Advanced Thermodynamics: Lecture 8

Shivasubramanian Gopalakrishnan
sgopalak@iitb.ac.in

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Exergy or Availability

- Work potential of an energy source – is the amount of energy that can be extracted as useful work.
- This property is exergy, which is also called the availability or available energy.
- Recall that the work done during a process depends on the initial state, the final state, and the process path.

$$\text{Work} = f(\text{initial state, process path, final state})$$

The work output is maximized when the process between two specified states is executed in a reversible manner. Therefore, all the irreversibilities are disregarded in determining the work potential.

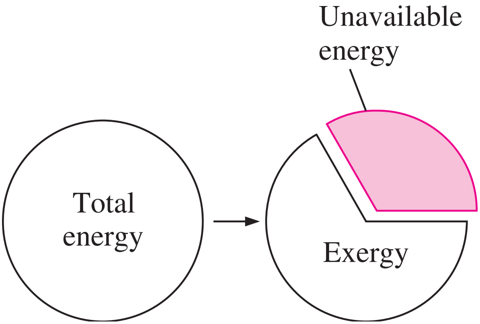
Exergy or Availability

- A system is said to be in the 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 (in thermal and mechanical equilibrium); it has no kinetic or potential energy relative to the environment (zero velocity and zero elevation above a reference level); and it does not react with the environment (chemically inert).
- Also, there are no unbalanced magnetic, electrical, and surface tension effects between the system and its surroundings, if these are relevant to the situation at hand.
- The properties of a system at the dead state are denoted by subscript zero, for example, P_0, T_0, h_0, u_0, and s_0.

Exergy or Avalability

- Distinction should be made between the surroundings, immediate surroundings, and the environment.
- Surroundings are everything outside the system boundaries.
- The immediate surroundings refer to the portion of the surroundings that is affected by the process, and environment refers to the region beyond the immediate surroundings whose properties are not affected by the process at any point.
- A system delivers the maximum possible work as it undergoes a reversible process from the specified initial state to the state of its environment, that is, the dead state.
- Exergy represents the upper limit on the amount of work a device can deliver without violating any thermodynamic laws.

Exergy or Avalability



Unavailable energy is the portion of energy that cannot be converted to work by even a reversible heat engine.

Image: Thermodynamics: An Engineering Approach by Cengel and Boles 7th edition

Exergy Transfer from a Furnace

Consider a large furnace that can transfer heat at a temperature of 2000 R at a steady rate of 3000 Btu/s. Determine the rate of exergy flow associated with this heat transfer. Assume an environment temperature of 77F.

Exergy (Work Potential) Associated with Kinetic and Potential Energy

Exergy of Kinetic Energy

$$x_{ke} = ke = \frac{V^2}{2}$$

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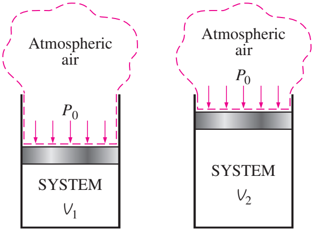
Exergy of Potential Energy

$$x_{pe} = pe = gz$$

The work done by work-producing devices is not always entirely in a usable form. For example, when a gas in a pistoncylinder device expands, part of the work done by the gas is used to push the atmospheric air out of the way of the piston.



This work, which cannot be recovered and utilized for any useful purpose, is equal to the atmospheric pressure P_0 times the volume change of the system, The difference between the actual work W and the surroundings work W_{surr} is called the useful work W_u

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

Image: Thermodynamics: An Engineering Approach by Cengel and Boles 7th edition

- Reversible work W_{rev} is defined as the maximum amount of useful work that can be produced (or the minimum work that needs to be supplied) 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.
- Any difference between the reversible work W_{rev} and the useful work W_u is due to the irreversibilities present during the process, and this difference is called irreversibility I.

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

The Rate of Irreversibility of a Heat Engine

A heat engine receives heat from a source at 1200 K at a rate of 500 kJ/s and rejects the waste heat to a medium at 300 K. The power output of the heat engine is 180 kW. Determine the reversible power and the irreversibility rate for this process.

Irreversibility during the Cooling of an Iron Block

A 500-kg iron block is initially at 200C and is allowed to cool to 27C by transferring heat to the surrounding air at 27C. Determine the reversible work and the irreversibility for this process.

Heating Potential of a Hot Iron Block

The iron block discussed previous example is to be used to maintain a house at 27C when the outdoor temperature is 5C. Determine the maximum amount of heat that can be supplied to the house as the iron cools to 27C.

Second Law efficiency

Thermal efficiency and the coefficient of performance for devices are defined as a measure of their performance. They are defined on the basis of the first law only, and they are sometimes referred to as the first-law efficiencies.

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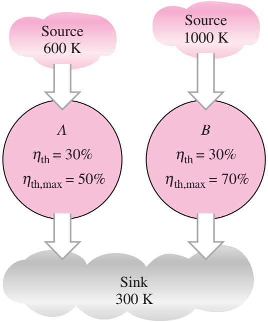

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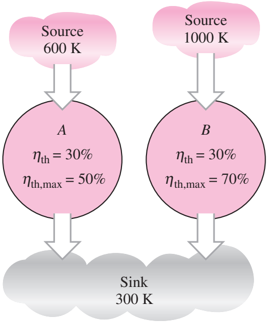

Engine B has greater availability.

Image: Thermodynamics: An Engineering Approach by Cengel and Boles 7th edition

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η_{II} as the ratio of the actual thermal efficiency to the maximum possible (reversible) thermal efficiency under the same conditions

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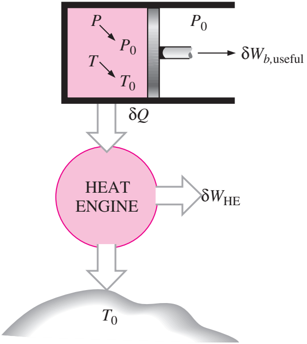
Second-Law Efficiency of Resistance Heaters

A dealer advertises that he has just received a shipment of electric resistance heaters for residential buildings that have an efficiency of 100 percent. Assuming an indoor temperature of 21C and outdoor temperature of 10C, determine the second-law efficiency of these heaters.

Exergy of a closed system



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

$$\delta W = PdV = (P - P_0)dV + P_0 dV = \delta W_{b,useful} + P_0 dV$$

Image: Thermodynamics: An Engineering Approach by Cengel and Boles 7th edition

The differential work produced by a engine as a result of this heat transfer is

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The total useful work is

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

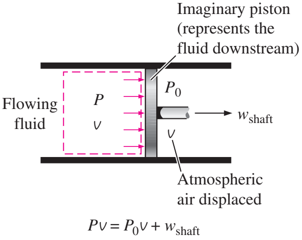
Integrating from given state to dead state

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

The exergy of a closed system including KE and PE is

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

Exergy of a flow systems



The flow work is Pv and the work done against the atmosphere is $P_0 v$, the exergy associated with flow energy can be expressed as

$$x_{flow} = Pv - P_0 v = (P - P_0) v$$

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Exergy of a flow systems

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

Also known as flow exergy ψ

Work Potential of Compressed Air in a Tank

A 200-m3 rigid tank contains compressed air at 1 MPa and 300 K. Determine how much work can be obtained from this air if the environment conditions are 100 kPa and 300 K.

Exergy Change during a Compression Process

Refrigerant-134a is to be compressed from 0.14 MPa and -10C to 0.8 MPa and 50C steadily by a compressor. Taking the environment conditions to be 20C and 95 kPa, determine the exergy change of the refrigerant during this process and the minimum work input that needs to be supplied to the compressor per unit mass of the refrigerant.

Decrease in Exergy principle

Energy balance for isolated system

$$\cancelto{0}{E_{in}} - \cancelto{0}{E_{out}} = \Delta E_{system} = 0$$

Entropy balance

$$\cancelto{0}{S_{in}} - \cancelto{0}{S_{out}} + S_{gen} = \Delta S_{system} = S_{gen}$$

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$$X_2 - X_1 = (E_2 - E_1) + \cancelto{0}{P_0(V_2 - V_1)} - T_0(S_2 - S_1)$$

$$X_2 - X_1 = -T_0 S_{gen} \leq 0$$

S_{gen} always greater than or equal to 0.

$$\Delta X_{isolated} = X_2 - X_1 \leq 0$$

Exergy Destruction during Heat Conduction

Consider steady heat transfer through a 5-m $\times$ 6-m brick wall of a house of thickness 30 cm. On a day when the temperature of the outdoors is 0C, the house is maintained at 27C. The temperatures of the inner and outer surfaces of the brick wall are measured to be 20C and 5C, respectively, and the rate of heat transfer through the wall is 1035 W. Determine the rate of exergy destruction in the wall, and the rate of total exergy destruction associated with this heat transfer process.

Exergy Destruction during Expansion of Steam

A pistoncylinder device contains 0.05 kg of steam at 1 MPa and 300C. Steam now expands to a final state of 200 kPa and 150C, doing work. Heat losses from the system to the surroundings are estimated to be 2 kJ during this process. Assuming the surroundings to be at $T_0 = 25$C and $P_0 = 100$ kPa, determine (a) the exergy of the steam at the initial and the final states, (b) the exergy change of the steam, (c) the exergy destroyed, and (d) the second-law efficiency for the process.

Exergy Destroyed during Stirring of a Gas

An insulated rigid tank contains 2 lbm of air at 20 psia and 70F. A paddle wheel inside the tank is now rotated by an external power source until the temperature in the tank rises to 130F . If the surrounding air is at $T_0 = 70$F, determine (a) the exergy destroyed and (b) the reversible work for this process.

Dropping a Hot Iron Block into Water

A 5-kg block initially at 350C is quenched in an insulated tank that contains 100 kg of water at 30C. Assuming the water that vaporizes during the process condenses back in the tank and the surroundings are at 20C and 100 kPa, determine (a) the final equilibrium temperature, (b) the exergy of the combined system at the initial and the final states, and (c) the wasted work potential during this process.

Exergy Destruction during Heat Transfer to a Gas

A frictionless piston cylinder device initially contains 0.01 m3 of argon gas at 400 K and 350 kPa. Heat is now transferred to the argon from a furnace at 1200 K, and the argon expands isothermally until its volume is doubled. No heat transfer takes place between the argon and the surrounding atmospheric air, which is at $T_0 = 300$ K and $P_0 = 100$ kPa. Determine (a) the useful work output, (b) the exergy destroyed, and (c) the reversible work for this process.

Second Law efficiency of flow devices

$$\eta_{II,turbine} = \frac{w}{w_{rev}} = \frac{h_1 - h_2}{\psi_1 - \psi_2} = 1 - \frac{T_0 s_{gen}}{\psi_1 - \psi_2}$$

$$\eta_{II,compressor} = \frac{w_{rev}}{w} = \frac{\psi_1 - \psi_2}{h_1 - h_2} = 1 - \frac{T_0 s_{gen}}{h_1 - h_2}$$

Second-Law Analysis of a Steam Turbine

Steam enters a turbine steadily at 3 MPa and 450C at a rate of 8 kg/s and exits at 0.2 MPa and 150C. The steam is losing heat to the surrounding air at 100 kPa and 25C at a rate of 300 kW, and the kinetic and potential energy changes are negligible. Determine (a) the actual power output, (b) the maximum possible power output, (c) the second-law efficiency, (d) the exergy destroyed, and (e) the exergy of the steam at the inlet conditions.