Introduction to Aerospace Propulsion

Prof. Bhaskar Roy, Prof. A M Pradeep
Department of Aerospace Engineering,
IIT Bombay

Lecture No - 11

In this lecture ...

- Reversible and Irreversible Processes
- Irreversibilities
- Internally and Externally Reversible Processes
- Clausius inequality and entropy
- Property of entropy
- Temperature-entropy plots
- Isentropic processes

Prof. Bhaskar Roy, Prof. A M Pradeep, Department of Aerospace, IIT Bombay

Reversible and irreversible processes

- 2nd law: no heat engine can have 100% efficiency
- What is the highest efficiency that an engine could have?
- Reversible process: a process that can be reversed without leaving any trace on the surroundings.
- The system and the surroundings are returned to their initial states at the end of the reverse process.

Prof. Bhaskar Roy, Prof. A M Pradeep, Department of Aerospace, IIT Bombay

Reversible and irreversible processes

- Reversible process: Net heat and work exchange between the system and surroundings (for original + reverse process) is zero.
- Why reversible processes are of interest?
- Consume least work in the case of work-consuming devices and generate maximum work in the case of work-producing devices.

Prof. Bhaskar Roy, Prof. A M Pradeep, Department of Aerospace, IIT Bombay

Reversible and irreversible processes

- Reversible processes serve as theoretical limits for the corresponding irreversible ones.
- Reversible processes leads to the definition of the second law efficiency for actual processes, which is the degree of approximation to the corresponding reversible processes.

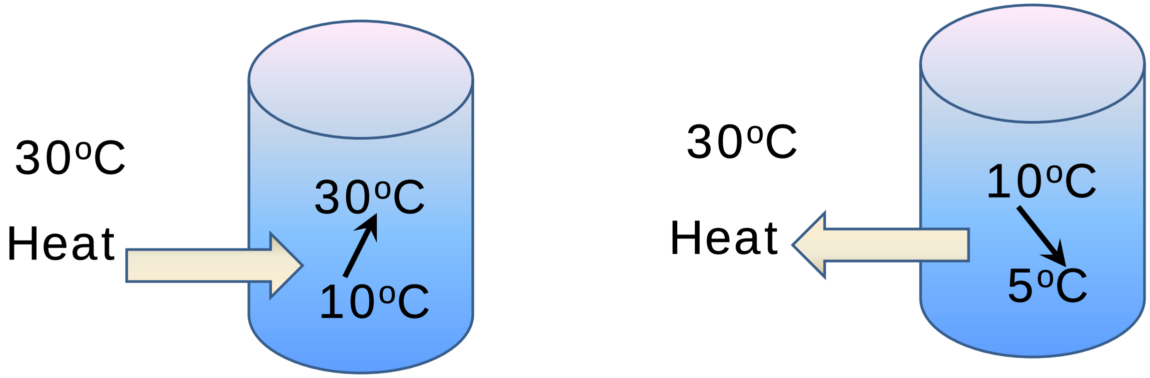
Prof. Bhaskar Roy, Prof. A M Pradeep, Department of Aerospace, IIT Bombay

Irreversibilities

- Commonly encountered causes of irreversibilities
  - friction, unrestrained expansion, mixing of two fluids, heat transfer across a finite temperature difference, electric resistance, inelastic deformation of solids, and chemical reactions.

Prof. Bhaskar Roy, Prof. A M Pradeep, Department of Aerospace, IIT Bombay

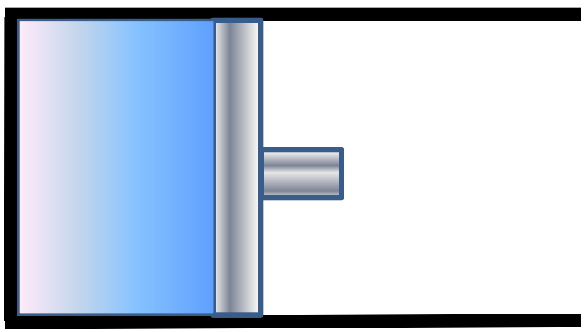
Irreversibilities



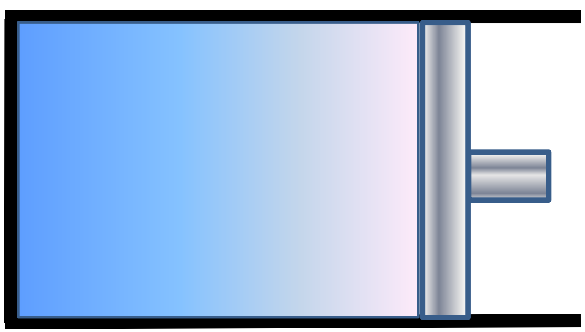
Heat transfer through a finite temperature difference is irreversible.

Prof. Bhaskar Roy, Prof. A M Pradeep, Department of Aerospace, IIT Bombay

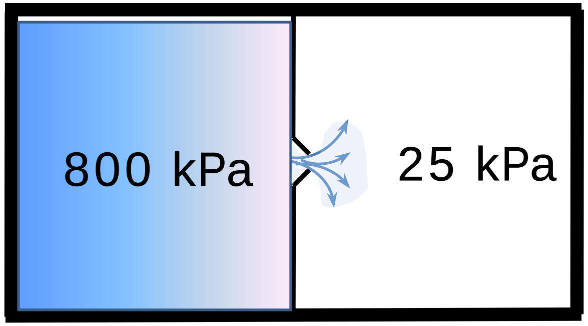
Irreversibilities



Fast compression



Fast expansion



Unrestrained expansion

Prof. Bhaskar Roy, Prof. A M Pradeep, Department of Aerospace, IIT Bombay

Internally and Externally Reversible Processes

- Internally reversible process
  - if no irreversibilities occur within the boundaries of the system during the process.
  - the paths of the forward and reverse processes coincide for an internally reversible process

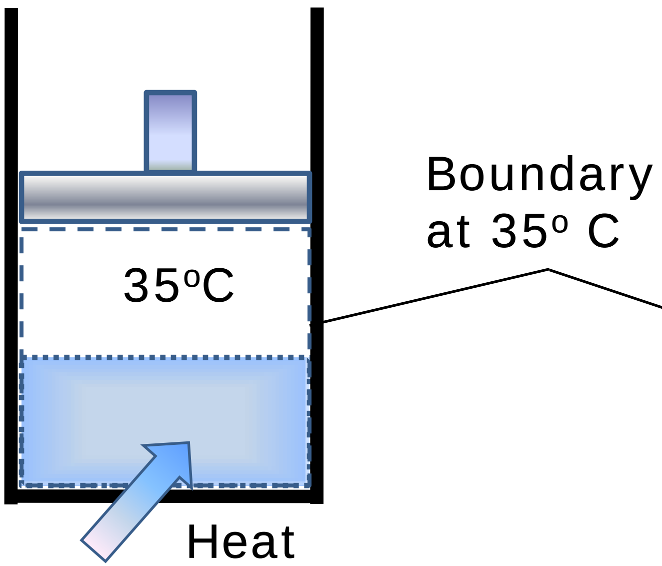
Prof. Bhaskar Roy, Prof. A M Pradeep, Department of Aerospace, IIT Bombay

Internally and Externally Reversible Processes

- Externally reversible process
  - no irreversibilities occur outside the system boundaries during the process.
  - Heat transfer between a reservoir and a system is an externally reversible process if the outer surface of the system is at the temperature of the reservoir.
- Totally reversible or reversible
  - no irreversibilities within the system or its surroundings.

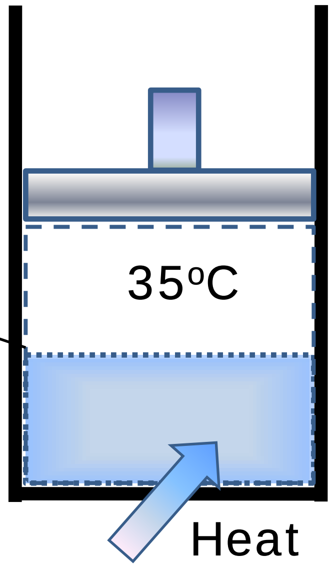
Prof. Bhaskar Roy, Prof. A M Pradeep, Department of Aerospace, IIT Bombay

Internally and Externally Reversible Processes



Thermal energy reservoir at 35.000001º C

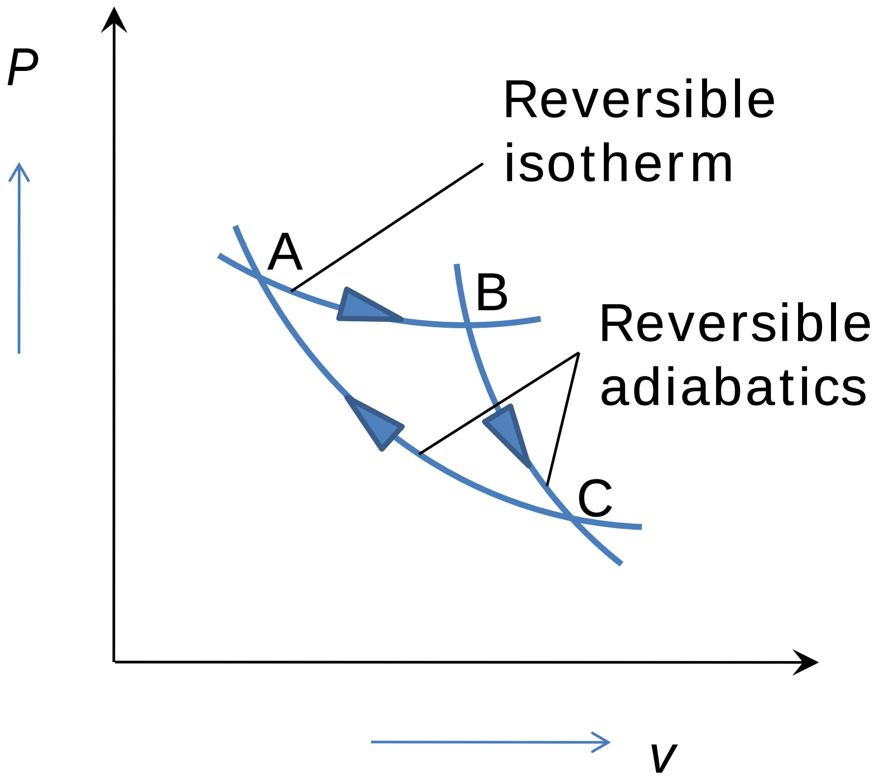
(a) Totally reversible



Thermal energy reservoir at 45º C

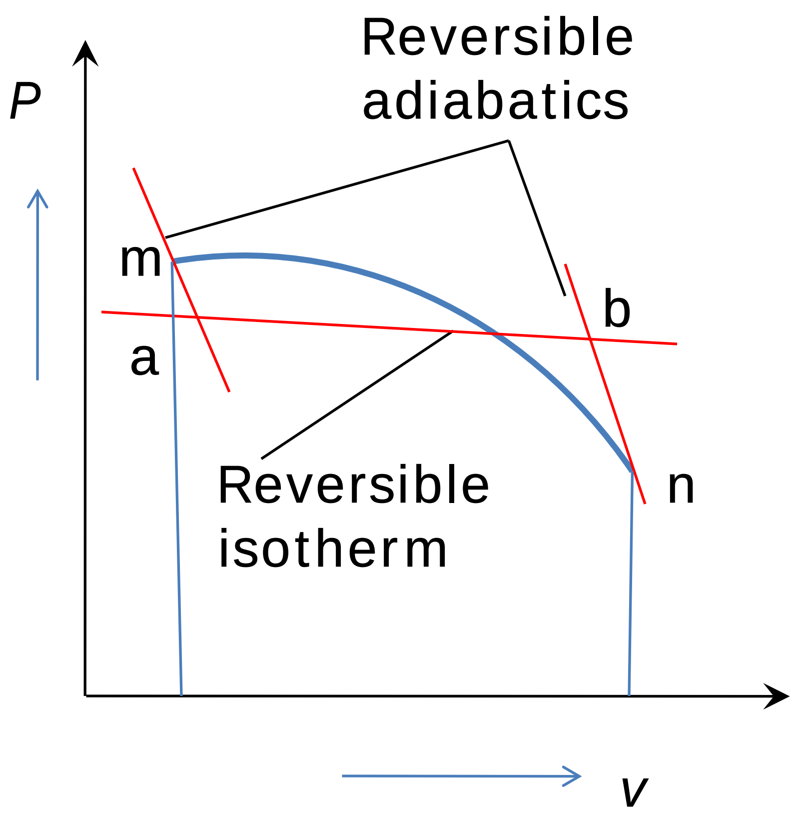
(b) Internally reversible

Reversible adiabatics



- Two reversible adiabatic paths cannot intersect
- Through one point, only one reversible adiabatic can pass
- Violation of Kelvin-Planck statement

Reversible adiabatics



Process m-n

$$Q_{m\text{-}n} = U_n - U_m + W_{mn}$$

Process m-a-b-n

$$Q_{m\text{-}a\text{-}b\text{-}n} = U_n - U_m + W_{m\text{-}a\text{-}b\text{-}n}$$

Since, $W_{m\text{-}a\text{-}b\text{-}n} = W_{mn}$

$$Q_{m\text{-}n} = Q_{m\text{-}a\text{-}b\text{-}n}$$

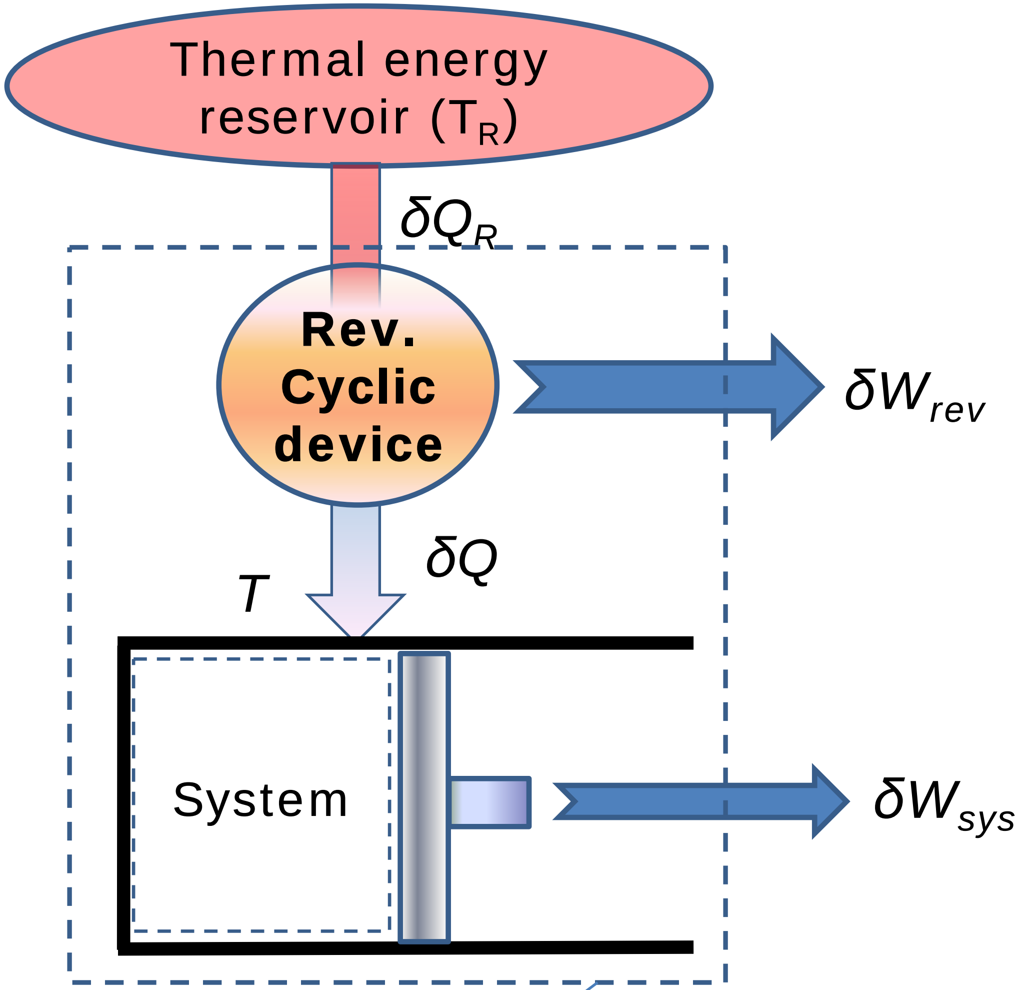
$$= Q_{m\text{-}a} + Q_{a\text{-}b} + Q_{b\text{-}n}$$

Since $Q_{m\text{-}a} = 0, Q_{b\text{-}n} = 0$

$$Q_{m\text{-}n} = Q_{a\text{-}b}$$

Reversible path can be substituted by two reversible adiabatics and a reversible isotherm

Clausius inequality



Combined system
(system and cyclic device)

Clausius inequality

- Applying the energy balance to the combined system identified by dashed lines yields: $\delta W_C = \delta Q_R - dE_C$
- where δW_C is the total work of the combined system ($\delta W_{rev} + \delta W_{sys}$) and dE_C is the change in the total energy of the combined system.
- Considering that the cyclic device is a reversible one $$\frac{\delta Q_R}{T_R} = \frac{\delta Q}{T}$$

Prof. Bhaskar Roy, Prof. A M Pradeep, Department of Aerospace, IIT Bombay

Clausius inequality

- From the above equations:

$$\delta W_C = T_R \frac{\delta Q}{T} - dE_C$$

- Let the system undergo a cycle while the cyclic device undergoes an integral number of cycles

$$W_C = T_R \oint \frac{\delta Q}{T}$$

- Since the cyclic integral of energy is zero.

Prof. Bhaskar Roy, Prof. A M Pradeep, Department of Aerospace, IIT Bombay

Clausius inequality

- The combined system is exchanging heat with a single thermal energy reservoir while involving (producing or consuming) work W_C during a cycle. Hence W_C cannot be a work output, and thus it cannot be a positive quantity.
- Considering T_R to be a positive quantity,

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

- This is the Clausius inequality.

Prof. Bhaskar Roy, Prof. A M Pradeep, Department of Aerospace, IIT Bombay

Clausius inequality

- Clausius inequality is valid for all thermodynamic cycles, reversible or irreversible, including the refrigeration cycles.
- If no irreversibilities occur within the system as well as the reversible cyclic device, then the cycle undergone by the combined system is internally reversible.

$$\oint \left(\frac{\delta Q}{T} \right)_{\mathrm{int}.rev} = 0$$

Prof. Bhaskar Roy, Prof. A M Pradeep, Department of Aerospace, IIT Bombay

Clausius inequality

- Clausius inequality provides the criterion for the irreversibility of a process.

$$\oint \frac{\delta Q}{T} = 0, \text{the process is reversible.}$$

$$\oint \frac{\delta Q}{T} < 0, \text{the process is irreversible and possible.}$$

$$\oint \frac{\delta Q}{T} > 0, \text{the process is impossible.}$$

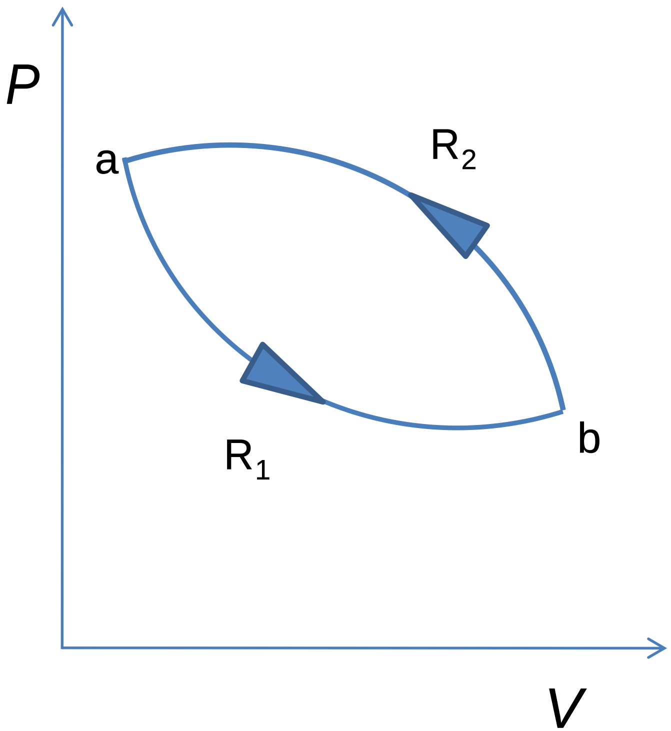
Prof. Bhaskar Roy, Prof. A M Pradeep, Department of Aerospace, IIT Bombay

Clausius inequality and entropy

- The cyclic integral of work and heat are not zero.
- However, the cyclic integral of volume (or any other property) is zero.
- Conversely, a quantity whose cyclic integral is zero depends on the state only and not the process path, and thus it is a property
- Clausius realized in 1865 that he had discovered a new thermodynamic property, and he chose to name this property entropy.

Prof. Bhaskar Roy, Prof. A M Pradeep, Department of Aerospace, IIT Bombay

The property of entropy



$$\oint_{R_1R_2} \frac{dQ}{T} = 0$$

$$\int_{R_1\, a}^{b} \frac{dQ}{T} + \int_{R_2\, b}^{a} \frac{dQ}{T} = 0$$

$$\text{or,} \int_{R_1\, a}^{b} \frac{dQ}{T} = -\int_{R_2\, b}^{a} \frac{dQ}{T}$$

Since R_2 is a reversible path,

$$\int_{R_1\, a}^{b} \frac{dQ}{T} = \int_{R_2\, a}^{b} \frac{dQ}{T}$$

Prof. Bhaskar Roy, Prof. A M Pradeep, Department of Aerospace, IIT Bombay

The property of entropy

- ${}_R\int_a^b \frac{dQ}{T}$ is independent of the reversible path connecting *a* and *b.*
- This property whose value at the final state minus the initial state is equal to ${}_R\int_a^b \frac{dQ}{T}$ is called entropy, denoted by *S.*

$$ {}_R\int_a^b \frac{dQ}{T} = S_b - S_a $$

- When the two equilibrium states are infinitesimally near,

$$ \frac{dQ_R}{T} = dS $$

Prof. Bhaskar Roy, Prof. A M Pradeep, Department of Aerospace, IIT Bombay

Entropy

- Entropy is an extensive property of a system and sometimes is referred to as total entropy. Entropy per unit mass, designated *s*, is an intensive property and has the unit kJ/kg · K
- The entropy change of a system during a process can be determined by

$$\Delta S = S_2 - S_1 = \int_1^2 \left(\frac{\delta Q}{T} \right)_{int.\,rev.} \qquad \text{(kJ/kg)}$$

Prof. Bhaskar Roy, Prof. A M Pradeep, Department of Aerospace, IIT Bombay

Entropy

- Entropy is a property, and like all other properties, it has fixed values at fixed states.
- Therefore, the entropy change *dS* between two specified states is the same no matter what path, reversible or irreversible.

Prof. Bhaskar Roy, Prof. A M Pradeep, Department of Aerospace, IIT Bombay

Temperature-entropy plot

$$dS = \frac{dQ_{rev}}{T}$$

If the process is reversible and adiabatic, $dQ_{rev} = 0$

$\therefore\ dS = 0 \quad or \quad S = \text{constant}$

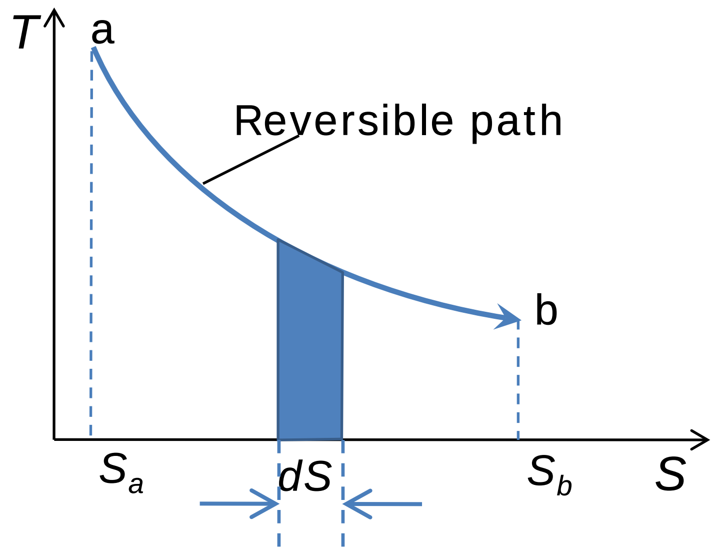
- A reversible adiabatic process is, therefore, and isentropic process.

$$dQ_{rev} = TdS$$

$$or,\ Q_{rev} = \int TdS$$

Prof. Bhaskar Roy, Prof. A M Pradeep, Department of Aerospace, IIT Bombay

Temperature-entropy plot



$$Q_{rev} = \int_a^b TdS = T\left(S_b - S_a\right)$$

- The area under the reversible path on the T-S plot represents heat transfer during that process.

Prof. Bhaskar Roy, Prof. A M Pradeep, Department of Aerospace, IIT Bombay

Isentropic processes

- A process where, $\Delta s=0$
- An isentropic process can serve as an appropriate model for actual processes.
- Isentropic processes enable us to define efficiencies for processes to compare the actual performance of these devices to the performance under idealized conditions.
- A reversible adiabatic process is necessarily isentropic, but an isentropic process is not necessarily a reversible adiabatic process.

In this lecture ...

- Reversible and Irreversible Processes
- Irreversibilities
- Internally and Externally Reversible Processes
- Clausius inequality and entropy
- Property of entropy
- Temperature-entropy plots
- Isentropic processes

In the next lecture…

- Increase of entropy principle
- Entropy change in liquids and solids
- Entropy change in ideal gases
- Third law of thermodynamics
- Absolute entropy
- Entropy change of a system and entropy generation