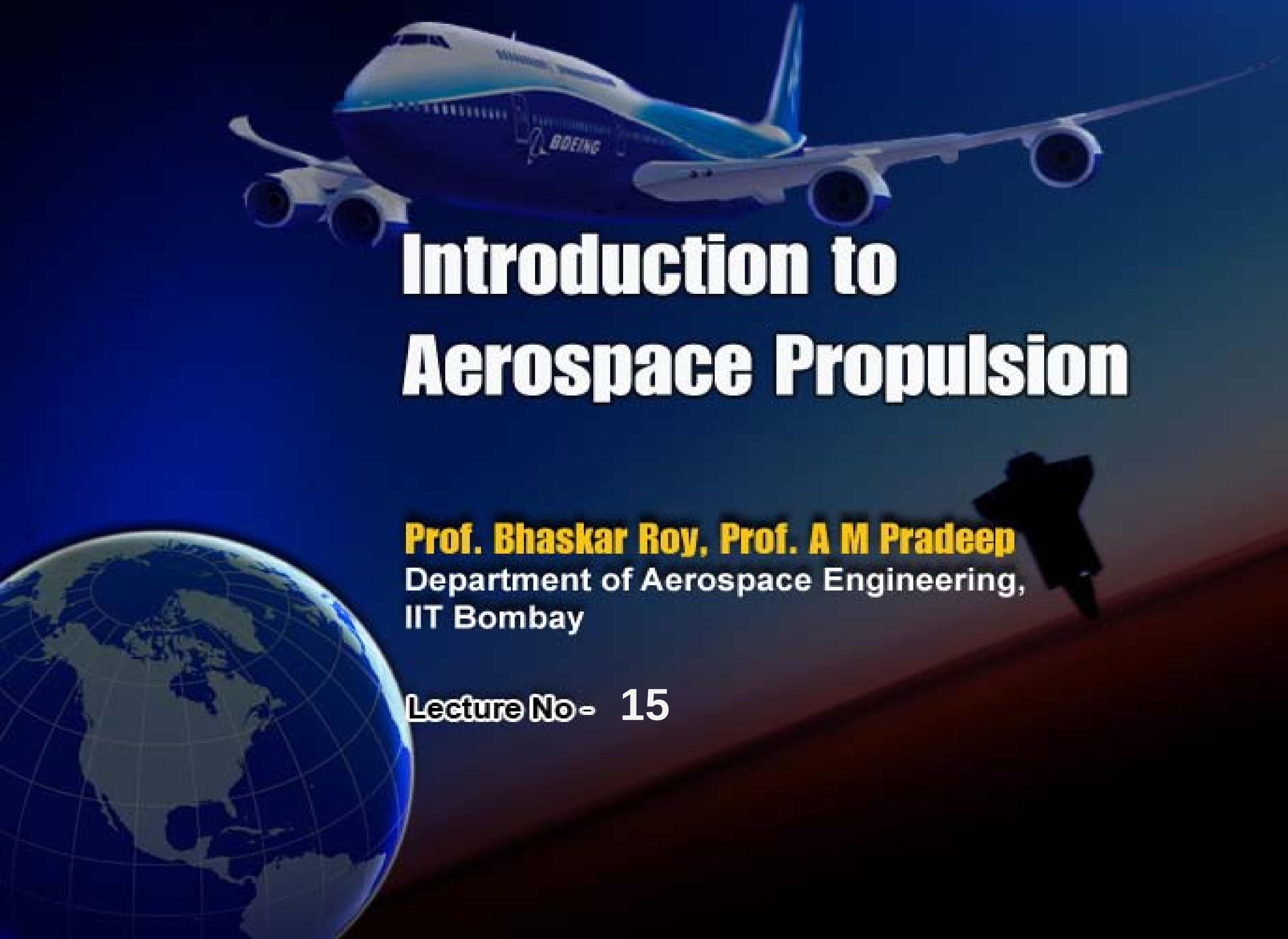

Introduction to Aerospace Propulsion

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Lecture No - 15

In this lecture ...

- Exergy: A Measure of Work Potential
- Reversible Work and Irreversibility
- Second-Law Efficiency
- Exergy Change of a System
- The Decrease of Exergy Principle and Exergy Destruction
- Exergy Balance

Exergy

- Exergy: a property that determines the useful work potential of a given amount of energy at some specified state.
- Also known as availability or available energy.
- The work potential of the energy contained in a system at a specified state is the maximum useful work that can be obtained from the system.
- Work = *f (initial state, process path, final state)*

Exergy

- Work output is maximized when the process between two specified states is executed in a reversible manner.
- The system must be in the dead state at the end of the process to maximize the work output.
- A system that is in equilibrium with its environment is said to be at the dead state.
- At the dead state, the useful work potential (exergy) of a system is zero.

Exergy

- Exergy does not represent the amount of work that a work-producing device will actually deliver upon installation.
- It represents the upper limit on the amount of work a device can deliver without violating any thermodynamic laws.
- There will always be a difference between exergy and the actual work delivered by a device.
- This difference represents the room engineers have for improvement.

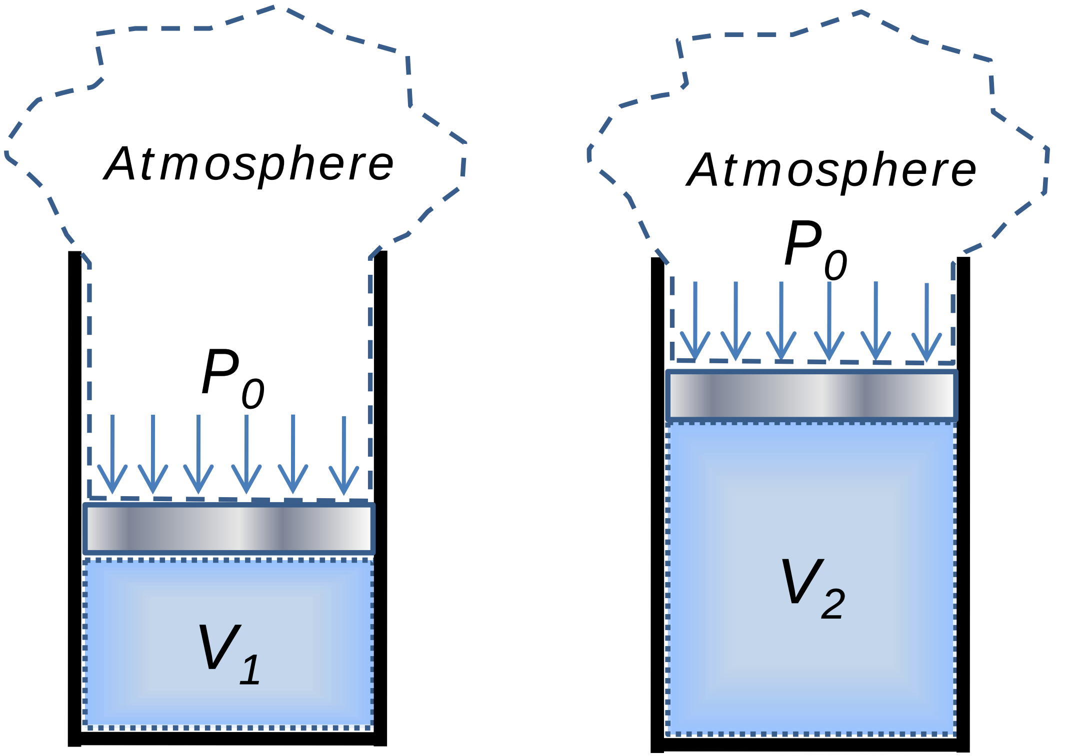
Exergy

- Exergy is a property of the system–environment combination and not of the system alone.
- Altering the environment is another way of increasing exergy, but not easy
- The atmosphere contains a tremendous amount of energy, but no exergy.
- Unavailable energy is the portion of energy that cannot be converted to work by even a reversible heat engine.

Reversible work and irreversibility

- The evaluation of exergy alone is not sufficient for studying engineering devices operating between two fixed states.
- The final state is always assumed to be the dead state; not the case in actual applications.
- Surroundings work: the work done by or against the surroundings during a process.
- Useful work: The difference between the actual work *W* and the surroundings work W_{surr}.

Reversible work and irreversibility



Surroundings work, $W_{surr} = P_0(V_2 - V_1)$

Useful work, $W_u = W - W_{surr} = W - P_0(V_2 - V_1)$

Reversible work and irreversibility

- W_{surr} represents a loss during expansion process and gain during compression.
- The work done by or against the atmospheric pressure has significance only for systems that involve moving boundary work.
- It has no significance for cyclic devices and systems whose boundaries remain fixed during a process such as rigid tanks and steady-flow devices.

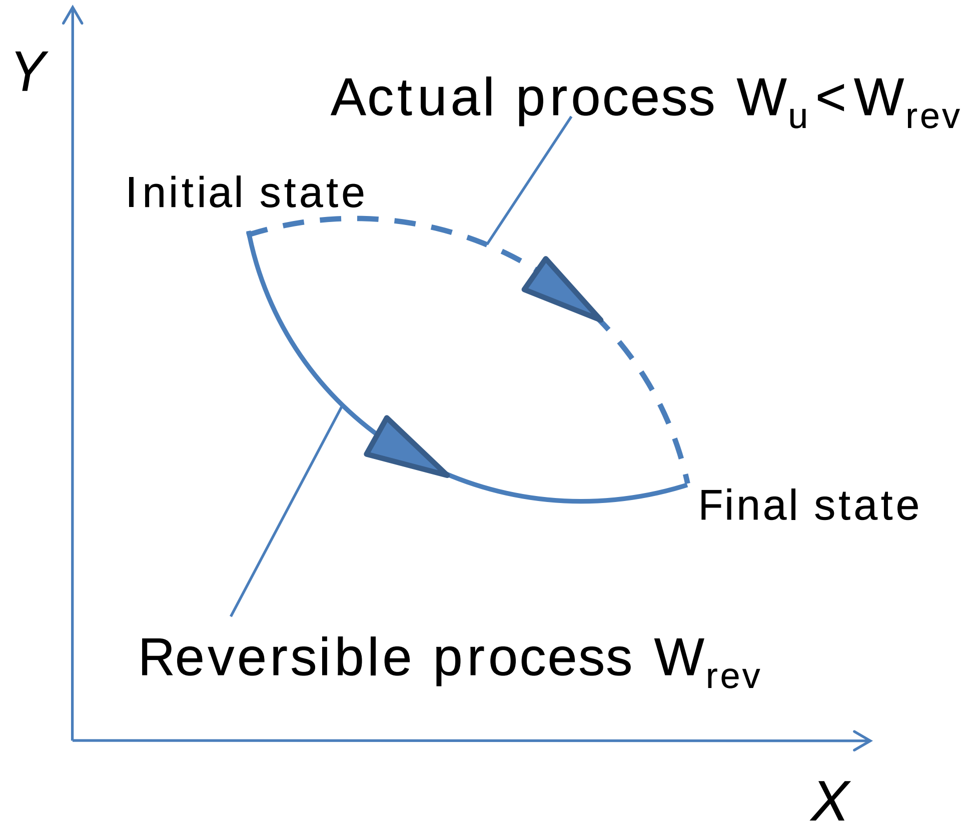
Reversible work and irreversibility

- Reversible work, W_{rev}: the maximum amount of useful work that can be produced as a system undergoes a process between the specified initial and final states.
- When the final state is the dead state, the reversible work equals exergy.
- For processes that require work, reversible work represents the minimum amount of work necessary to carry out that process.

Reversible work and irreversibility

- Difference between the reversible work, W_{rev}, and the useful work, W_u, is due to the irreversibilities: Irreversibility, I
- The irreversibility is equivalent to the exergy destroyed.
- For a totally reversible process, the actual and reversible work terms are identical, and thus the irreversibility is zero.
- Irreversibility represents the energy that could have been converted to work but was not.

Reversible work and irreversibility



Irreversibility = Reversible work – Useful work

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

Second law efficiency

- Thermal efficiency, $COP_{R/HP}$ based on the first law: first law efficiency
- Makes no reference to the best possible performance.
- The ratio of the actual thermal efficiency to the maximum possible (reversible) thermal efficiency under the same conditions: Second law efficiency, η_{II}

Second law efficiency

- The second law efficiency is expressed in different forms depending upon the type of device under consideration.

For heat engines, $\eta_{II} = \dfrac{\eta_{th}}{\eta_{th,rev}}$

For work producing devices, $\eta_{II} = \dfrac{W_u}{W_{rev}}$

For work consuming devices, $\eta_{II} = \dfrac{W_{rev}}{W_u}$

For refrigerators and heat pumps, $\eta_{II} = \dfrac{COP}{COP_{rev}}$

Second law efficiency

- In general,

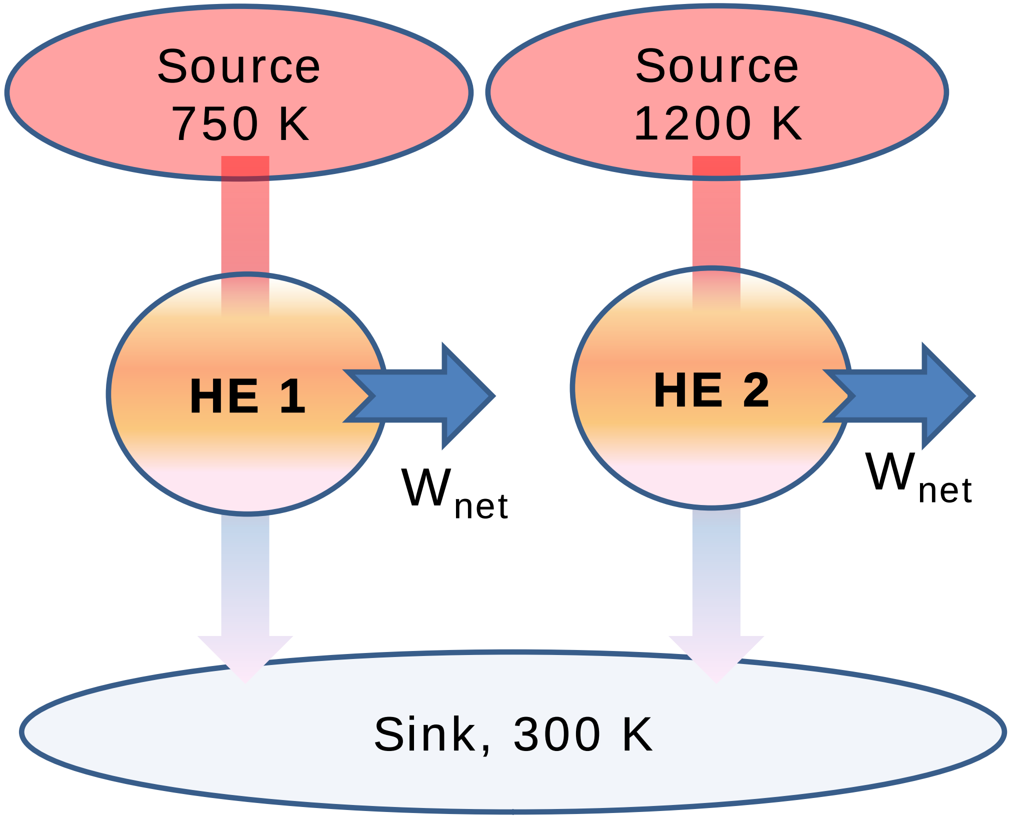
  η_{II} = Exergy recovered/Exergy supplied

  = 1- Exergy destroyed/Exergy supplied
- Second-law efficiency is a measure of the performance of a device relative to its performance under reversible conditions.
- Hence, second-law efficiency of all reversible devices is 100 percent.

Second law efficiency

- For a heat engine,
  - The exergy supplied is the decrease in the exergy of the heat transferred to the engine, which is the difference between the exergy of the heat supplied and the exergy of the heat rejected.
  - The exergy of the heat rejected at the temperature of the surroundings is zero.
  - The net work output is the recovered exergy.

Second law efficiency



HE 1

$$\eta_{th,1} = 25\ \%$$
$$\eta_{th,rev} = 60\ \%$$
$$\eta_{II,1} = 25/60 = 0.417$$

HE 2

$$\eta_{th,2} = 25\ \%$$
$$\eta_{th,rev} = 75\ \%$$
$$\eta_{II,2} = 25/75 = 0.333$$

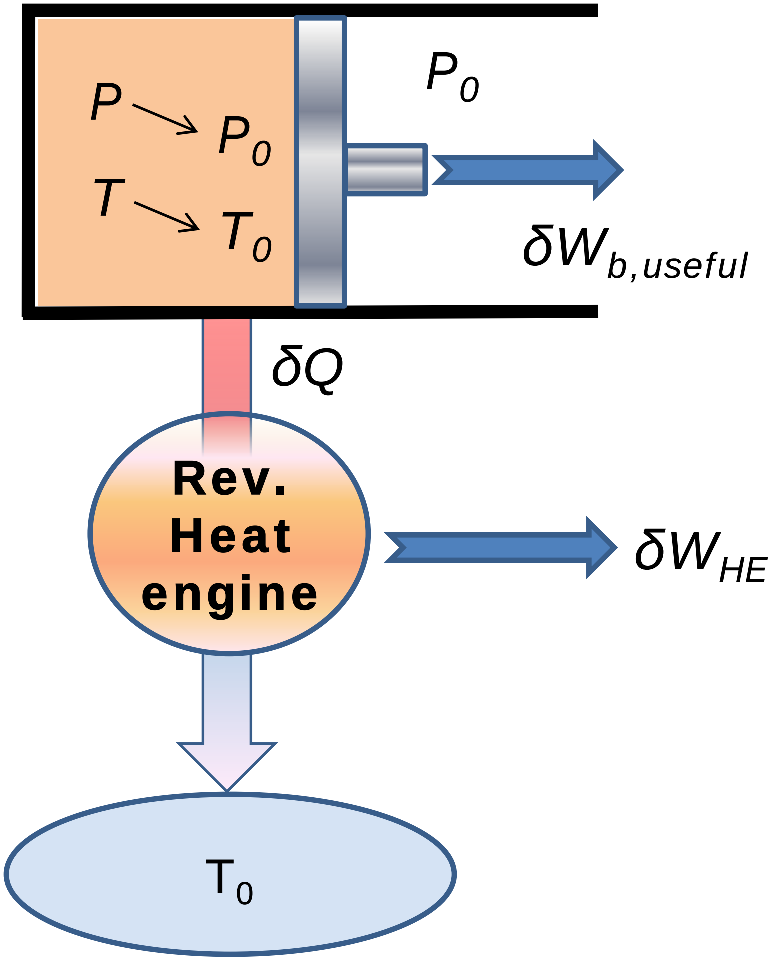
Exergy change of a system

- The value of exergy (unlike energy) depends on the state of the environment as well as the state of the system.
- The exergy of a system that is in equilibrium with its surroundings is zero.
- This state of the system is referred to as a "dead state".

Exergy of a closed system

- To derive an expression for exergy change of a closed system, we consider a piston-cylinder assembly.
- The system undergoes a differential change of state.
- Heat transfer from the system occurs through a reversible heat engine (to avoid any irreversibilities).
- The total work done = Work done (PdV) + the work done by the reversible heat engine.

Exergy of a closed system



From the first law for the system,

$$-\delta Q - \delta W = dU$$

Here, $\delta W = PdV$

$$= (P - P_0)dV + P_0 dV$$

$$= \delta W_{b,useful} + P_0 dV$$

Exergy of a closed system

For the reversible heat engine,

$$dS = \delta Q / T \quad and \quad \eta_{th} = 1 - T_0 / T$$

$$\text{Therefore, } \delta W_{HE} = \left(1 - \frac{T_0}{T}\right)\delta Q = \delta Q - \frac{T_0}{T}\delta Q$$

$$= \delta Q - (-T_0 dS)$$

$$or, \delta Q = \delta W_{HE} - T_0 dS$$

$$\therefore \delta W_{total,useful} = \delta W_{HE} + \delta W_{b,useful} = -dU - P_0 dV + T_0 dS$$

Integrating from given state to the dead state (0),

$$W_{total,useful} = (U - U_0) + P_0(V - V_0) - T_0(S - S_0)$$

Exergy of a closed system

A closed system may possess KE and PE.

Therefore the exergy of a closed system is

$$X = (U - U_0) + P_0(V - V_0) - T_0(S - S_0) + m\frac{V^2}{2} + mgz$$

(Since KE and PE are themselves forms of exergy)

For unit mass,

$$\phi = (u - u_0) + P_0(v - v_0) - T_0(s - s_0) + \frac{V^2}{2} + gz$$

Exergy change of a closed system

Exergy change of a system is the difference between the initial and final exergies of the system.

$$\Delta X = X_2 - X_1 = m(\phi_2 - \phi_1)$$

$$= (U_2 - U_1) + P_0(V_2 - V_1) - T_0(S_2 - S_1) + m\frac{V_2^2 - V_1^2}{2} + mg(z_2 - z_1)$$

Or, per unit mass,

$$\Delta\phi = (u_2 - u_1) + P_0(v_2 - v_1) - T_0(s_2 - s_1) + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1)$$

Exergy of a flow system

Exergy change of a flow system will consist of

enthalpy $(h = u + pv)$

$$x_{flowing\ fluid} = x_{non-flowing\ fluid} + x_{flow}$$

$$= (u - u_0) + P_0(v - v_0) - T_0(s - s_0) + \frac{V^2}{2} + gz + (P - P_0)v$$

$$= (u + Pv) - (u_0 + P_0 v_0) - T_0(s - s_0) + \frac{V^2}{2} + gz$$

$$= (h - h_0) - T_0(s - s_0) + \frac{V^2}{2} + gz$$

This is known as the flow exergy, Ψ or ψ (per unit mass)

Exergy change of a flow system

Flow exergy change,

$$\Delta\Psi = (H_2 - H_1) + T_0(S_2 - S_1) + m\frac{V_2^2 - V_1^2}{2} + mg(z_2 - z_1)$$

Flow exergy change per unit mass,

$$\Delta\psi = (h_2 - h_1) + T_0(s_2 - s_1) + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1)$$

How do the exergy equations compare with the energy equations for closed systems and flow systems?

Decrease of exergy principle

- The exergy of an isolated system during a process always decreases or, in the limiting case of a reversible process, remains constant.
- Exergy never increases and exergy is destroyed during an actual process.
- From the energy and entropy balances, we can show that: $-T_0S_{gen} = X_2 - X_1 \leq 0$
- Since $T_0S_{gen} \geq 0$, *i*t follows that for an isolated system $(X_2 - X_1) \leq 0$

Exergy destruction

- Irreversibilities always cause increase in entropy.
- Increase in entropy leads to destruction of exergy.
- Exergy destroyed is proportional to entropy generated.
- For actual processes, exergy destroyed is always a positive quantity.
- Exergy destroyed represents the lost work potential and is also called the irreversibility or lost work.

Exergy destruction

$$X_{destroyed} = T_0 S_{gen} \geq 0$$

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

Exergy balance

- The exergy change of a system during a process is equal to the difference between the net exergy transfer through the system boundary and the exergy destroyed within the system boundaries as a result of irreversibilities.

$$\underbrace{X_{in} - X_{out}}_{\substack{\text{Net exergy transfer} \\ \text{by heat and mass}}} - \underbrace{X_{destroyed}}_{\substack{\text{Exergy} \\ \text{generation}}} = \underbrace{\Delta X_{system}}_{\substack{\text{Change in} \\ \text{exergy}}}$$

This can also be expressed in the rate form as,

$$\underbrace{\dot{X}_{in} - \dot{X}_{out}}_{\substack{\text{Rate of net exergy} \\ \text{transfer by heat and mass}}} - \underbrace{\dot{X}_{destroyed}}_{\substack{\text{Rate of exergy} \\ \text{generation}}} = \underbrace{\Delta \dot{X}_{system}}_{\substack{\text{Rate of change} \\ \text{in exergy}}}$$

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In the next lecture …

- Solve problems from
  - Entropy
  - Carnot cycle
  - Exergy
  - Second law efficiency