C. This engine operates a reversible refrigerator operating between 40°C and −18°C. Still there is a network output of 370 kJ and the heat received by the engine is 2100 kJ. Then the cooling effect produced by refrigerator in kJ is

(A) 2500 (B) 3500
(C) 4294 (D) 5295

8. 1600 kJ of energy is transferred from a heat reservoir at 800 K to another heat reservoir at 400 K. The amount of entropy generated during the process would be

(A) 6 kJ/K (B) 4 kJ/K
(C) 2 kJ/K (D) Zero

Direction for questions 9 and 10: 2 kg of water at 95°C is mixed with 3 kg of water at 10°C in an isolated system.

9. The final temperature after mixing process is

(A) 95° (B) 30°C
(C) 62.5°C (D) 44°C

10. The change of entropy due to mixing process in kJ/K is

(A) 2.56 (B) 0.54
(C) 0.35 (D) 0.17

Direction for questions 11 and 12: One kg of air is compressed according to the law $PV^{1.25} = C$ from a pressure of 1.03 bar and temperature of 15°C to a pressure of 17 bar.

11. The temperature at the end of the compression in K is

(A) 605.4 (B) 550.2
(C) 504.56 (D) 300

12. The heat rejected or received by the air during the process in kJ/kg is

(A) 52 (B) 65
(C) 96 (D) 100

13. The change in entropy in kJ/kg.K is

(A) −0.56 (B) −0.248
(C) −0.13 (D) 0.248

Direction for questions 14 and 15: Air at 6 bar and 72°C flows through a turbine with a velocity of 100 m/s. It leaves the turbine at 1.05 bar, 10°C with a velocity of 55 m/s. Air may be considered as a perfect gas having a specific heat = 1.005 kJ/kg K and the surroundings are at 27°C and 1.03 bar. Calculate

14. The useful work obtainable per kg of air

(A) 156.13 kJ/kg (B) 160 kJ/kg
(C) 175.23 kJ/kg (D) 190 kJ/kg

15. Actual work as a percentage of maximum useful work

(A) 20.52% (B) 32.25%
(C) 41.95% (D) 55.45%

16. Joule–Thomson co-efficient is defined as

(A) $\left(\frac{\partial T}{\partial P}\right)_h$ (B) $\left(\frac{\partial h}{\partial T}\right)_p$

(C) $\left(\frac{\partial h}{\partial P}\right)_T$ (D) $\left(\frac{\partial P}{\partial T}\right)_n$

17. When a system undergoes a process such that $\oint \frac{dQ}{T} = 0$ and $\Delta S > 0$, the process is

(A) Isobaric
(B) Isothermal
(C) Irreversible adiabatic
(D) Reversible adiabatic

18. Clausisus – Clapeyron equation gives the 'slope' of a curve in

(A) P-V diagram
(B) p-h diagram
(C) P-T diagram
(D) T-S diagram

19. For a real thermodynamic cycle, which one of the following is correct?

(A) $\oint \frac{dQ}{T} > 0$
(B) $\oint \frac{dQ}{T} < 0$
(C) $\oint \frac{dQ}{T} = 0$
(D) $\oint ds = 0$

20. When a real gas undergoes Joule-Thomson expansion the temperature

(A) May remain constant
(B) Always increases
(C) May increase or decrease
(D) Always decreases

21. Tds equation is

(A) $Tds = C_v dT + \frac{T\beta}{K} dv$

(B) $Tds = C_p dT - \frac{T\beta}{K} dv$

(C) $Tds = C_v dT + \frac{Tk}{\beta} dv$

(D) $Tds = C_v dT + \frac{T\beta}{k} dp$

22. The specific heat relation is

(A) $C_p - C_v = \frac{VT\beta^2}{K_T}$
(B) $C_p - C_v = \frac{vTk}{\beta^2}$
(C) $C_p - C_v = \frac{PTk}{\beta^2}$
(D) $C_p - C_v = \frac{v^2 T\beta}{K_T}$

23. In case of refrigeration machine, COP will be equal to

(A) $\frac{Q_2}{Q_1 - Q_2}$
(B) $\frac{Q_1}{Q_1 - Q_2}$
(C) $\frac{Q_1 - Q_2}{Q_1}$
(D) $\frac{Q_2 - Q_1}{Q_1}$

24. The value of entropy at 0°C is taken as

(A) 1
(B) Zero
(C) –1
(D) Infinite

25. The slope of constant pressure line on temperature entropy diagram is given by

(A) C_p/T
(B) S/T
(C) T/C_p
(D) T/S

26. During throttling process

(A) Heat exchange does not take place
(B) No work is done by expanding steam
(C) There is no change of internal energy of steam
(D) All of the above

27. Kelvin–Planck's law deals with

(A) Conservation of heat
(B) Conservation of work
(C) Conservation of heat into work
(D) Conservation of work into heat

28. Isentropic flow is

(A) Reversible adiabatic flow
(B) Irreversible adiabatic flow
(C) Frictionless fluid flow
(D) None of the above

29. It is not a conserved quantity

(A) Mass
(B) Energy
(C) Momentum
(D) Exergy

30. The energy of an isolated system in a process

(A) Can never increase
(B) Can never decrease
(C) Always remains constant
(D) is always positive

31. The specific heats of an ideal gas C_p and C_v

(A) Vary with temperature
(B) Vary with pressure
(C) Vary with both pressure and temperature
(D) Are constant

32. The magnitude of this quantity does not indicate the departure of a real gas from the ideal gas behavior.

(A) Compressibility factor
(B) Joule–Kelvin co-efficient
(C) Entropy
(D) Fugacity

33. An isentropic process

(A) Is always reversible
(B) Is always adiabatic
(C) Need not be adiabatic or reversible
(D) Is always friction less

34. For an inviscid incompressible fluid flowing through a duct, the steady flow energy equation reduces to

(A) Bernoulli equation
(B) Euler equation
(C) Stoke equation
(D) Navier-stoke equation

35. It is the basis of temperature measurement

(A) Zeroth law of thermodynamics
(B) First law of thermodynamics
(C) Second law of thermodynamics
(D) Law of stable equilibrium

PREVIOUS YEARS' QUESTIONS

1. A heat engine having an efficiency of 70% is used to drive a refrigerator having a co-efficient of performance of 5. The energy absorbed from low temperature reservoir by the refrigerator for each kJ of energy absorbed from high temperature sources by the engine is **[2004]**

(A) 0.14 kJ (B) 0.71 kJ
(C) 3.5 kJ (D) 7.1 kJ

2. A solar collector receiving solar radiation at the rate of 0.6 kW/m^2 transforms it to the internal energy of a fluid at an overall efficiency of 50%. The fluid heated to 350 K is used to run a heat engine which rejects heat at 313 K. If the heat engine is to deliver 2.5 kW power, the minimum area of the solar collector required would be **[2004]**

(A) 83.33 m^2 (B) 0.71 m^2
(C) 3.5 m^2 (D) 7.1 m^2

3. A steel billet of 2000 kg mass is to be cooled from 1250 K to 450 K. The heat released during this process is to be used as a source of energy. The ambient temperature is 303 K and specific heat of steel is 0.5 kJ/kg K. The available energy of this billet is **[2004]**

(A) 490.44 MJ (B) 30.95 MJ
(C) 10.35 MJ (D) 0.10 MJ

4. The following four figures have been drawn to represent a fictitious thermodynamics cycle, on the P-V and T-S planes.

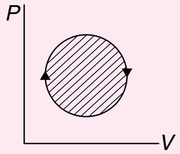


Figure 1

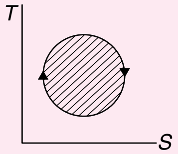


Figure 2

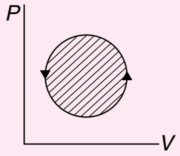


Figure 3

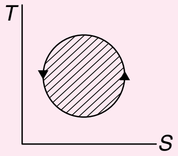


Figure 4

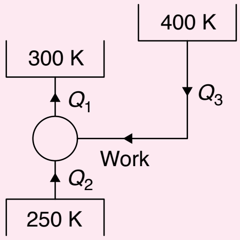
According to the first law of thermodynamics, equal areas are enclosed by **[2005]**

(A) Figures 1 and 2 (B) Figures 1 and 3
(C) Figures 1 and 4 (D) Figures 2 and 3

5. A reversible thermodynamic cycle containing only three processes and producing work is to be constructed. The constraints are (i) there must be one isothermal process, (ii) there must be one isentropic process, (iii) the maximum and minimum cycle pressures and the clearance volume are fixed, and (iv) polytropic processes are not allowed. Then the numbers of possible cycles are **[2005]**

(A) 1 (B) 2
(C) 3 (D) 4

6. A vapour absorption refrigeration system is a heat pump with three thermal reservoirs as shown in the figure. A refrigeration effect of 100 W is required at 250 K when the heat source available is at 400 K. Heat rejection occurs at 300 K. The minimum value of heat required (in W) is **[2005]**

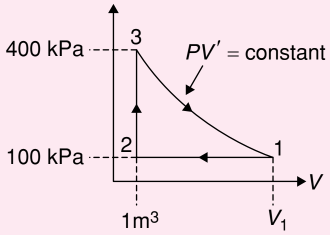


(A) 167 (B) 100
(C) 80 (D) 20

7. A heat transformer is a device that transfers a part of the heat, supplied to it at an intermediate temperature, to a high temperature reservoir while rejecting the remaining part to a low temperature heat sink. In such a heat transformer, 100 kJ of heat is supplied at 350 K. The maximum amount of heat in kJ that can be transferred to 400 K, when the rest is rejected to a heat sink at 300 K is **[2007]**

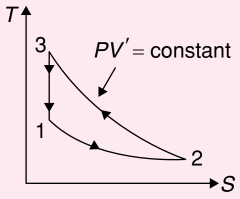
(A) 12.50 (B) 14.29
(C) 33.33 (D) 57.14

Direction for questions 8 and 9: A thermodynamic cycle with an ideal gas as working fluid is shown below.

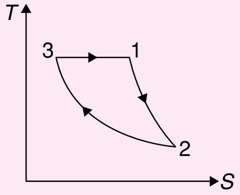


8. The above cycle is represented on T-S plane by **[2007]**

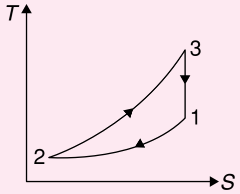
(A)



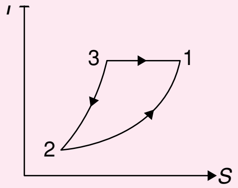
(B)



(C)



(D)



9. If the specific heats of the working fluid are constant and the value of specific heat ratio γ is 1.4, the thermal efficiency (%) of the cycle is **[2007]**

(A) 21 (B) 40.9

(C) 42.6 (D) 59.7

10. 2 moles of oxygen are mixed adiabatically with another 2 moles of oxygen in a mixing chamber, so that the final total pressure and temperature of the mixture become same as those of the individual constituents at their initial states. The universal gas constant is given as R. The change in entropy due to mixing, per mole of oxygen, is given by **[2008]**

(A) $-R \ln 2$ (B) 0

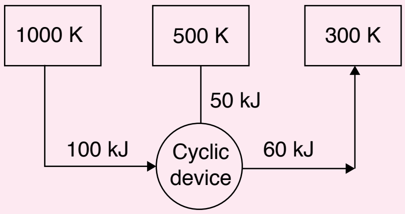
(C) $R \ln 2$ (D) $R \ln 4$

11. A gas expands in a frictionless piston-cylinder arrangement. The expansion process is very slow, and is resisted by an ambient pressure of 100 kPa. During the expansion process, the pressure of the system (gas) remains constant at 300 kPa. The change in volume of the gas is 0.01 m^3. The maximum amount of work that could be utilized from the above process is **[2008]**

(A) 0 kJ (B) 1 kJ

(C) 2 kJ (D) 3 kJ

12. A cyclic device operates between three thermal reservoirs, as shown in the figure. Heat is transferred to/from the cyclic device. It is assumed that heat transfer between each thermal reservoir and the cyclic device takes place across negligible temperature difference. Interactions between the cyclic device and the respective thermal reservoirs that are shown in the figure are all in the form of heat transfer. **[2008]**



The cyclic device can be

(A) A reversible heat engine

(B) A reversible heat pump or a reversible refrigerator

(C) An irreversible heat engine

(D) An irreversible heat pump or an irreversible refrigerator

13. If a closed system is undergoing an irreversible process, the entropy of the system **[2009]**

(A) Must increase

(B) Always remains constant

(C) Must decrease

(D) Can increase, decrease or remain constant

14. An irreversible heat engine extracts heat from a high temperature source at a rate of 100 kW and rejects heat to a sink at a rate of 50 kW. The entire work output of the heat engine is used to drive a reversible heat pump operating between a set of independent isothermal heat reservoirs at 17°C and 75°C. The rate (in kW) at which the heat pump delivers heat to its high temperature sink is **[2009]**

(A) 50 (B) 250

(C) 300 (D) 360

15. One kilogram of water at room temperature is brought into contact with a high temperature thermal reservoir. The entropy change of the universe is **[2010]**

(A) Equal to entropy change of the reservoir

(B) Equal to entropy change of water

(C) Equal to zero

(D) Always positive

16. Consider the following two processes:

(a) A heat source at 1200 K loses 2500 kJ of heat to sink at 800 K

(b) A heat source at 800 K loses 2000 kJ of heat to sink at 500 K

Which of the following statements is TRUE? **[2010]**

(A) Process I is more irreversible than Process II

(B) Process II is more irreversible than Process I

(C) Irreversibility associated in both the processes is equal

(D) Both the processes are reversible

Direction for questions 17 and 18: In an experimental setup, air flows between two stations P and Q adiabatically. The direction of flow depends on the pressure and temperature conditions maintained at P and Q. The conditions at station P are 150 kPa and 350 K. The temperature at station Q is 300 K.

The following are the properties and relations pertaining to air:

Specific heat at constant pressure,

$C_p = 1.005$ kJ/kgK;

Specific heat at constant volume,

$C_v = 0.718$kJ/kgK;

Characteristic gas constant, $R = 0.287$ kJ/kgK

Enthalpy, $h = C_pT$

Internal energy, $u = C_vT$

17. If the air has to flow from station P to station Q, the maximum possible value of pressure in kPa at station Q is close to **[2011]**

(A) 50 (B) 87 (C) 128 (D) 150

18. If the pressure at station Q is 50 kPa, the change in entropy ($S_Q - S_P$) in kJ/kgK is **[2011]**

(A) −0.155 (B) 0

(C) 0.160 (D) 0.355

19. An ideal gas of mass m and temperature T_1 undergoes a reversible isothermal process from an initial pressure P_1 to final pressure P_2. The heat loss during the process is Q. The entropy change ΔS of the gas is **[2012]**

(A) $mR\ln\left(\dfrac{P_2}{P_1}\right)$ (B) $mR\ln\left(\dfrac{P_1}{P_2}\right)$

(C) $mR\ln\left(\dfrac{P_2}{P_1}\right) - \dfrac{Q}{T_1}$ (D) Zero

20. The pressure, temperature and velocity of air flowing in a pipe are 5 bar, 500 K and 50 m/s, respectively. The specific heats of air at constant pressure and at constant volume are 1.005 kJ/kgK and 0.718 kJ/kgK, respectively. Neglect potential energy. If the pressure and temperature of the surroundings are 1 bar and 300 K, respectively, the available energy in kJ/kg of the air steam is **[2013]**

(A) 170 (B) 187

(C) 191 (D) 213

21. The maximum theoretical work obtainable, when a system interacts to equilibrium with a reference environment, is called **[2014]**

(A) Entropy (B) Enthalpy

(C) Exergy (D) Rothalpy

22. A reversible heat engine receives 2 kJ of heat from a reservoir at 1000 K and a certain amount of heat from a reservoir at 800 K. It rejects 1 kJ of heat to a reservoir at 400 K. The net work output (in kJ) of the cycle is **[2014]**

(A) 0.8 (B) 1.0

(C) 1.4 (D) 2.0

23. Which one of the following pairs of equations describes an irreversible heat engine? **[2014]**

(A) $\oint \delta Q > 0$ and $\oint \dfrac{\delta Q}{T} < 0$

(B) $\oint \delta Q < 0$ and $\oint \dfrac{\delta Q}{T} < 0$

(C) $\oint \delta Q > 0$ and $\oint \dfrac{\delta Q}{T} > 0$

(D) $\oint \delta Q < 0$ and $\oint \dfrac{\delta Q}{T} > 0$

24. A source at a temperature of 500 K provides 1000 kJ of heat. The temperature of environment is 27°C. The maximum useful work (in kJ) that can be obtained from the heat source is_________ **[2014]**

25. An amount of 100 kW of heat is transferred through a wall in steady state. One side of the wall is maintained at 127°C and the other side at 27°C. The entropy generated (in W/K) due to the heat transfer through the wall is ______ **[2014]**

26. A reversed Cannot cycle refrigerator maintains a temperature of −5°C, The ambient air temperature is 35°C. The heat gained by the refrigerator at a continuous rate is 2.5 kJ/s. The power (in watt) required to pump this heat out continuously is _____ **[2014]**

27. Two identical metals blocks L and M (specific heat = 0.4 kJ/kg.K), each having a mass of 5 kg, are initially at 313 K. A reversible refrigerator extracts heat from block L and rejects heat to block M until the temperature of block L reaches 293 K. The final temperature (in K) of block M is ______ **[2014]**

28. A Carnot engine (CE-1) works between two temperature reservoirs A and B, where $T_A = 900$ K and $T_B = 500$ K. A second Carnot engine (CE-2) works between temperature reservoirs B and C, where $T_C = 300$ K. In each cycle CE-1 and CE-2, all the heat rejected by CE-1 to reservoir B is used by CE-2. For one cycle of operation, if the net Q absorbed by CE-1 from reservoir A is 150 MJ, the net heat rejected to reservoir C by CE-2 (in MJ) is ________. **[2015]**

29. The COP of a Carnot heat pump operating between 6°C and 37°C is _______. **[2015]**

30. One kg of air ($R = 287$ J/kg-K) undergoes an irreversible process between equilibrium state 1 (20°C, 0.9 m^3) and equilibrium state 2(20°C, 0.6 m^3). The change in entropy $s_2 - s_1$ (in J/kg-K) is ________. **[2015]**

31. The heat removal rate from a refrigerated space and the power input to the compressor are 7.2 kW and 1.8 kW, respectively. The coefficient of performance (COP) of the refrigerator is ________. **[2016]**

32. A reversible cycle receives 40 kJ of heat from one heat source at a temperature of 127°C and 37 kJ from another heat source at 97°C. The heat rejected (in kJ) to the heat sink at 47°C is ________. **[2016]**

ANSWER KEYS

EXERCISES

Practice Problems 1

1. A **2.** C **3.** B **4.** B **5.** B **6.** B **7.** C **8.** C **9.** C **10.** A
11. B **12.** A **13.** B **14.** D **15.** B **16.** A **17.** B **18.** C **19.** B **20.** A
21. A **22.** A **23.** A

Practice Problems 2

1. A **2.** A **3.** B **4.** B **5.** B **6.** B **7.** C **8.** C **9.** D **10.** D
11. C **12.** C **13.** B **14.** A **15.** C **16.** A **17.** C **18.** C **19.** B **20.** C
21. A **22.** A **23.** A **24.** B **25.** C **26.** D **27.** C **28.** A **29.** D **30.** A
31. D **32.** C **33.** C **34.** A **35.** A

Previous Years' Questions

1. C **2.** A **3.** A **4.** A 5 D **6.** C **7.** D **8.** C **9.** A **10.** B
11. C **12.** A **13.** D **14.** C **15.** D **16.** B **17.** B **18.** C **19.** B **20.** B
21. C **22.** C **23.** A **24.** 399 to 401 **25.** 80 to 85 **26.** 370 to 375
27. 333 to 335 **28.** 50 **29.** 9.8 to 10.2 **30.** –117 to –115 **31.** 4.0 **32.** 64