Y14_Fall_4

Thermodynamics II

Youngsuk Nam

ysnam1@khu.ac.kr

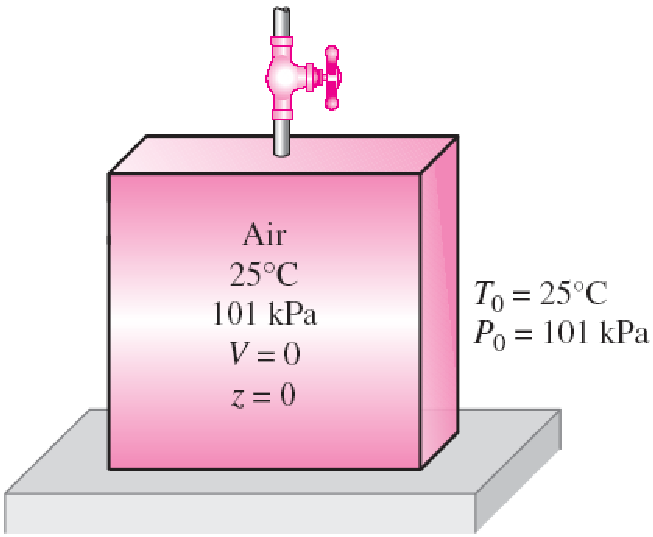
Ch. 8 Exergy - Objectives

- 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: WORK POTENTIAL OF ENERGY

The useful work potential of a given amount of energy at some specified state is called *exergy*, which is also called the *availability* or *available energy*.

A system is said to be in the dead state when it is in thermodynamic equilibrium with the environment it is in.



A system that is in equilibrium with its environment is said to be at the dead state.

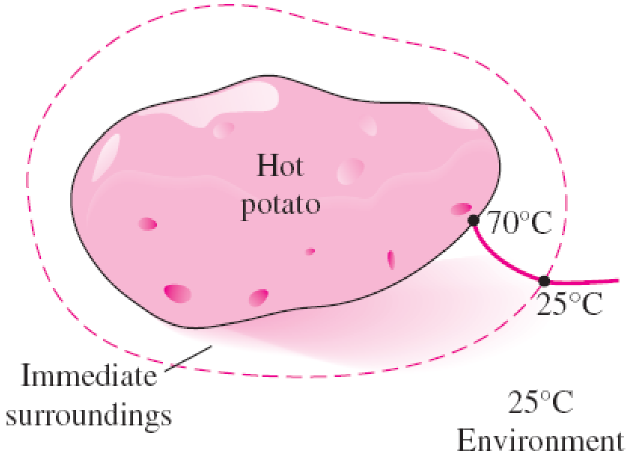
At the dead state, the useful work potential (exergy) of a system is zero.

EXERGY: WORK POTENTIAL OF ENERGY

A *system delivers the maximum possible work as it undergoes a reversible process from the specified initial state to the dead state*.

This represents the *useful work potential* of the system at the specified state and is called **exergy**

Exergy represents the upper limit on the amount of work a device can deliver without violating any thermodynamic laws.



The immediate surroundings of a hot potato are simply the temperature gradient zone of the air next to the potato.

Exergy Associated with Kinetic and Potential Energy

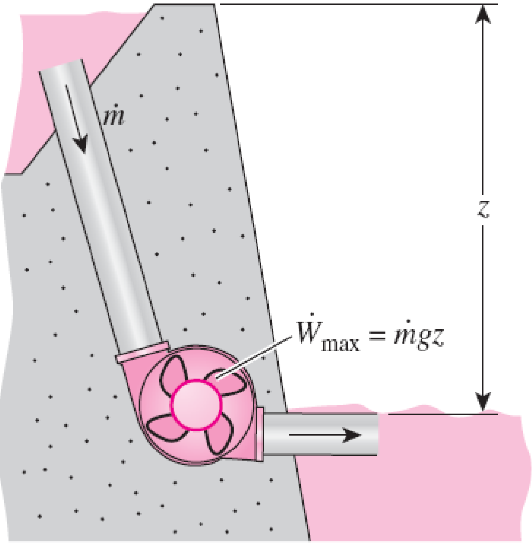
Exergy of kinetic energy:

$$x_{ke} = ke = \frac{V^2}{2} \qquad (kJ/kg)$$

Exergy of potential energy:

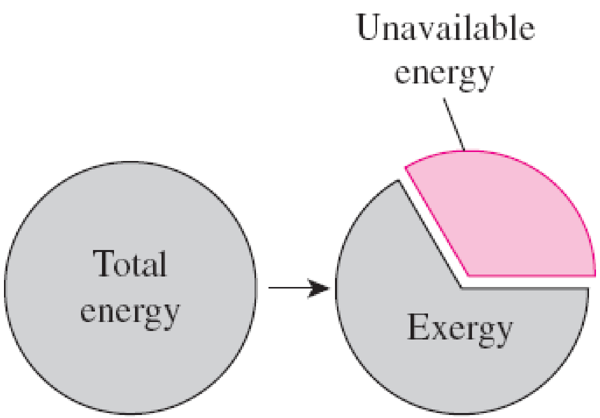
$$x_{pe} = pe = gz \qquad (kJ/kg)$$

The *work potential* or *exergy* of potential energy is equal to the potential energy itself.

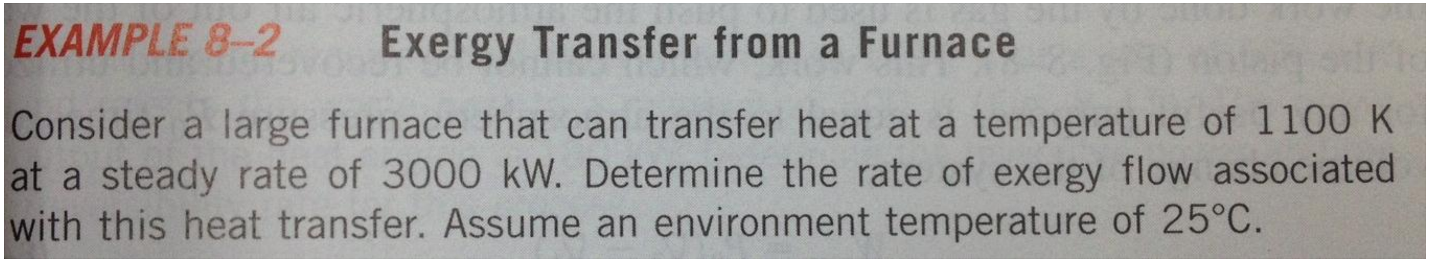


The exergies of kinetic and potential energies are equal to themselves, and they are entirely available for work.

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



Example



EXAMPLE 8–2 Exergy Transfer from a Furnace

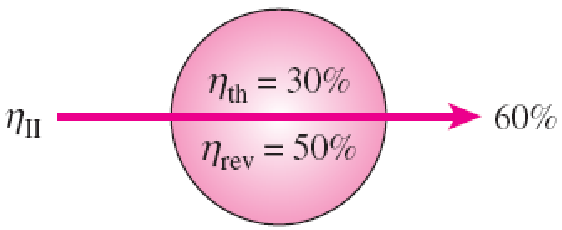
Consider a large furnace that can transfer heat at a temperature of 1100 K at a steady rate of 3000 kW. Determine the rate of exergy flow associated with this heat transfer. Assume an environment temperature of 25°C.

SECOND-LAW EFFICIENCY II

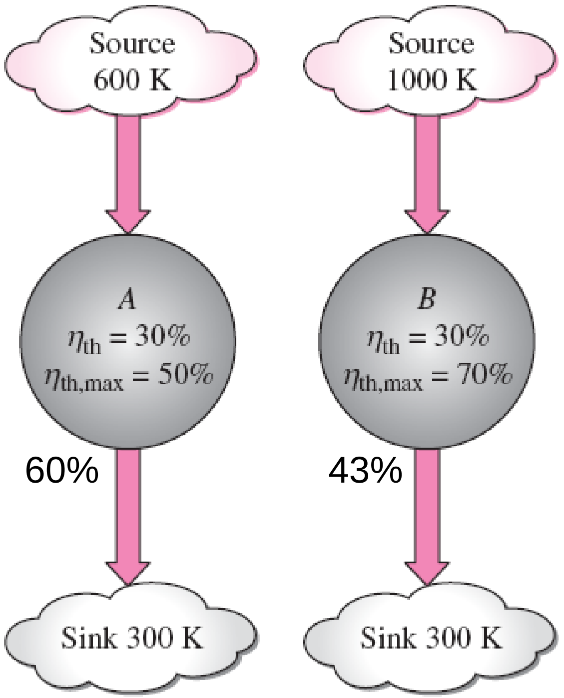
$$\eta_{II} = \frac{\eta_{th}}{\eta_{th,rev}} \qquad \text{(heat engines)}$$

$$\eta_{II} = \frac{W_u}{W_{rev}} \qquad \text{(work-producing devices)}$$

$$\eta_{II} = \frac{COP}{COP_{rev}} \qquad \text{(refrigerators and heat pumps)}$$

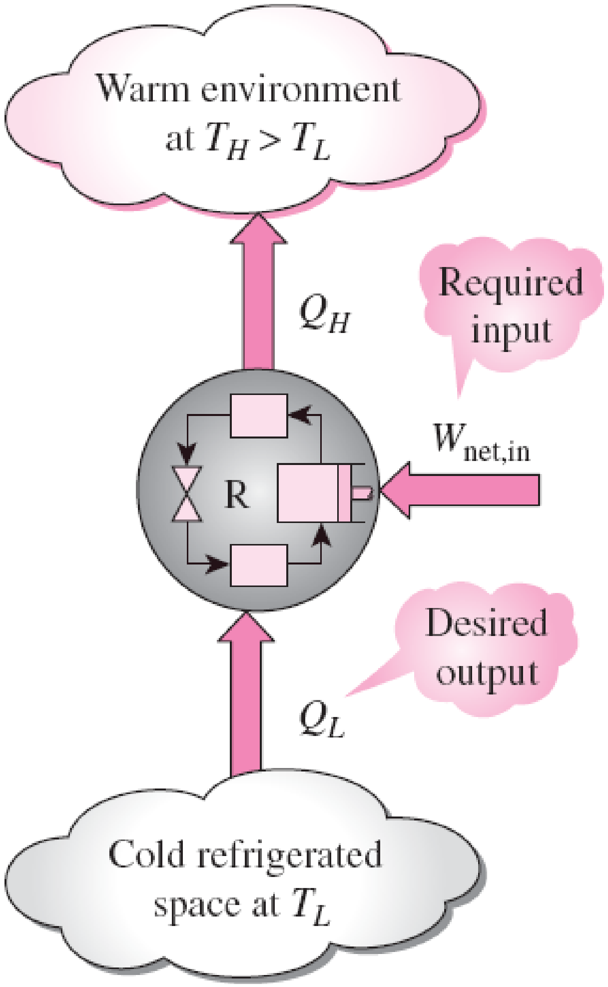


Second-law efficiency is a measure of the performance of a device relative to its performance under reversible conditions.



Two heat engines that have the same thermal efficiency, but different maximum thermal efficiencies.

Review: Coefficient of Performance



The *efficiency* of a refrigerator is expressed in terms of the **coefficient of performance** (COP).

The objective of a refrigerator is to remove heat (Q_L) from the refrigerated space.

$$\mathrm{COP_R} = \frac{\text{Desired output}}{\text{Required input}} = \frac{Q_L}{W_{\text{net,in}}}$$

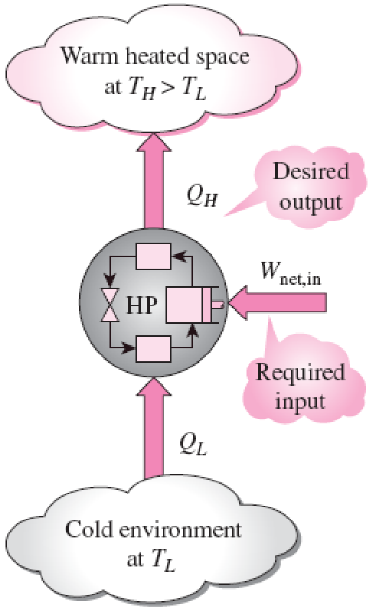
$$W_{\text{net,in}} = Q_H - Q_L \qquad (\text{kJ})$$

$$\mathrm{COP_R} = \frac{Q_L}{Q_H - Q_L} = \frac{1}{Q_H/Q_L - 1}$$

Can the value of $\mathrm{COP_R}$ be greater than unity?

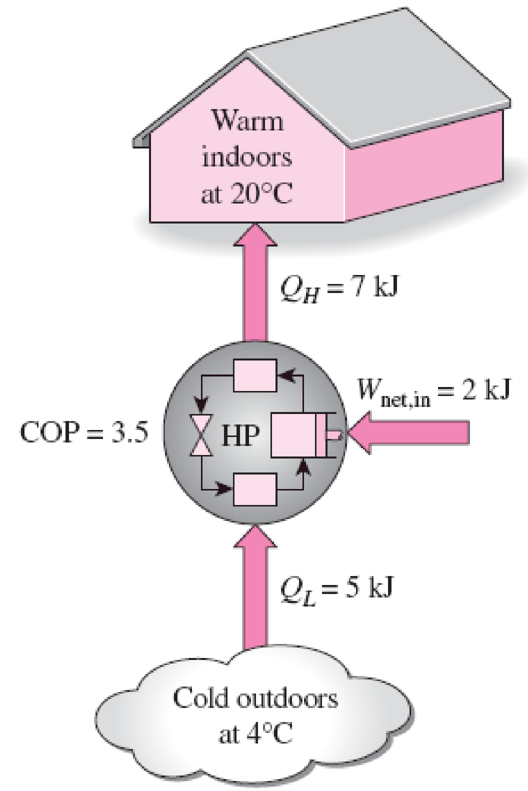
The objective of a refrigerator is to remove Q_L from the cooled space.

Review: Heat Pump



The objective of a heat pump is to supply heat Q_H into the warmer space.

The work supplied to a heat pump is used to extract energy from the cold outdoors and carry it into the warm indoors.



$$\text{COP}_{\text{HP}} = \frac{\text{Desired output}}{\text{Required input}} = \frac{Q_H}{W_{\text{net,in}}}$$

$$\text{COP}_{\text{HP}} = \frac{Q_H}{Q_H - Q_L} = \frac{1}{1 - Q_L/Q_H}$$

$\text{COP}_{\text{HP}} = \text{COP}_{\text{R}} + 1$ for fixed values of Q_L and Q_H

Example

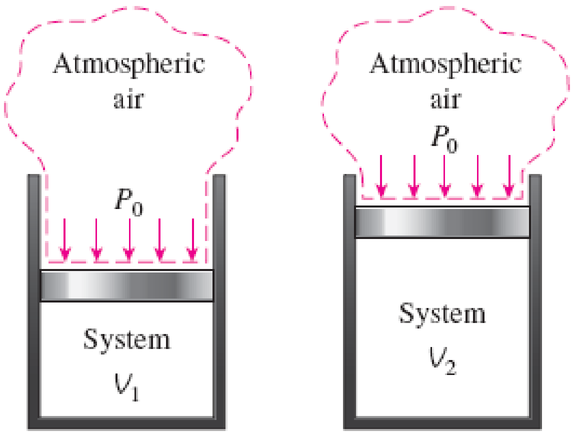
EXAMPLE 8–6 Second-Law Efficiency of Resistance Heaters

A dealer advertises that he has just received a shipment of electric resistance heaters for residential buildings that have an efficiency of 100 percent (Fig. 8–19). Assuming an indoor temperature of 21°C and outdoor temperature of 10°C, determine the second-law efficiency of these heaters.

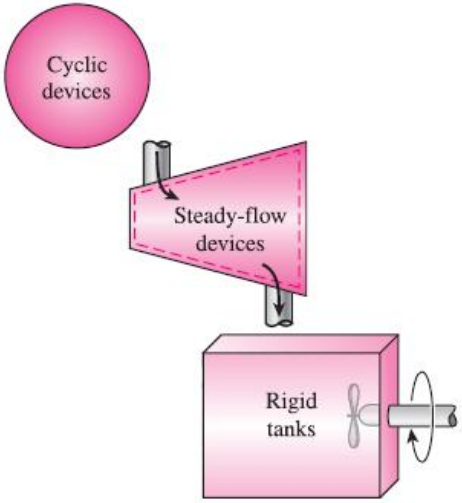
REVERSIBLE WORK AND IRREVERSIBILITY

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

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

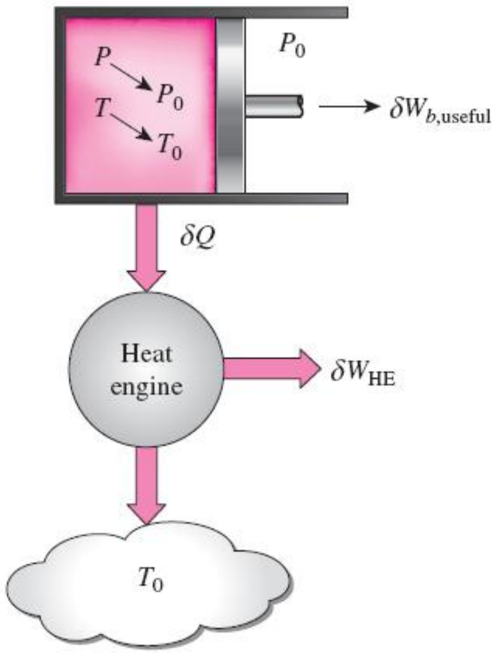


As a closed system expands, some work needs to be done to push the atmospheric air out of the way (W_{surr}).



For constant-volume systems, the total actual and useful works are identical ($W_u = W$).

EXERGY CHANGE OF A SYSTEM



The *exergy* of a specified mass at a specified state is the useful work that can be produced as the mass undergoes a reversible process to the state of the environment.

Exergy of a Fixed Mass: Nonflow (or Closed System) Exergy

e.g. piston-cylinder with T, P, V, U, S

$$\underbrace{\delta E_{\text{in}} - \delta E_{\text{out}}}_{\substack{\text{Net energy transfer} \\ \text{by heat, work, and mass}}} = \underbrace{dE_{\text{system}}}_{\substack{\text{Change in internal, kinetic,} \\ \text{potential, etc., energies}}}$$

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

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

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

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

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

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

Exergy of a closed system

EXERGY CHANGE OF A SYSTEM

$$\phi = (u - u_0) + P_0(v - v_0) - T_0(s - s_0) + \frac{V^2}{2} + gz$$
$$= (e - e_0) + P_0(v - v_0) - T_0(s - s_0)$$

Closed system exergy per unit mass

$$\Delta X = X_2 - X_1 = m(\phi_2 - \phi_1) = (E_2 - E_1) + P_0(V_2 - V_1) - T_0(S_2 - S_1)$$
$$= (U_2 - U_1) + P_0(V_2 - V_1) - T_0(S_2 - S_1) + m\frac{V_2^2 - V_1^2}{2} + mg(z_2 - z_1)$$

$$\Delta\phi = \phi_2 - \phi_1 = (u_2 - u_1) + P_0(v_2 - v_1) - T_0(s_2 - s_1) + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1)$$
$$= (e_2 - e_1) + P_0(v_2 - v_1) - T_0(s_2 - s_1)$$

Exergy change of a closed system

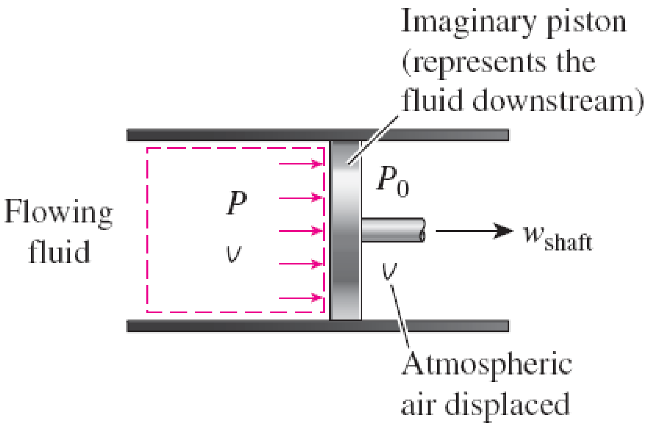
When the properties of a system are not uniform, the exergy of the system is

$$X_{\text{system}} = \int \phi\, \delta m = \int_V \phi\rho\, dV$$

EXERGY CHANGE OF A SYSTEM

Exergy of a Flow Stream: Flow (or Stream) Exergy

The *exergy* associated with *flow energy* is the useful work that would be delivered by an imaginary piston in the flow section.



$$P v = P_0 v + w_{shaft}$$

Exergy of flow energy

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

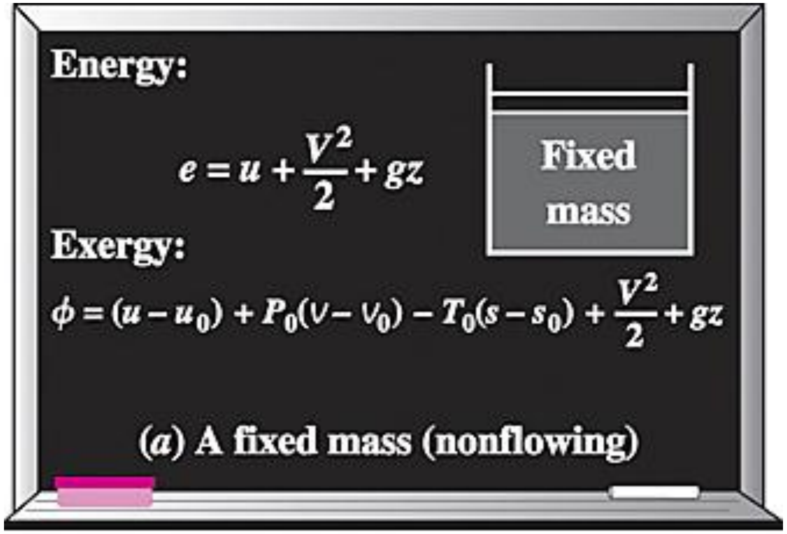
EXERGY CHANGE OF A SYSTEM

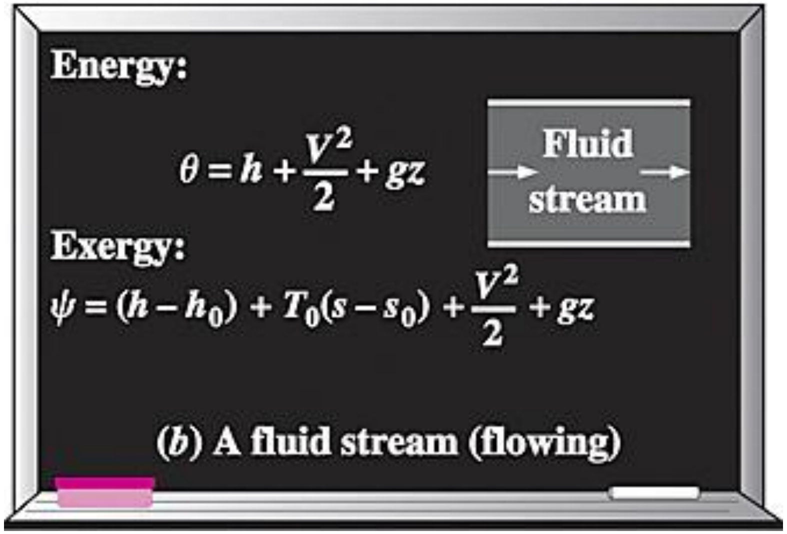
$$
\begin{aligned}
x_{\text{flowing fluid}} &= x_{\text{nonflowing fluid}} + x_{\text{flow}} \\
&= (u - u_0) + P_0(v - v_0) - T_0(s - s_0) + \frac{V^2}{2} + gz + (P - P_0)v \\
&= (u + Pv) - (u_0 + P_0v_0) - T_0(s - s_0) + \frac{V^2}{2} + gz \\
&= (h - h_0) - T_0(s - s_0) + \frac{V^2}{2} + gz
\end{aligned}
$$

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

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

EXERGY CHANGE OF A SYSTEM



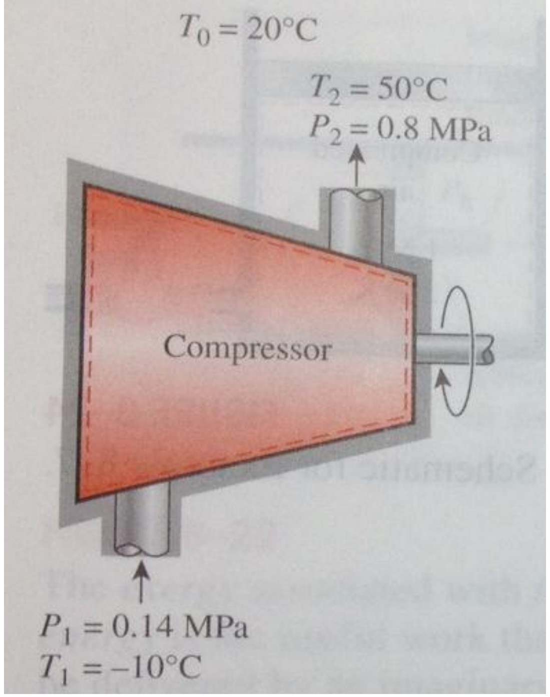


The *energy* and *exergy* contents of
(*a*) a fixed mass
(*b*) a fluid stream.

Example

EXAMPLE 8–8 Exergy Change During a Compression Process

Refrigerant-134a is to be compressed from 0.14 MPa and −10°C to 0.8 MPa and 50°C steadily by a compressor. Taking the environment conditions to be 20°C 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.



EXERGY TRANSFER BY HEAT, WORK, AND MASS

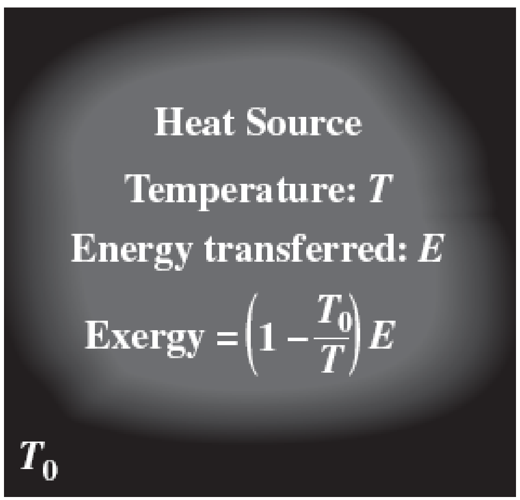
Exergy by Heat Transfer, *Q*

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

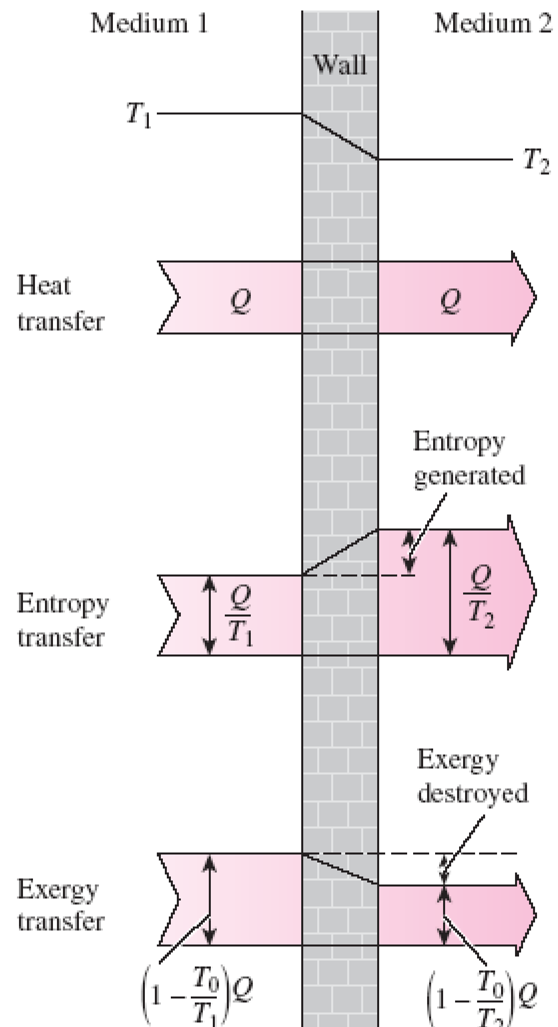
Exergy transfer by heat when T=constant

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

When temperature is not constant



The transfer and destruction of exergy during a heat transfer process through a finite temperature difference.



The Carnot efficiency $\eta_c = 1 - T_0/T$ represents the fraction of the energy transferred from a heat source at temperature T that can be converted to work in an environment at temperature T_0.

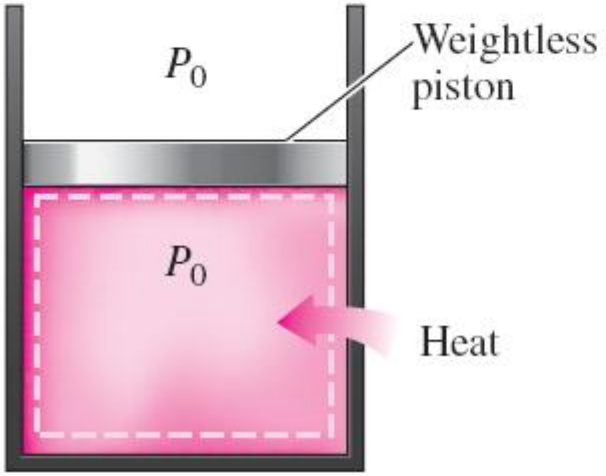
EXERGY TRANSFER BY HEAT, WORK, AND MASS

Exergy Transfer by Work, *W*

$$X_{work} = \begin{cases} W - W_{surr} & \text{(for boundary work)} \\ W & \text{(for other forms of work)} \end{cases}$$

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

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



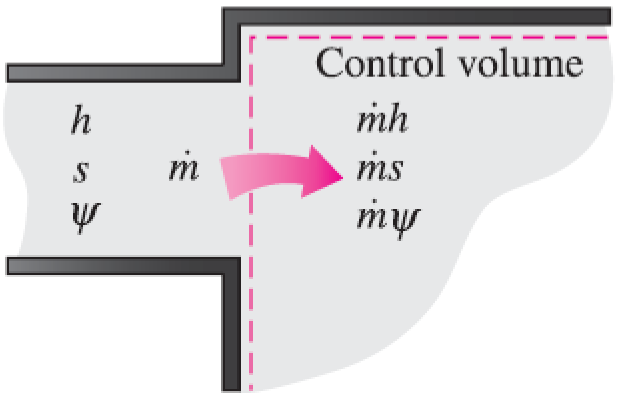
There is no useful work transfer associated with boundary work when the pressure of the system is maintained constant at atmospheric pressure.

EXERGY TRANSFER BY HEAT, WORK, AND MASS

Exergy Transfer by Mass, *m*

$$X_{\text{mass}} = m\psi \qquad \psi = (h - h_0) - T_0(s - s_0) + \frac{V^2}{2} + gz$$

$$\dot{X}_{\text{mass}} = \int_{A_c} \psi \rho V_n \, dA_c \qquad X_{\text{mass}} = \int \psi \, \delta m = \int_{\Delta t} \dot{X}_{\text{mass}} \, dt$$



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

THE DECREASE OF EXERGY PRINCIPLE AND EXERGY DESTRUCTION

Isolated system

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

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

Multiplying the second relation by T_0 and subtracting it from the first one gives

$$-T_0 S_{\text{gen}} = E_2 - E_1 - T_0(S_2 - S_1) \tag{8–29}$$

From Eq. 8–17 we have

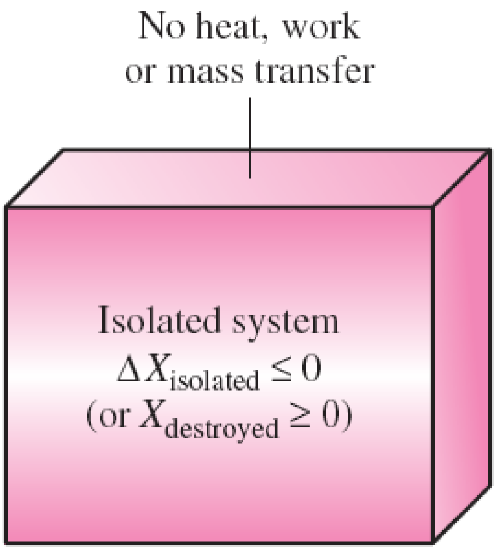
$$\begin{aligned} X_2 - X_1 &= (E_2 - E_1) + P_0\cancelto{0}{(V_2 - V_1)} - T_0(S_2 - S_1) \\ &= (E_2 - E_1) - T_0(S_2 - S_1) \end{aligned} \tag{8–30}$$

since $V_2 = V_1$ for an isolated system (it cannot involve any moving boundary and thus any boundary work). Combining Eqs. 8–29 and 8–30 gives

$$-T_0 S_{\text{gen}} = X_2 - X_1 \leq 0 \tag{8–31}$$

since T_0 is the thermodynamic temperature of the environment and thus a positive quantity, $S_{\text{gen}} \geq 0$, and thus $T_0 S_{\text{gen}} \geq 0$. Then we conclude that

$$\Delta X_{\text{isolated}} = (X_2 - X_1)_{\text{isolated}} \leq 0 \tag{8–32}$$



The isolated system considered in the development of the 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. In other words, it *never* increases and *exergy is destroyed* during an actual process. This is known as the **decrease of exergy principle**.

THE DECREASE OF EXERGY PRINCIPLE AND EXERGY DESTRUCTION

Exergy Destruction

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

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

Exergy destroyed is a *positive quantity* for any actual process and becomes *zero* for a reversible process.

Exergy destroyed represents the lost work potential and is also called the *irreversibility* or *lost work.*