ESO 201A: Thermodynamics

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Exergy: part 3

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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 by heat transfer

Exergy, like energy, can be transferred to or from a system in three forms: heat, work, and mass flow.

- Heat is a form of disorganised energy
- Only a small portion of heat can be converted to work, which is form of organised energy
- Carnot efficiency $\eta_C = 1 - T_0/T$ represents the fraction of energy of a heat source at T that can be converted to work
- Thus exergy transfer by a heat:

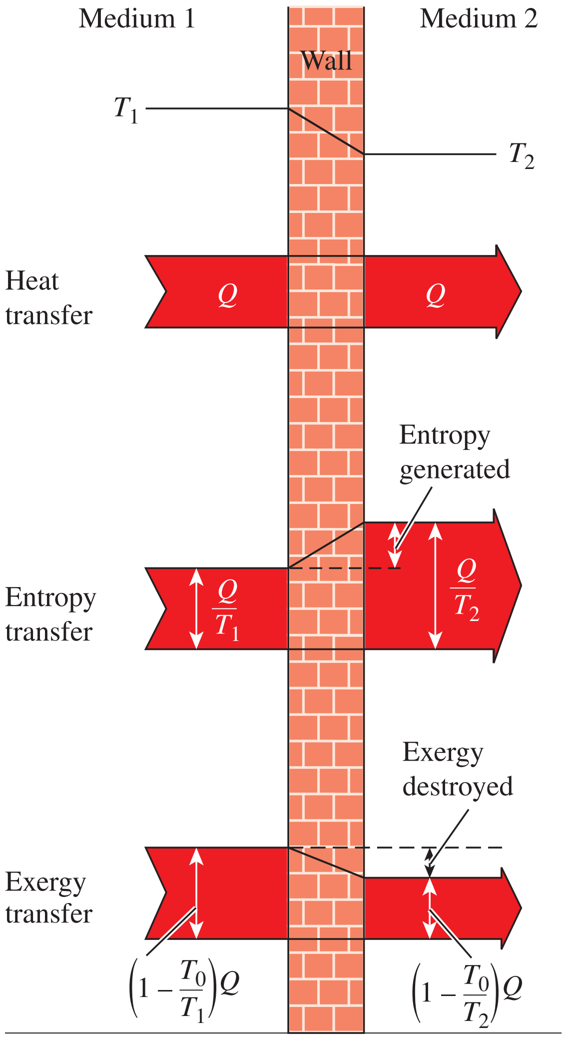
Exergy transfer by heat: $$X_{\text{heat}} = \left(1 - \frac{T_0}{T}\right)Q$$

Where Q is the heat transfer at T

When T is not constant

$$X_{\text{heat}} = \int \left(1 - \frac{T_0}{T}\right)\delta Q$$

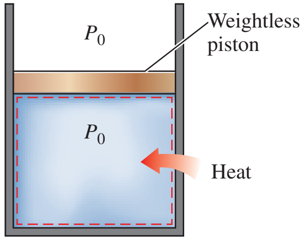
Exergy by heat transfer



- Direction of heat transfer and exergy same for T > To
- Direction of heat transfer and exergy opposite for T < To (cold medium)
- Energy of cold medium increases with heat transfer but exergy decreases (and eventually become zero when T=To)

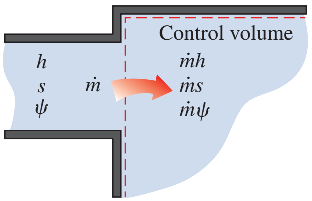
Exergy transfer by work or by mass

$$\textit{Exergy transfer by work:} \quad X_{\text{work}} = \begin{cases} W - W_{\text{surr}} & \text{(for boundary work)} \\ W & \text{(for other forms of work)} \end{cases}$$



$$W_{\text{surr}} = P_0(V_2 - V_1)$$

$$\textit{Exergy transfer by mass:} \qquad X_{\text{mass}} = m\psi$$



$$\psi = (h - h_0) - T_0(s - s_0) + V^2/2 + gz$$

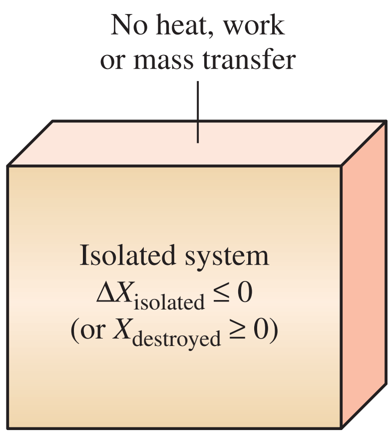
Mass contains energy, entropy, and exergy, and thus mass flow into or out of a system is accompanied by energy, entropy, and exergy transfer.

Decrease of Exergy principle

$S_{gen} >= 0$

Decrease of exergy principle: alternate statement of second law

Exergy of an isolated systems during a process always decrease or remain constant (for a reversible process).



Consider an isolated system:

Energy balance: $$E_{in}^{\nearrow 0} - E_{out}^{\nearrow 0} = \Delta E_{system} \rightarrow 0 = E_2 - E_1$$

Entropy balance: $$S_{in}^{\nearrow 0} - S_{out}^{\nearrow 0} + S_{gen} = \Delta S_{system} \rightarrow S_{gen} = S_2 - S_1$$

$$-T_0 S_{gen} = E_2 - E_1 - T_0(S_2 - S_1)$$

Exergy change:

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

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

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

Exergy destruction

Irreversibility always increase entropy or destroy exergy.
-friction, mixing, chemical reaction, heat transfer through a finite temp difference, unrestrained expansion, nonquasi-equilibrium compression or expansion

For an isolated system, the decrease in exergy equals exergy destroyed.

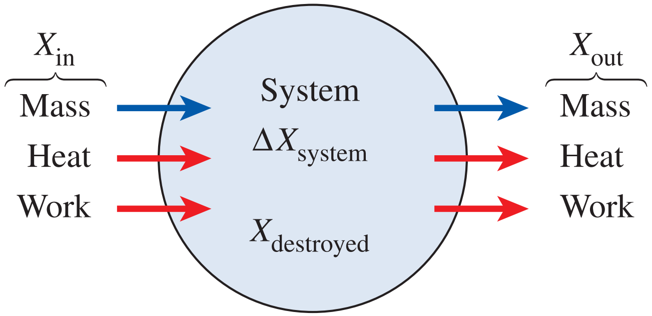
$$X_{\text{destroyed}} = T_0 S_{\text{gen}} \geq 0$$

Exergy destroyed is proportional to entropy generated

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

Exergy change can be negative
But exergy destruction cannot!

Exergy balance: closed system



Exergy can be destroyed but cannot be created!

- Opposite to that of entropy

Decrease in exergy principle

$$\begin{pmatrix}\text{Total}\\ \text{exergy}\\ \text{entering}\end{pmatrix} - \begin{pmatrix}\text{Total}\\ \text{exergy}\\ \text{leaving}\end{pmatrix} - \begin{pmatrix}\text{Total}\\ \text{exergy}\\ \text{destroyed}\end{pmatrix} = \begin{pmatrix}\text{Change in the}\\ \text{total exergy}\\ \text{of the system}\end{pmatrix}$$

General:

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

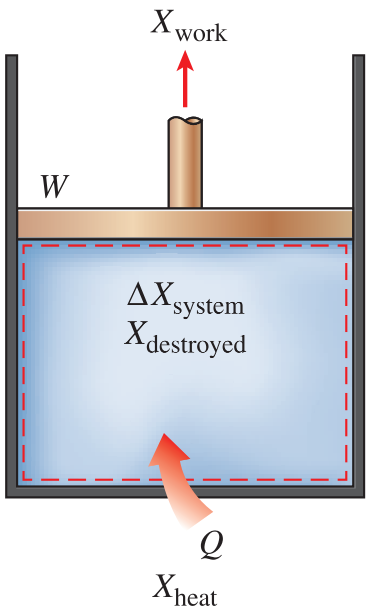
General, rate form:

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

For reversible process, Xdestroyed is dropped from the equation

Exergy balance: closed system

as $\dot{X}_{heat} = (1 - T_0/T)\dot{Q}$, $\dot{X}_{work} = \dot{W}_{useful}$, and $\dot{X}_{mass} = \dot{m}\psi$



$X_{heat} - X_{work} - X_{destroyed} = \Delta X_{system}$

Closed system: $X_{heat} - X_{work} - X_{destroyed} = \Delta X_{system}$

or

Closed system: $\sum\left(1 - \frac{T_0}{T_k}\right)Q_k - [W - P_0(V_2 - V_1)] - T_0 S_{gen} = X_2 - X_1$

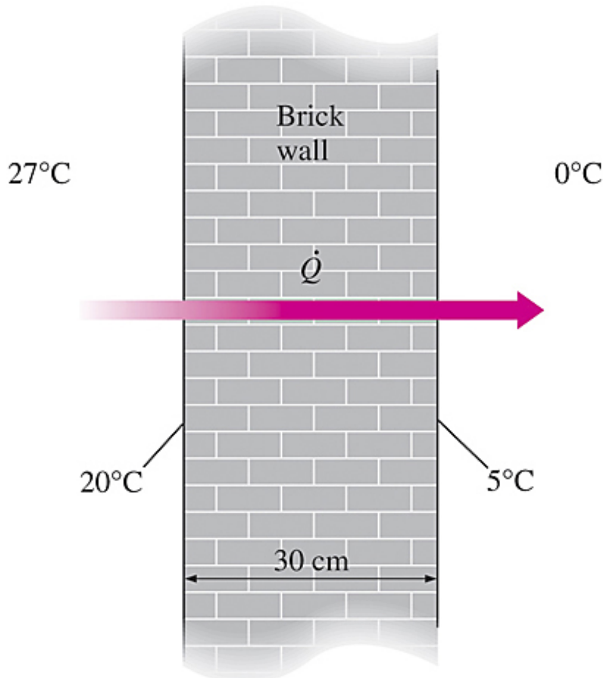
Rate form: $\sum\left(1 - \frac{T_0}{T_k}\right)\dot{Q}_k - \left(\dot{W} - P_0\frac{dV_{system}}{dt}\right) - T_0\dot{S}_{gen} = \frac{dX_{system}}{dt}$

EXAMPLES

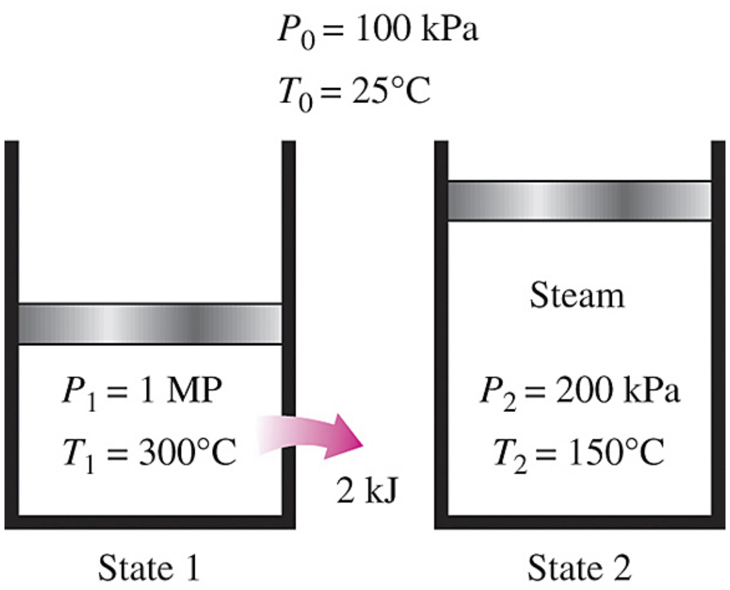
Exergy balance for heat conduction

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

$$\dot{Q}\left(1 - \frac{T_0}{T}\right)_{in} - \dot{Q}\left(1 - \frac{T_0}{T}\right)_{out} - \dot{X}_{destroyed} = 0$$



Exergy balance for expansion of steam



The total exergy destroyed during the process: balance applied on the *extended system* (system + immediate surroundings) whose boundary is at the environment temperature of T_0 gives

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

$$-X_{work,out} - X_{heat,out}^{\nearrow 0} - X_{destroyed} = X_2 - X_1$$

$$X_{destroyed} = X_1 - X_2 - W_{u,out}$$

Exergy balance for an air tank

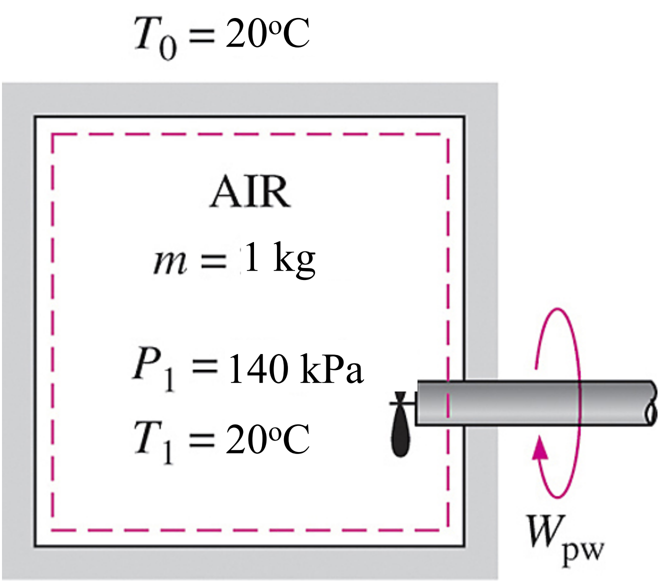
$$\underbrace{X_{in} - X_{out}}_{\substack{\text{Net exergy transfer} \\ \text{by heat, work, and mass}}} - \underbrace{X_{destroyed}^{\nearrow 0 \text{ (reversible)}}}_{\substack{\text{Exergy} \\ \text{destruction}}} = \underbrace{\Delta X_{system}}_{\substack{\text{Change} \\ \text{in exergy}}}$$

$$W_{rev,in} = X_2 - X_1$$

$$= (E_2 - E_1) + P_0(V_2 - V_1)^{\nearrow 0} - T_0(S_2 - S_1)$$

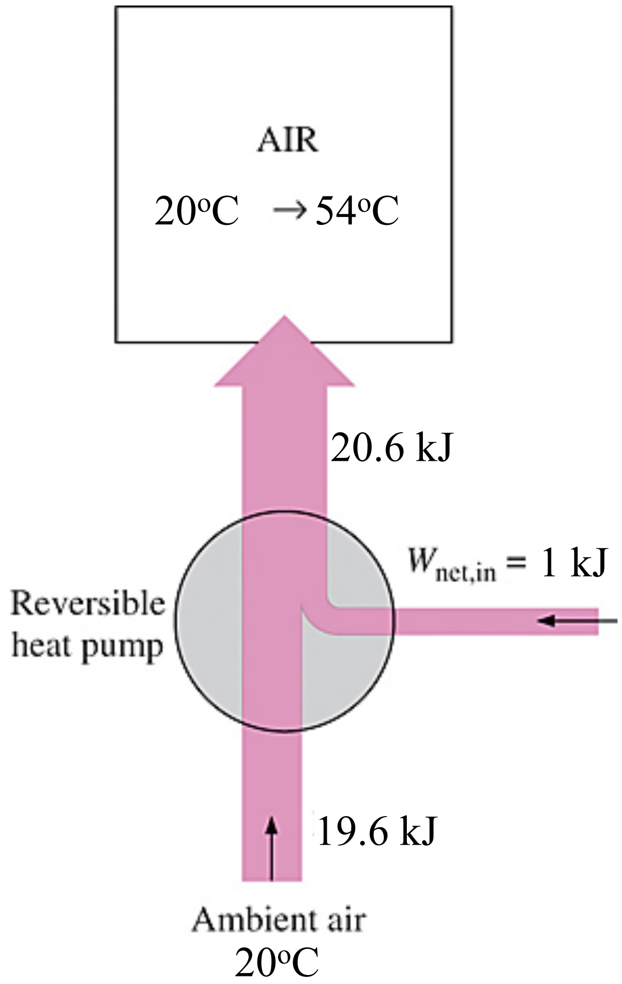
$$= (U_2 - U_1) - T_0(S_2 - S_1)$$

$$= 1 \text{ kJ}$$



$W_{pw,in} = \Delta U = 20.6$ kJ

$W_{rev,in} = 1$ kJ



The same effect on the insulated tank system can be accomplished by a reversible heat pump that consumes only 1 kJ of work.

Next lecture

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