Introduction to Aerospace Propulsion

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

Lecture No - 12

In this lecture...

- Entropy change of a system and entropy generation
- Increase of entropy principle
- TdS equations
- Entropy change in liquids and solids and ideal gases
- Third law of thermodynamics and absolute entropy
- Entropy and energy transfer
- Entropy balance

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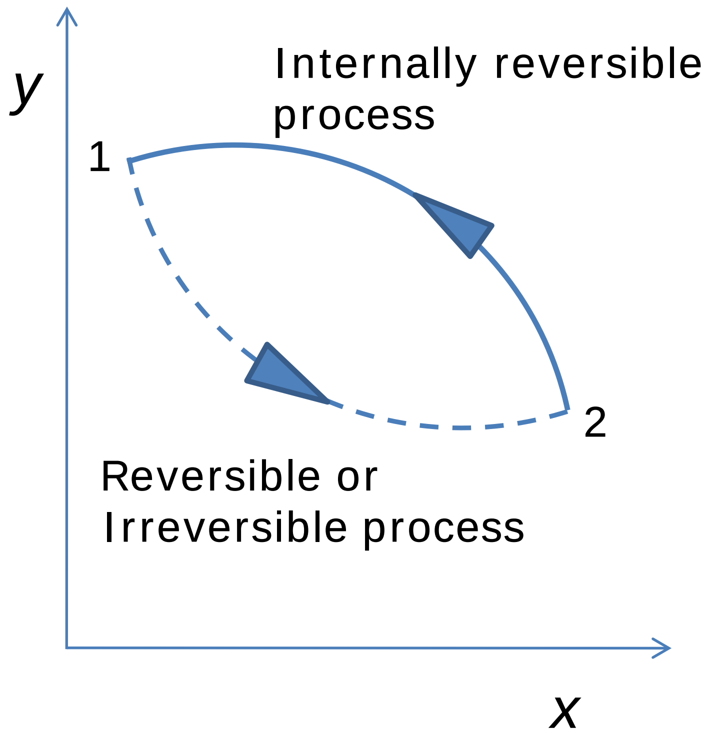
Entropy change and entropy generation



- Consider a cycle made up of two processes (1-2 and 2-1)

$$\oint \frac{\delta Q}{T} \leq 0 \quad \text{(Clausius inequality)}$$

$$or, \int_1^2 \frac{\delta Q}{T} + \int_2^1 \left(\frac{\delta Q}{T} \right)_{\mathrm{int}.rev} \leq 0$$

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Entropy change and entropy generation

- The second integral is equal to entropy change during that process.

$$\int_1^2 \frac{\delta Q}{T} + (S_1 - S_2) \le 0$$

$$\text{or, } S_2 - S_1 \ge \int_1^2 \frac{\delta Q}{T} \quad \text{which can be written as } dS \ge \frac{\delta Q}{T}$$

- Here, the equality holds for an internally reversible process and the inequality for an irreversible process.

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Entropy change and entropy generation

- The entropy change of a closed system during an irreversible process is greater than the integral of dQ/T evaluated for that process.
- In the limiting case of a reversible process, these two quantities become equal.
- Note: T in these relations is the temperature at the boundary where the differential heat dQ is transferred between the system and the surroundings.

Entropy change and entropy generation

- Inequality sign: entropy change of a closed system during an irreversible process is always greater than the entropy transfer.
- Some entropy is generated or created during an irreversible process, and this generation is entirely due to the irreversibilities.
- This entropy generated during a process is called entropy generation and is denoted by S_{gen}.

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Entropy change and entropy generation

$$\Delta S_{sys} = S_2 - S_1 = \int_1^2 \frac{\delta Q}{T} + S_{gen}$$

- The entropy generation S_{gen} is always a positive quantity or zero.
- Its value depends on the process, and thus it is not a property of the system.
- For an isolated system (or simply an adiabatic closed system), the heat transfer is zero.

$$\Delta S_{isolated} \geq 0$$

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Increase of entropy principle

- The entropy of an isolated system during a process always increases or, in the limiting case of a reversible process, remains constant.
- This is known as the increase of entropy principle.
- In the absence of any heat transfer, entropy change is due to irreversibilities only, and their effect is always to increase entropy.

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Increase of entropy principle

- The entropy of the universe is continuously increasing.
- No entropy is generated during reversible processes.
- The increase of entropy principle does not imply that the entropy of a system cannot decrease.
- The entropy change of a system can be negative during a process, but entropy generation cannot.

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Increase of entropy principle

$$S_{gen} \begin{cases} > 0 & \text{Irreversible process} \\ = 0 & \text{Reversible process} \\ < 0 & \text{Impossible process} \end{cases}$$

- A system and its surroundings form an isolated system.

$$S_{gen} = \Delta S_{total} = \Delta S_{system} + \Delta S_{surroundings} \geq 0$$

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Increase of entropy principle

- Processes can occur in a certain direction only, not in any direction.
- A process must proceed in the direction that complies with the increase of entropy principle, that is, $S_{gen} \geq 0$.
- Entropy is a non-conserved property, and there is no such thing as the conservation of entropy principle.
- Entropy is conserved during the idealized reversible processes only and increases during all actual processes.

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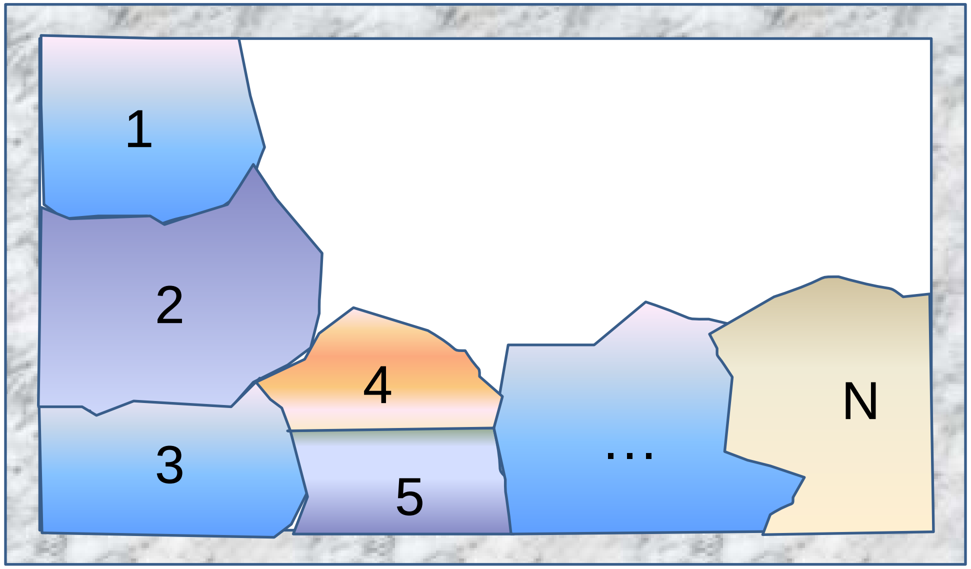
Increase of entropy principle



The entropy change of an isolated system is the sum of the entropy changes of its components, and is always greater than zero.

$$\Delta S_{total} = \sum_{i=1}^{N} \Delta S_i > 0$$

TdS equations

- From the first law for an internally reversible process, we know that

$$\delta Q_{\text{int}\,rev} - \delta W_{\text{int}\,rev,out} = dU$$

$$\text{Since, } \delta Q_{\text{int}\,rev} = TdS \text{ and } \delta W_{\text{int}\,rev,out} = PdV$$

$$TdS = dU + PdV \;\; or,\; Tds = du + Pdv$$

- This is known as the first TdS equation.

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TdS equations

- From the definition of enthalpy, we know that,

$$h = u + Pv$$

$$\text{or, } dh = du + Pdv + vdP$$

$$\text{since, } Tds = du + Pdv,$$

$$Tds = dh - vdP$$

- This is known as the second TdS equation.

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TdS equations

- Since the TdS equations are property relations, they are therefore independent of the type of the processes.
- The *Tds* relations are hence, valid for both reversible and irreversible processes and for both closed and open systems.

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Entropy change of liquids and solids

- Liquids and solids can be approximated as incompressible substances since their specific volumes remain nearly constant during a process.
- Thus, *dv = 0* for liquids and solids.

$$ds = \frac{du}{T} = \frac{c\,dT}{T} \quad (\because c_p = c_v = c \text{ and } du = cdT)$$

$$s_2 - s_1 = \int_1^2 c(T)\frac{dT}{T} \cong c_{avg} \ln\frac{T_2}{T_1} \quad (\text{kJ/kg. K})$$

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Entropy change of ideal gases

- For ideal gases we know that,

$$du = c_v dT,\ P = RT/v$$

From the TdS relations,

$$ds = c_v \frac{dT}{T} + R\frac{dv}{v}$$

- The entropy change for a process,

$$s_2 - s_1 = \int_1^2 c_v(T)\frac{dT}{T} + R\ln\frac{v_2}{v_1}$$

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Entropy change of ideal gases

If we use these relations,

$$dh = c_p dT, \ v = RT / P$$

Then, from the TdS relations,

$$s_2 - s_1 = \int_1^2 c_p(T) \frac{dT}{T} - R \ln \frac{P_2}{P_1}$$

- Usually, we assume average values of c_p and c_v in the above equations and thus can replace $c_p(T)$ with $c_{p,av}$ and $c_v(T)$ with $c_{v,av}$.

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Third law of thermodynamics

- Entropy can be viewed as a measure of molecular disorder, or molecular randomness.
- As a system becomes more disordered, the positions of the molecules become less predictable and the entropy increases.
- The entropy of a system is related to the total number of possible microscopic states of that system, called thermodynamic probability p, by the Boltzmann relation.

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Third law of thermodynamics

- Boltzmann relation is expressed as

$$S = k \ln p$$

Where, k = 1.3806 x 10^{-23} J/K is the Boltzmann constant.

- From a microscopic point of view, the entropy of a system increases whenever the molecular randomness or uncertainty (i.e., molecular probability) of a system increases.

Third law of thermodynamics

- 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: the third law of thermodynamics.
- The entropy determined relative to this point is called absolute entropy.
- A pure crystalline substance at absolute zero temperature is in perfect order, and its entropy is zero.

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Entropy and energy transfer

- An organized form of energy like work is free of disorder or randomness and thus free of entropy.
- There is no entropy transfer associated with energy transfer as work.
- The quantity of energy is always preserved during an actual process (the 1st law), but the quality is bound to decrease (the 2nd law).

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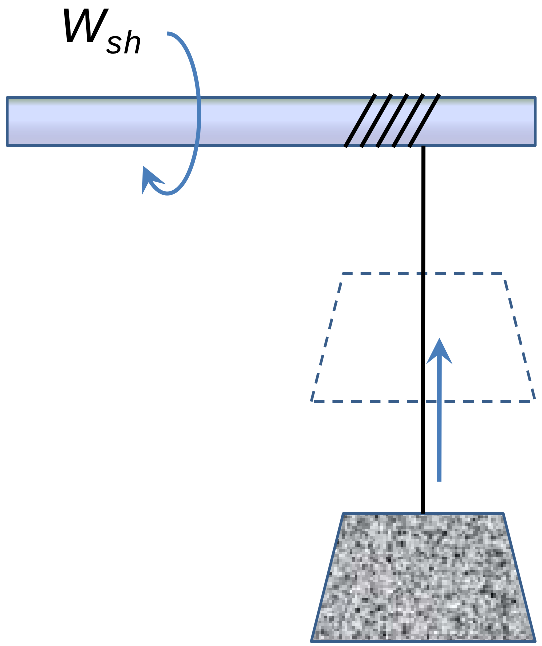
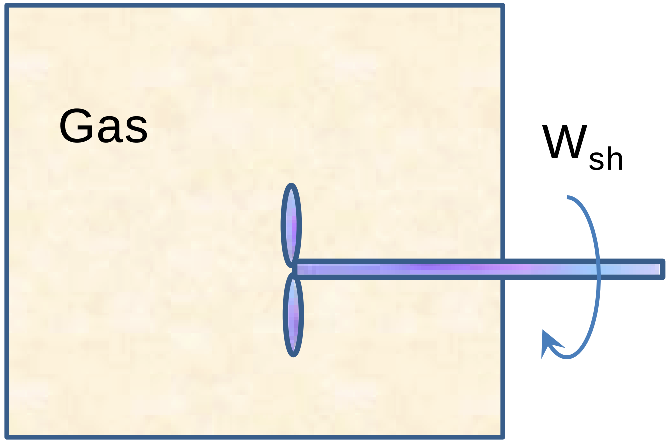
Entropy and energy transfer





Raising of a weight by a rotating shaft does not generate entropy, and so energy is not degraded during this process (if we assume frictional effects can be neglected).

The work done on a gas increases the entropy of the gas, and thus energy is degraded during this process.

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Entropy and energy transfer

- This decrease in quality is always accompanied by an increase in entropy.
- Heat is a form of disorganized energy, and hence, there is increase in entropy with heat.
- Processes can occur only in the direction of increased overall entropy or molecular disorder.
- That is, the entire universe is getting more and more chaotic every day.

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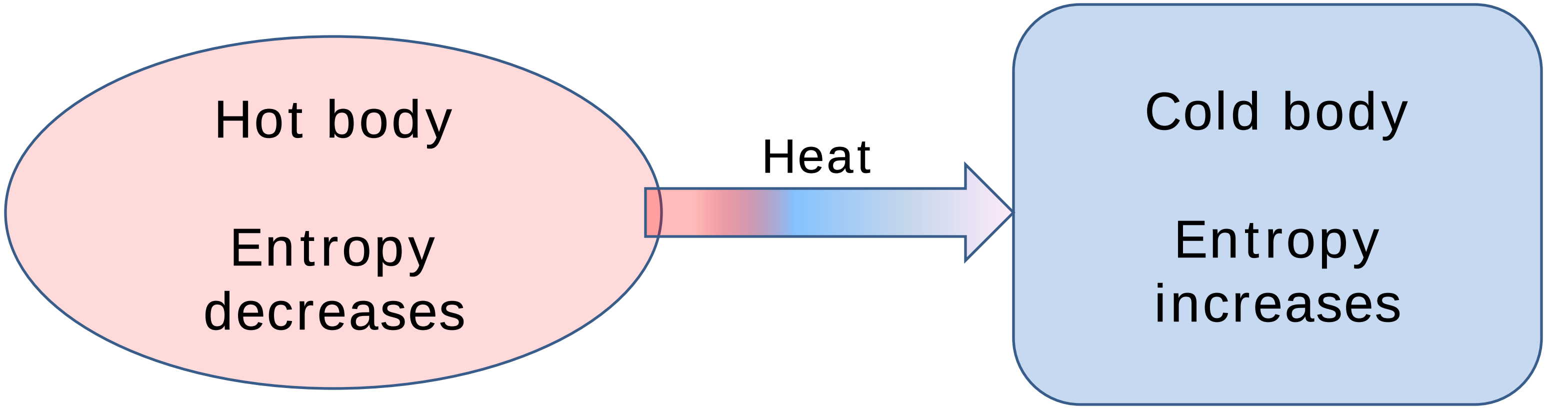
Entropy and energy transfer



- During a heat transfer process, the net entropy increases.
- This is because, the increase in the entropy of the cold body is more than the decrease in the entropy of the hot body.

Entropy and energy transfer

- Work is entropy-free, and no entropy is transferred by work.
- Closed systems
  - Energy is transferred by both heat and work, whereas entropy is transferred only by heat (closed systems).
  - Only energy is exchanged during work interaction whereas both energy and entropy are exchanged during heat transfer.
- Open systems
  - Entropy transfer in open systems: heat and mass flow.

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Entropy balance

- Entropy balance for any system undergoing any process is:

$$\underbrace{S_{in} - S_{out}}_{\substack{\text{Net entropy transfer}\\ \text{by heat and mass}}} + \underbrace{S_{gen}}_{\substack{\text{Entropy}\\ \text{generation}}} = \underbrace{\Delta S_{system}}_{\substack{\text{Change in}\\ \text{entropy}}}$$

This can also be expressed in the rate form as,

$$\underbrace{\dot{S}_{in} - \dot{S}_{out}}_{\substack{\text{Rate of net entropy}\\ \text{transfer by heat and mass}}} + \underbrace{\dot{S}_{gen}}_{\substack{\text{Rate of entropy}\\ \text{generation}}} = \underbrace{\Delta \dot{S}_{system}}_{\substack{\text{Rate of change}\\ \text{in entropy}}}$$

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In the next lecture ...

- Solve problems related to
  - First law of thermodynamics for closed and open systems
  - Heat engines
  - Refrigerators and heat pumps

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