ESO 201A: Thermodynamics
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Exergy: part 4

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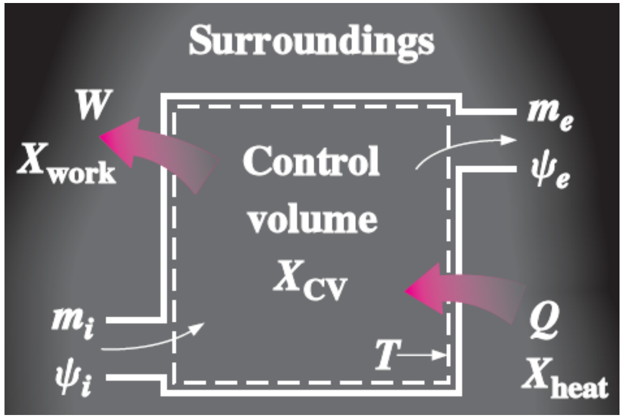
Learning objectives

- Examine the performance of engineering devices in light of the second law of thermodynamics.
- Define *exergy*, which is the maximum useful work that could be obtained from the system at a given state in a specified environment.
- Define *reversible work*, which is the maximum useful work that can be obtained as a system undergoes a process between two specified states.
- Define the exergy destruction, which is the wasted work potential during a process as a result of irreversibilities.
- Define the *second-law efficiency*.
- Develop the exergy balance relation.
- Apply exergy balance to closed systems and control volumes.

Exergy balance: control volume

The rate of exergy change within the control volume during a process is equal to the rate of net exergy transfer through the control volume boundary by heat, work, and mass flow minus the rate of exergy destruction within the boundaries of the control volume.



$$X_{heat} - X_{work} + X_{mass,in} - X_{mass,out} - X_{destroyed} = (X_2 - X_1)_{CV}$$

$$\sum\left(1 - \frac{T_0}{T_k}\right)Q_k - [W - P_0(V_2 - V_1)] + \sum_{in} m\psi - \sum_{out} m\psi - X_{destroyed} = (X_2 - X_1)_{CV}$$

Exergy is transferred into or out of a control volume by mass as well as heat and work transfer.

Rate form

$$\sum\left(1 - \frac{T_0}{T_k}\right)\dot{Q}_k - \left(\dot{W} - P_0\frac{dV_{CV}}{dt}\right) + \sum_{in} \dot{m}\psi - \sum_{out} \dot{m}\psi - \dot{X}_{destroyed} = \frac{dX_{CV}}{dt}$$

When initial and final state of the control volume specified

$$X_2 - X_1 = m_2\phi_2 - m_1\phi_1.$$

Exergy balance for steady flow systems

For steady flow systems: $dV_{CV}/dt = 0$ and $dX_{CV}/dt = 0$

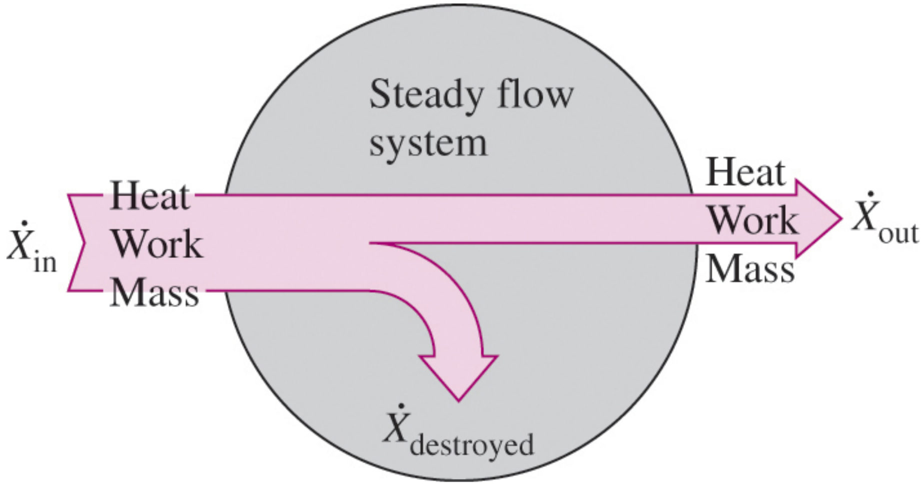
$$\sum\left(1-\frac{T_0}{T_k}\right)\dot{Q}_k - \dot{W} + \sum_{\text{in}}\dot{m}\psi - \sum_{\text{out}}\dot{m}\psi - \dot{X}_{\text{destroyed}} = 0$$

Single Stream: $$\sum\left(1-\frac{T_0}{T_k}\right)\dot{Q}_k - \dot{W} + \dot{m}(\psi_1 - \psi_2) - \dot{X}_{\text{destroyed}} = 0$$

$$\psi_1 - \psi_2 = (h_1 - h_2) - T_0(s_1 - s_2) + \frac{V_1^2 - V_2^2}{2} + g(z_1 - z_2)$$

$$\sum\left(1-\frac{T_0}{T_k}\right)q_k - w + (\psi_1 - \psi_2) - x_{\text{destroyed}} = 0$$

Unit-Mass Basis



Reversible Work, W_{rev}

The exergy balance relations presented above can be used to determine the reversible work W_{rev} by setting the exergy destroyed equal to zero.

$$W = W_{\text{rev}} \qquad \text{when } X_{\text{destroyed}} = 0$$

$$\dot{W}_{\text{rev}} = \dot{m}(\psi_1 - \psi_2) + \sum \left(1 - \frac{T_0}{T_k}\right)\dot{Q}_k$$

Single stream

$$\dot{W}_{\text{rev}} = \dot{m}(\psi_1 - \psi_2)$$

Adiabatic

The exergy destroyed is zero only for a reversible process, and reversible work represents the maximum work output for work-producing devices such as turbines and the minimum work input for work-consuming devices such as compressors.

Second-Law Efficiency of Steady-Flow Devices, η_{II}

The *second-law efficiency* of various steady-flow devices can be determined from its general definition,

η_{II} = (Exergy recovered)/(Exergy supplied).

When the changes in kinetic and potential energies are negligible and the devices are adiabatic:

Turbine

$$\eta_{\mathrm{II,turb}} = \frac{w_{\mathrm{out}}}{\psi_1 - \psi_2} = \frac{h_1 - h_2}{\psi_1 - \psi_2} = \frac{w_{\mathrm{out}}}{w_{\mathrm{rev,out}}} \quad \text{or} \quad \eta_{\mathrm{II,turb}} = 1 - \frac{T_0 s_{\mathrm{gen}}}{\psi_1 - \psi_2}$$

$$s_{\mathrm{gen}} = s_2 - s_1$$

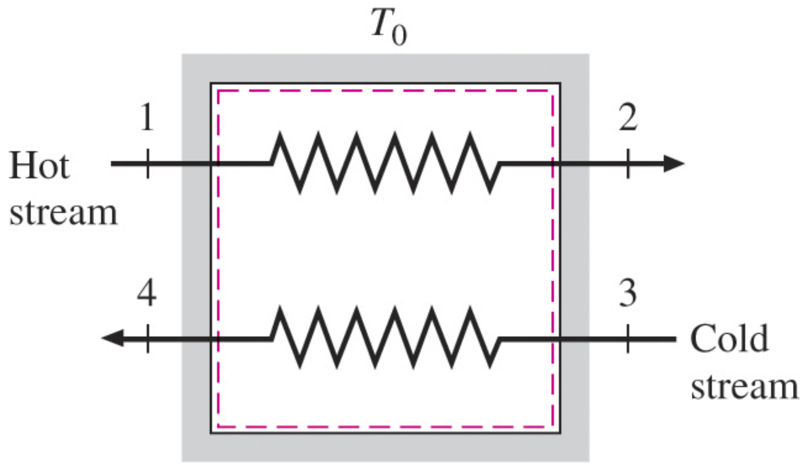
Adiabatic Compressor

$$\eta_{\mathrm{II,comp}} = \frac{\psi_2 - \psi_1}{w_{\mathrm{in}}} = \frac{\psi_2 - \psi_1}{h_2 - h_1} = \frac{w_{\mathrm{in,rev}}}{w_{\mathrm{in}}} \quad \text{or} \quad \eta_{\mathrm{II,comp}} = 1 - \frac{T_0 s_{\mathrm{gen}}}{h_2 - h_1}$$

Second-Law Efficiency of Steady-Flow Devices, η_{II}

A heat exchanger with two unmixed fluid streams.

- the exergy expended is the decrease in the exergy of the hot stream
- the exergy recovered is the increase in the exergy of the cold stream, provided that the cold stream is not at a lower temperature than the surroundings



$$\eta_{\text{II,HX}} = \frac{\dot{m}_{\text{cold}}(\psi_4 - \psi_3)}{\dot{m}_{\text{hot}}(\psi_1 - \psi_2)} \quad or \quad \eta_{\text{II,HX}} = 1 - \frac{T_0 \dot{S}_{\text{gen}}}{\dot{m}_{\text{hot}}(\psi_1 - \psi_2)}$$

$$\dot{S}_{\text{gen}} = \dot{m}_{\text{hot}}(s_2 - s_1) + \dot{m}_{\text{cold}}(s_4 - s_3)$$

Mixing chamber (hot steam 1 with a cold stream 2-forming a mixture 3)

$$\eta_{\text{II,mix}} = \frac{\dot{m}_{\text{cold}}(\psi_3 - \psi_2)}{\dot{m}_{\text{hot}}(\psi_1 - \psi_3)}$$

Examples

Exergy analysis of a steam turbine

$$\underbrace{\dot{X}_{in} - \dot{X}_{out}}_{\substack{\text{Rate of net exergy transfer}\\\text{by heat, work, and mass}}} - \underbrace{\dot{X}_{destroyed}\nearrow^{0\ \text{(reversible)}}}_{\substack{\text{Rate of exergy}\\\text{destruction}}} = \underbrace{dX_{system}/dt\nearrow^{0\ \text{(steady)}}}_{\substack{\text{Rate of change}\\\text{in exergy}}} = 0$$

$$\dot{X}_{in} = \dot{X}_{out}$$

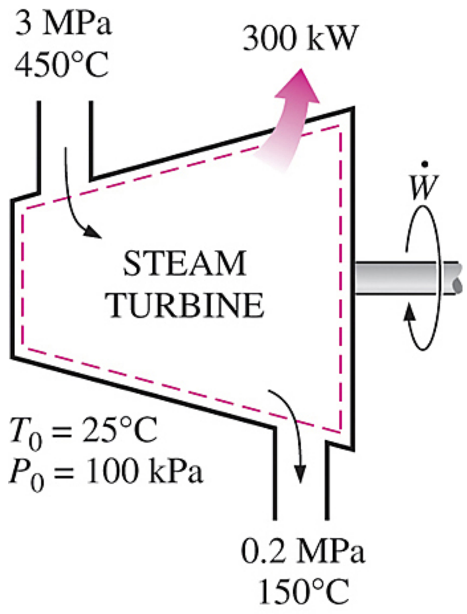
$$\boxed{\eta_{II} = \frac{\dot{W}_{out}}{\dot{W}_{rev,out}}}$$

$$\dot{m}\psi_1 = \dot{W}_{rev,out} + \dot{X}_{heat}\nearrow^{0} + \dot{m}\psi_2$$

$$\dot{W}_{rev,out} = \dot{m}(\psi_1 - \psi_2)$$

$$\boxed{\dot{X}_{destroyed} = \dot{W}_{rev,out} - \dot{W}_{out}}$$

$$= \dot{m}[(h_1 - h_2) - T_0(s_1 - s_2) - \Delta ke\nearrow^{0} - \Delta pe\nearrow^{0}]$$



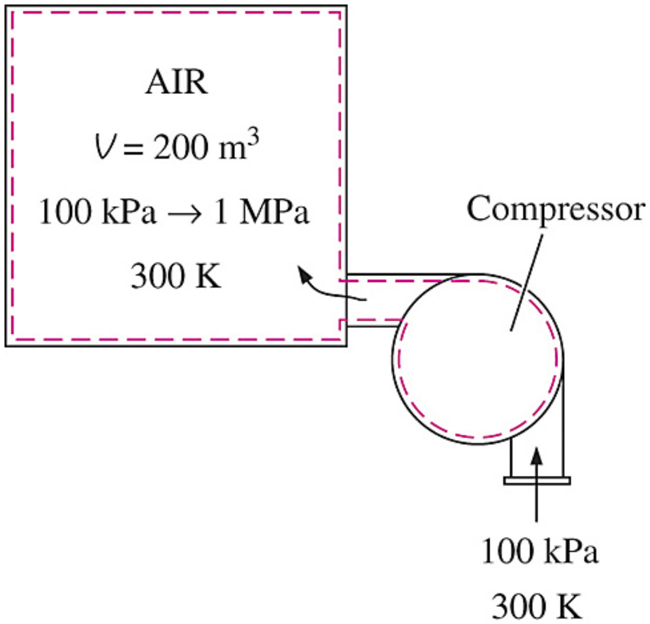
Exergy balance for a charging process

$$\underbrace{X_{in} - X_{out}}_{\substack{\text{Net exergy transfer}\\\text{by heat, work, and mass}}} - \underbrace{X_{destroyed}\nearrow^{0\ \text{(reversible)}}}_{\substack{\text{Exergy}\\\text{destruction}}} = \underbrace{\Delta X_{system}}_{\substack{\text{Change}\\\text{in exergy}}}$$

$$X_{in} - X_{out} = X_2 - X_1$$

$$W_{rev,in} + m_1\psi_1\nearrow^{0} = m_2\phi_2 - m_1\phi_1\nearrow^{0}$$

$$W_{rev,in} = m_2\phi_2$$



Summary

- Exergy: Work potential of energy
  - Exergy (work potential) associated with kinetic and potential energy
- Reversible work and irreversibility
- Second-law efficiency
- Exergy change of a system
  - Exergy of a fixed mass: Nonflow (or closed system) exergy
  - Exergy of a flow stream: Flow (or stream) exergy
- Exergy transfer by heat, work, and mass
- The decrease of exergy principle and exergy destruction
- Exergy balance: Closed systems
- Exergy balance: Control volumes
  - Exergy balance for steady-flow systems
  - Reversible work
  - Second-law efficiency of steady-flow devices