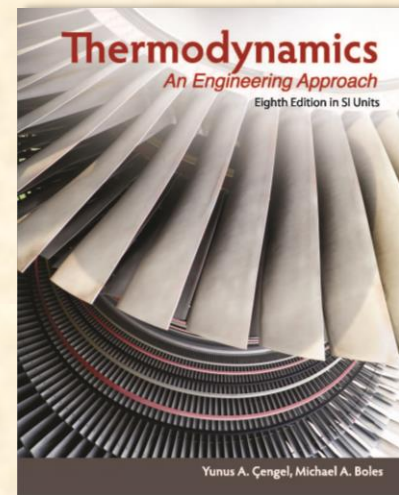**Thermodynamics: An Engineering Approach**
8th Edition in SI Units
Yunus A. Çengel, Michael A. Boles
McGraw-Hill, 2015

CHAPTER 8
EXERGY

Lecture slides by

Mehmet Kanoglu

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*.

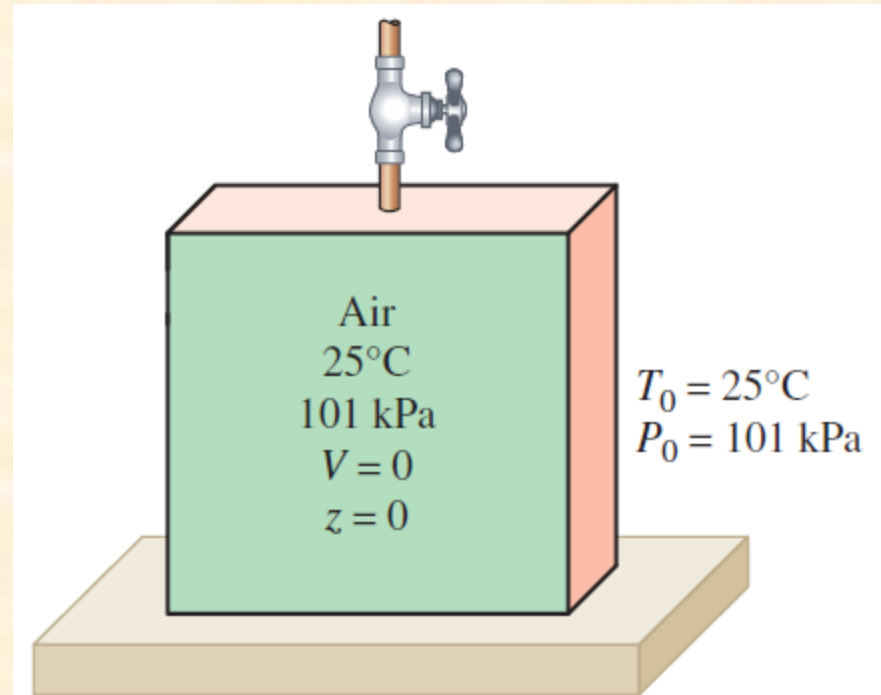A system is said to be in the dead state when it is in thermodynamic equilibrium with the environment it is in.

Air
25°C
101 kPa
$V = 0$
$z = 0$

$T_0 = 25°C$
$P_0 = 101$ kPa

FIGURE 8–1

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

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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.*

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.

FIGURE 8–3

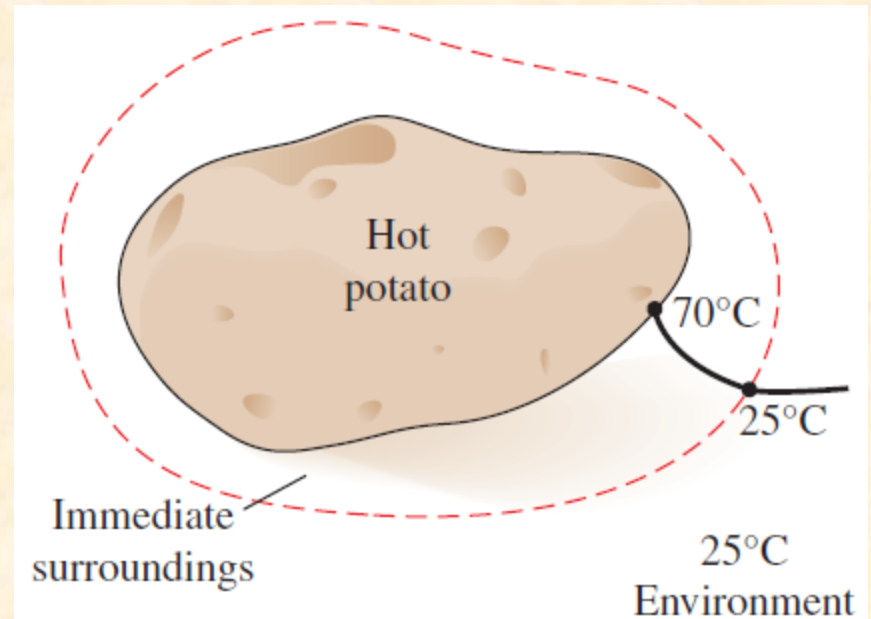The atmosphere contains a tremendous amount of energy, but no exergy.

Hot potato

70°C

25°C

Immediate surroundings

25°C Environment

FIGURE 8–2

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

Exergy (Work Potential) Associated with Kinetic and Potential Energy

Exergy of kinetic energy:

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

Exergy of potential energy:
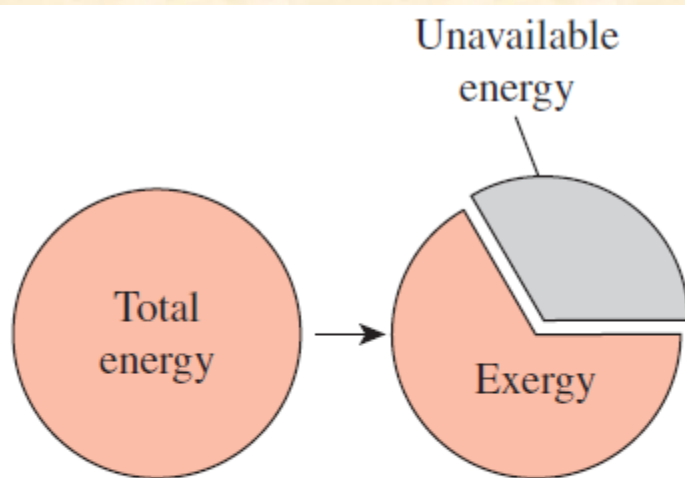
$$x_{ke} = ke = \frac{V^2}{2} \qquad (kJ/kg)$$

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

FIGURE 8–6

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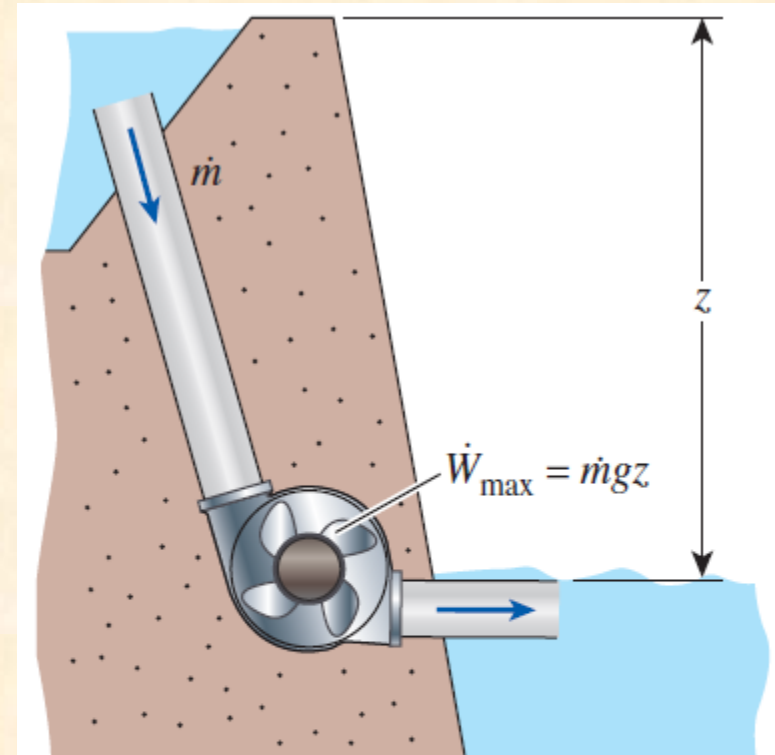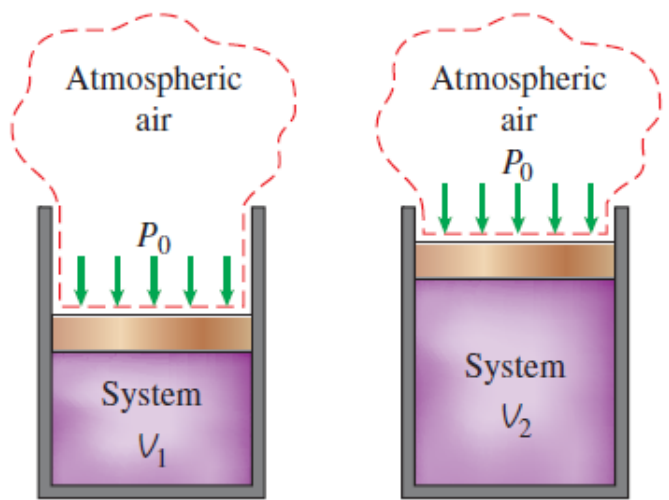

$$\dot{W}_{max} = \dot{m}gz$$

FIGURE 8–4

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

REVERSIBLE WORK AND IRREVERSIBILITY

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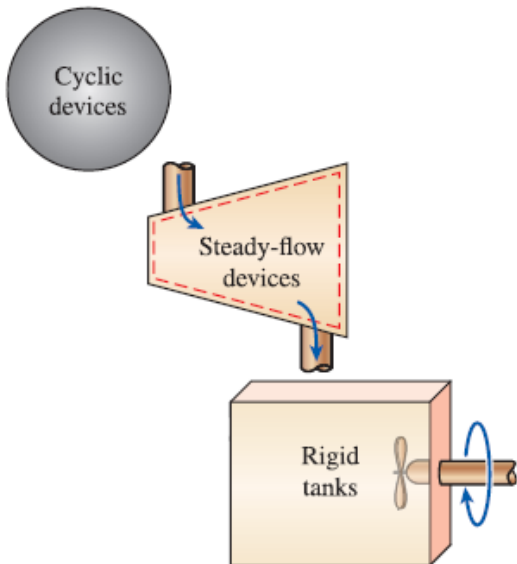
$$W_u = W - W_{surr} = W - P_0(V_2 - V_1)$$

Reversible work W_{rev}: *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.*
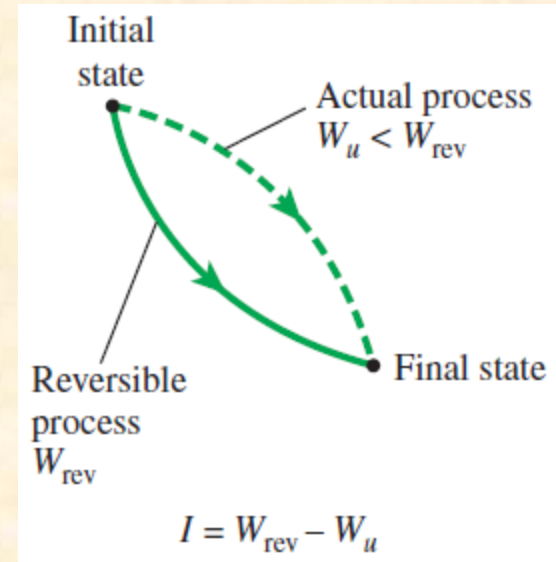
$$I = W_{rev,out} - W_{u,out}$$

$$I = W_{u,in} - W_{rev,in}$$

Atmospheric air
P_0
System
V_1

Atmospheric air
P_0
System
V_2

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

The difference between reversible work and actual useful work is the irreversibility.

Initial state
Actual process $W_u < W_{rev}$
Final state
Reversible process W_{rev}

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

Cyclic devices

Steady-flow devices

Rigid tanks

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

Source 1200 K

$\dot{Q}_{in} = 500$ kJ/s

$\dot{W} = 180$ kW

HE

Sink 300 K

The Rate of Irreversibility of a Heat Engine
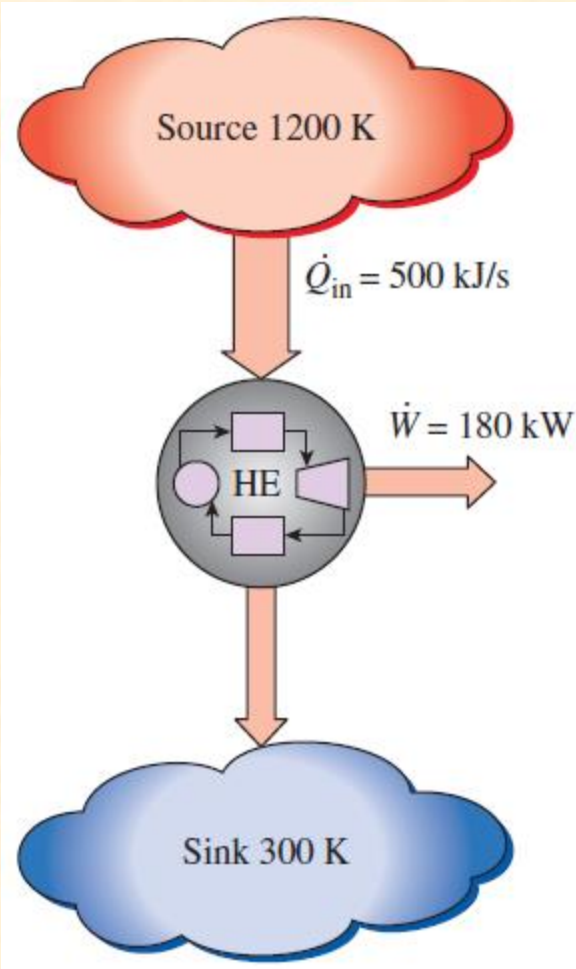
$$\dot{W}_{rev,out} = \eta_{th,rev}\,\dot{Q}_{in} = \left(1 - \frac{T_{sink}}{T_{source}}\right)\dot{Q}_{in}$$

$$= \left(1 - \frac{300\text{ K}}{1200\text{ K}}\right)(500\text{ kW}) = \mathbf{375\text{ kW}}$$

$$\dot{I} = \dot{W}_{rev,out} - \dot{W}_{u,out} = 375 - 180 = \mathbf{195\text{ kW}}$$
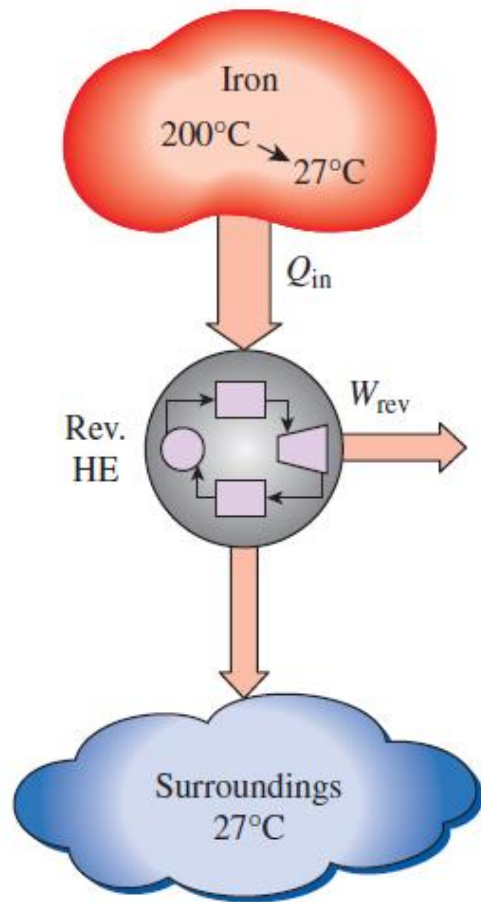
Irreversibility during the Cooling of an Iron Block

FIGURE 8–12

An irreversible heat transfer process can be made reversible by the use of a reversible heat engine.

$$\delta W_{rev} = \eta_{th,rev}\, \delta Q_{in} = \left(1 - \frac{T_{sink}}{T_{source}}\right)\delta Q_{in} = \left(1 - \frac{T_0}{T}\right)\delta Q_{in}$$

$$W_{rev} = \int\left(1 - \frac{T_0}{T}\right)\delta Q_{in}$$
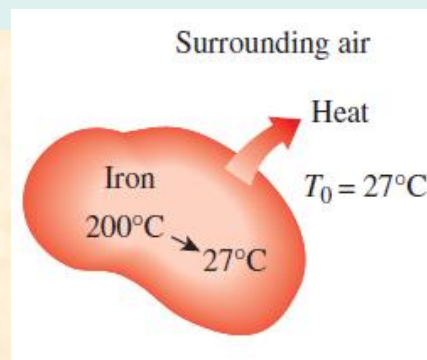
$$\underbrace{\delta E_{in} - \delta E_{out}}_{\substack{\text{Net energy transfer} \\ \text{by heat, work, and mass}}} = \underbrace{dE_{system}}_{\substack{\text{Change in internal, kinetic,} \\ \text{potential, etc., energies}}}$$

$$-\delta Q_{out} = dU = mc_{avg}\,dT$$

$$\delta Q_{in,heat\ engine} = \delta Q_{out,system} = -mc_{avg}\,dT$$

$$W_{rev} = \int_{T_1}^{T_0}\left(1 - \frac{T_0}{T}\right)(-mc_{avg}\,dT) = mc_{avg}(T_1 - T_0) - mc_{avg}\,T_0\,\ln\frac{T_1}{T_0}$$

$$= (500\ kg)(0.45\ kJ/kg\cdot K)\left[(473 - 300)\ K - (300\ K)\ln\frac{473\ K}{300\ K}\right]$$

$$= \mathbf{8191\ kJ}$$

SECOND-LAW EFFICIENCY

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

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

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

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

η_{II} → $\eta_{th} = 30\%$, $\eta_{rev} = 50\%$ → 60%

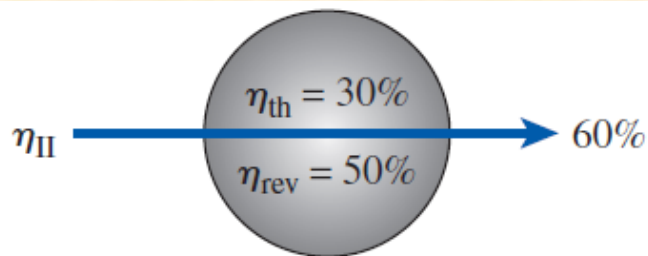## FIGURE 8–15

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

Source 600 K

Source 1000 K

A
$\eta_{th} = 30\%$
$\eta_{th,max} = 50\%$

B
$\eta_{th} = 30\%$
$\eta_{th,max} = 70\%$

Sink 300 K

Sink 300 K
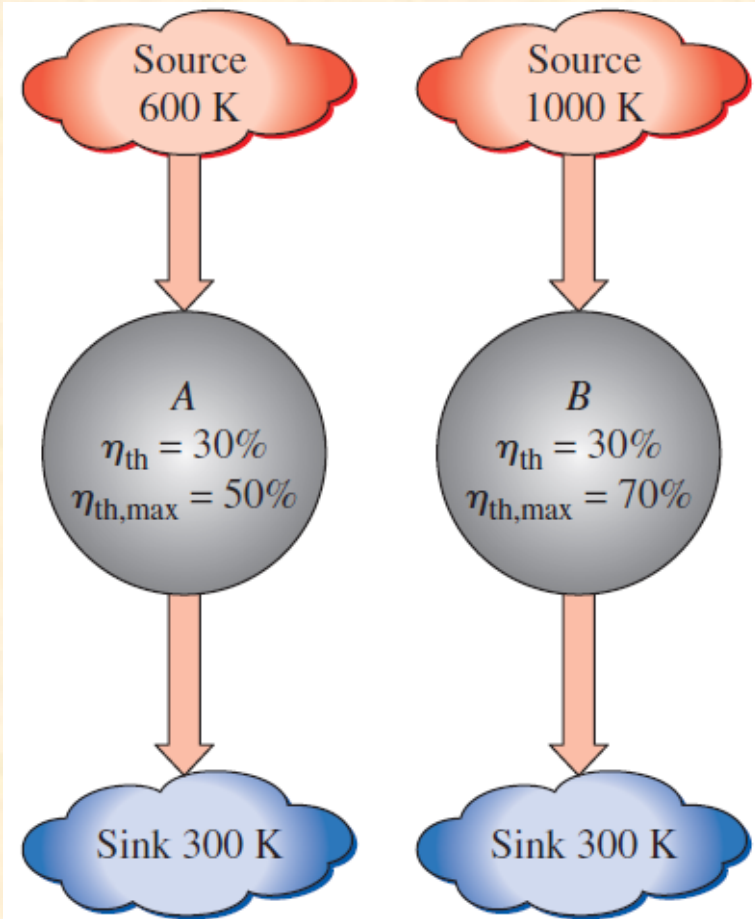
FIGURE 8–14

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

FIGURE 8–16
Second-law efficiency of all reversible
devices is 100 percent.

General definition of exergy efficiency:

$$\eta_{II} = \frac{\text{Exergy recovered}}{\text{Exergy expended}} = 1 - \frac{\text{Exergy destroyed}}{\text{Exergy expended}}$$
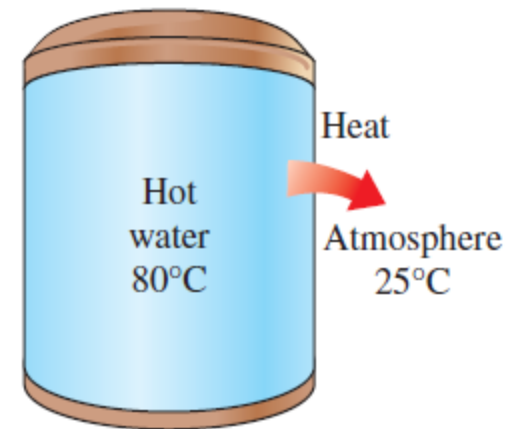
FIGURE 8–17
The second-law efficiency of naturally
occurring processes is zero if none of
the work potential is recovered.

Second-Law Efficiency of Resistance Heaters

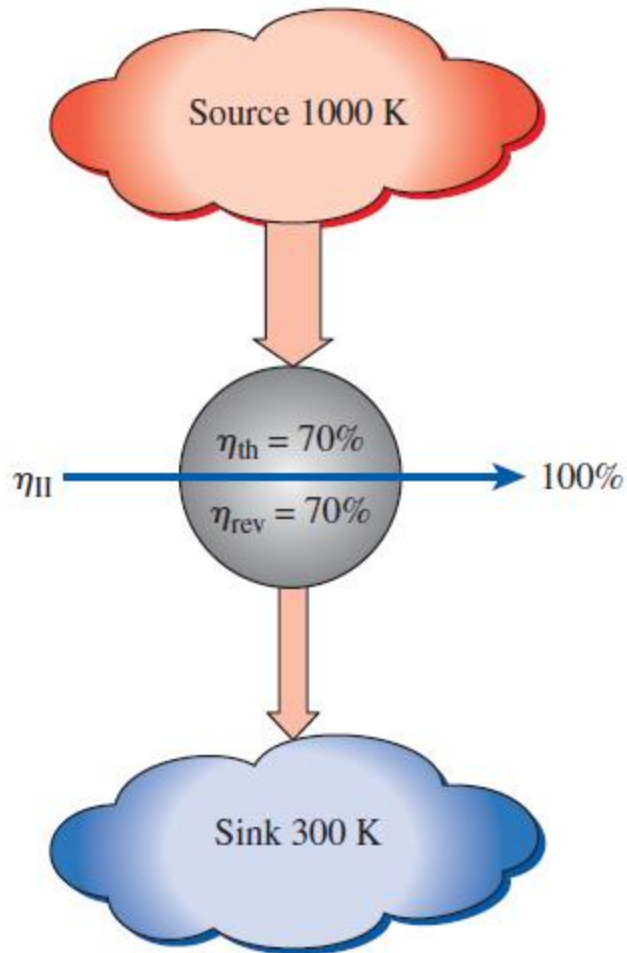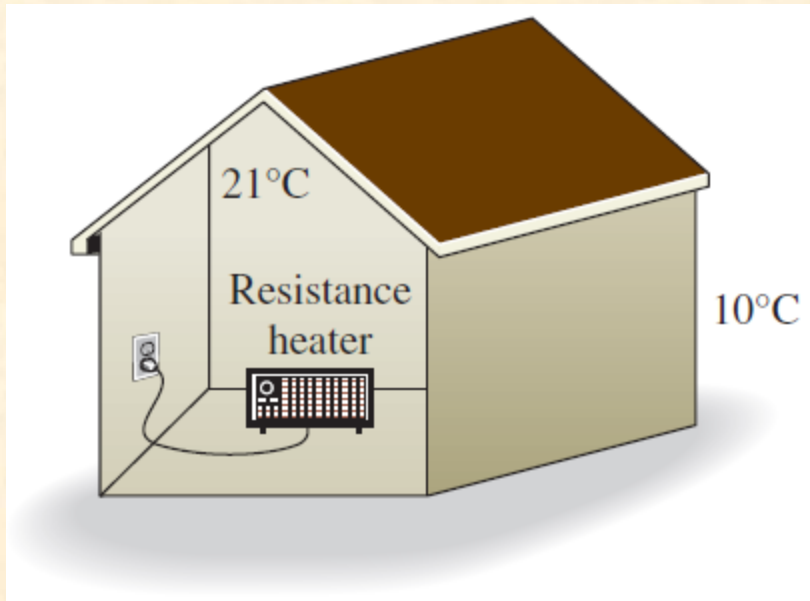$$\eta_{\text{II,electric heater}} = \frac{\dot{X}_{\text{recovered}}}{\dot{X}_{\text{expended}}} = \frac{\dot{X}_{\text{heat}}}{\dot{W}_e}$$

$$\dot{Q}_e = \dot{W}_e$$

$$= \frac{\dot{Q}_e(1 - T_0/T_H)}{\dot{W}_e} = 1 - \frac{T_0}{T_H}$$

$$\text{COP}_{\text{HP,rev}} = \frac{1}{1 - T_L/T_H} = \frac{1}{1 - (10 + 273 \text{ K})/(21 + 273 \text{ K})} = 26.7$$

$$\eta_{\text{II}} = \frac{\text{COP}}{\text{COP}_{\text{rev}}} = \frac{1.0}{26.7} = \mathbf{0.037} \text{ or } \mathbf{3.7\%}$$

$$\eta_{\text{II,electric heater}} = 1 - \frac{T_0}{T_H} = 1 - \frac{(10 + 273)\text{K}}{(21 + 273)\text{K}} = 0.037 \text{ or } 3.7\%$$

EXERGY CHANGE OF A SYSTEM

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

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

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

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

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

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

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

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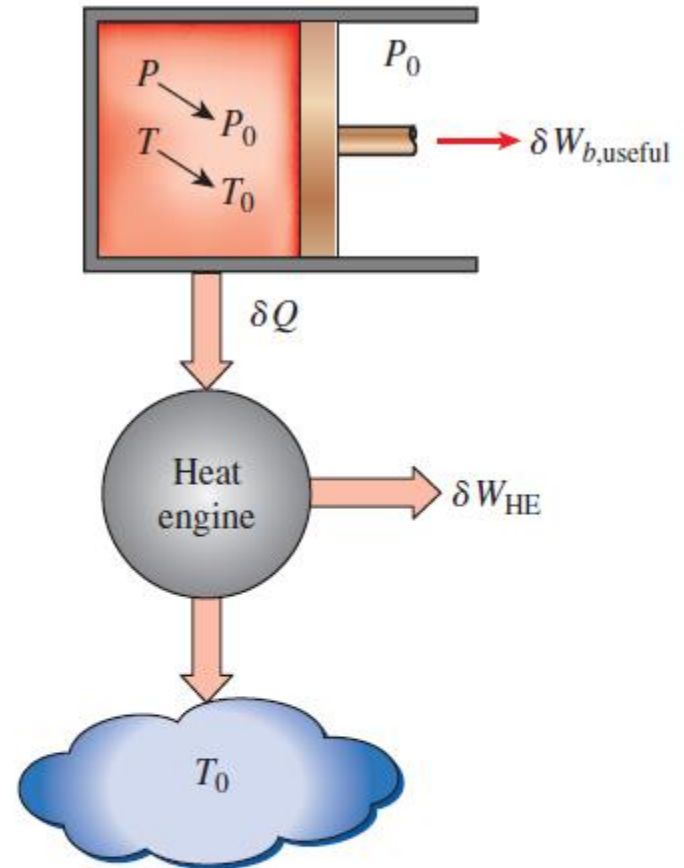
Exergy of a closed system

FIGURE 8–19

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.

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

Closed system exergy per unit mass

$$= (e - e_0) + P_0(v - v_0) - T_0(s - s_0)$$

$$\Delta X = X_2 - X_1 = m(\phi_2 - \phi_1) = (E_2 - E_1) + P_0(V_2 - V_1) - T_0(S_2 - S_1)$$

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

Exergy change of a closed system

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

$$= (e_2 - e_1) + P_0(v_2 - v_1) - T_0(s_2 - s_1)$$

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

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

Atmosphere
$T_0 = 25°C$

Heat engine

Work output

Cold medium
$T = 3°C$

FIGURE 8–20

The *exergy* of a cold medium is also a *positive* quantity since work can be produced by transferring heat to it.
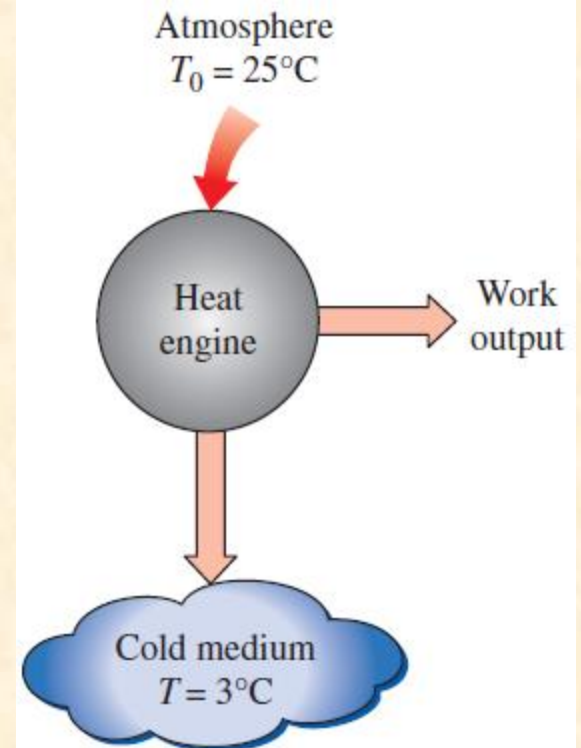
Exergy of a Flow Stream: Flow (or Stream) Exergy

$$x_{\text{flowing fluid}} = x_{\text{nonflowing fluid}} + x_{\text{flow}}$$

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

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

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

Exergy of flow energy

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

Flow exergy

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

Exergy change of flow

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

Imaginary piston (represents the fluid downstream)

P_0

Flowing fluid

P

v

w_{shaft}

v

Atmospheric air displaced

$Pv = P_0 v + w_{\text{shaft}}$
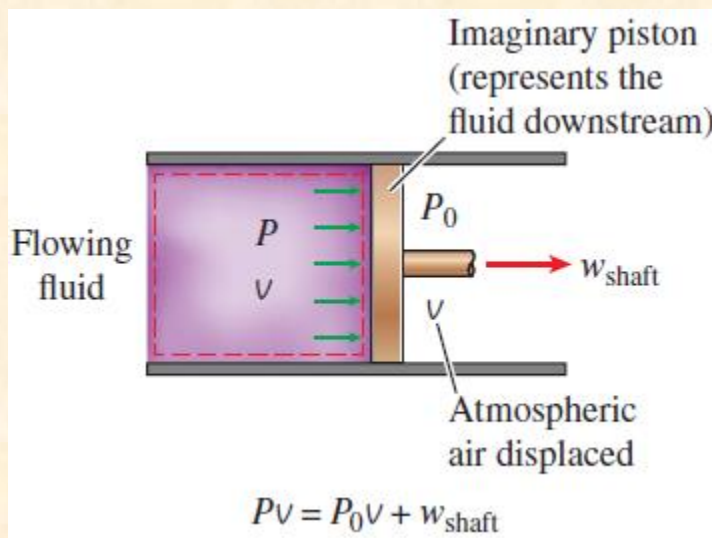
FIGURE 8–21

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

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Energy:

$$e = u + \frac{V^2}{2} + gz$$

Fixed mass

Exergy:

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

(a) A fixed mass (nonflowing)

Energy:

$$\theta = h + \frac{V^2}{2} + gz$$

Fluid stream

Exergy:

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

(b) A fluid stream (flowing)

FIGURE 8–22

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

Compressed air

1 MPa
300 K

Work Potential of Compressed Air in a Tank
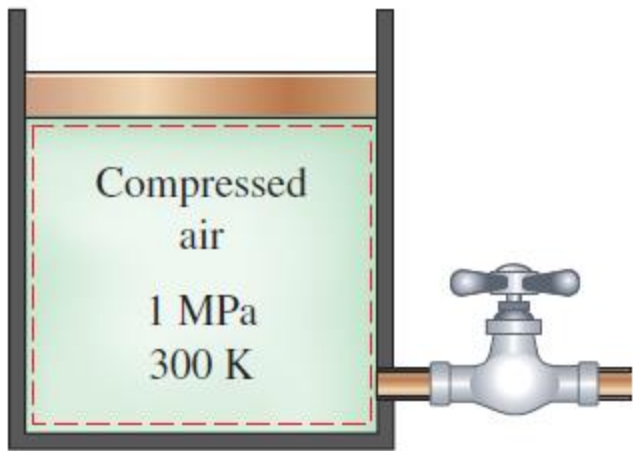
$$X_1 = m\phi_1$$

$$= m\left[(u_1 - u_0)^{\nearrow 0} + P_0(v_1 - v_0) - T_0(s_1 - s_0) + \frac{V_1^2}{2}^{\nearrow 0} + gz_1^{\nearrow 0}\right]$$

$$= m[P_0(v_1 - v_0) - T_0(s_1 - s_0)]$$

$$P_0(v_1 - v_0) = P_0\left(\frac{RT_1}{P_1} - \frac{RT_0}{P_0}\right) = RT_0\left(\frac{P_0}{P_1} - 1\right) \quad \text{(since } T_1 = T_0\text{)}$$

$$T_0(s_1 - s_0) = T_0\left(c_p \ln\frac{T_1}{T_0} - R \ln\frac{P_1}{P_0}\right) = -RT_0 \ln\frac{P_1}{P_0} \quad \text{(since } T_1 = T_0\text{)}$$

$$\phi_1 = RT_0\left(\frac{P_0}{P_1} - 1\right) + RT_0 \ln\frac{P_1}{P_0} = RT_0\left(\ln\frac{P_1}{P_0} + \frac{P_0}{P_1} - 1\right) \qquad X_1 = m_1\phi_1$$

$T_0 = 20°C$

$T_2 = 50°C$
$P_2 = 0.8 \text{ MPa}$

Compressor

$P_1 = 0.14 \text{ MPa}$
$T_1 = -10°C$

Exergy Change During a Compression Process
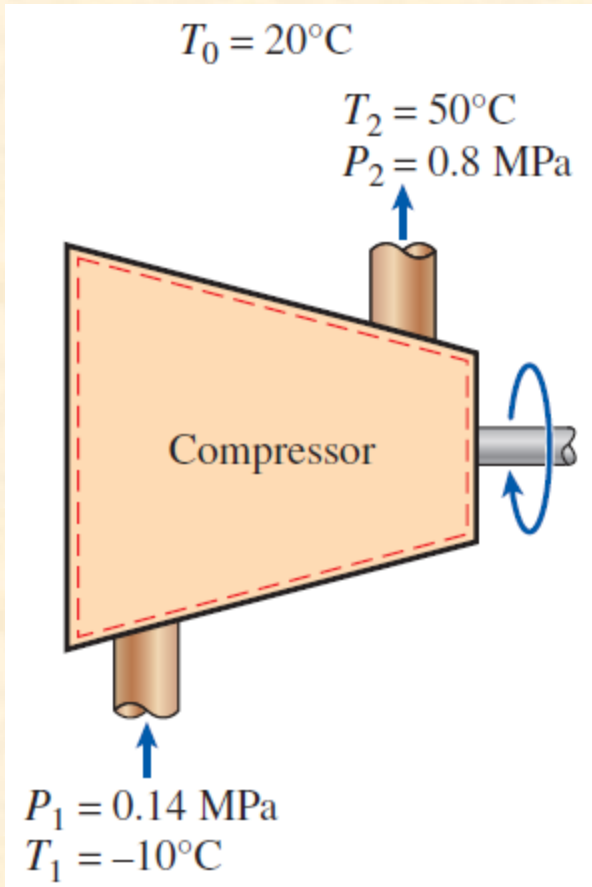
$$w_{in,min} = \psi_2 - \psi_1 = \mathbf{38.0 \ kJ/kg}$$

$$\Delta\psi = \psi_2 - \psi_1 = (h_2 - h_1) - T_0(s_2 - s_1) + \frac{V_2^2 - V_1^2}{2}\nearrow^0 + g(z_2 - z_1)\nearrow^0$$

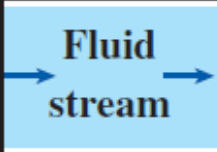$$= (h_2 - h_1) - T_0(s_2 - s_1)$$

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

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

When temperature is not constant

FIGURE 8–25

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.

Heat Source

Temperature: T

Energy transferred: E

Exergy $= \left(1 - \dfrac{T_0}{T}\right) E$

T_0
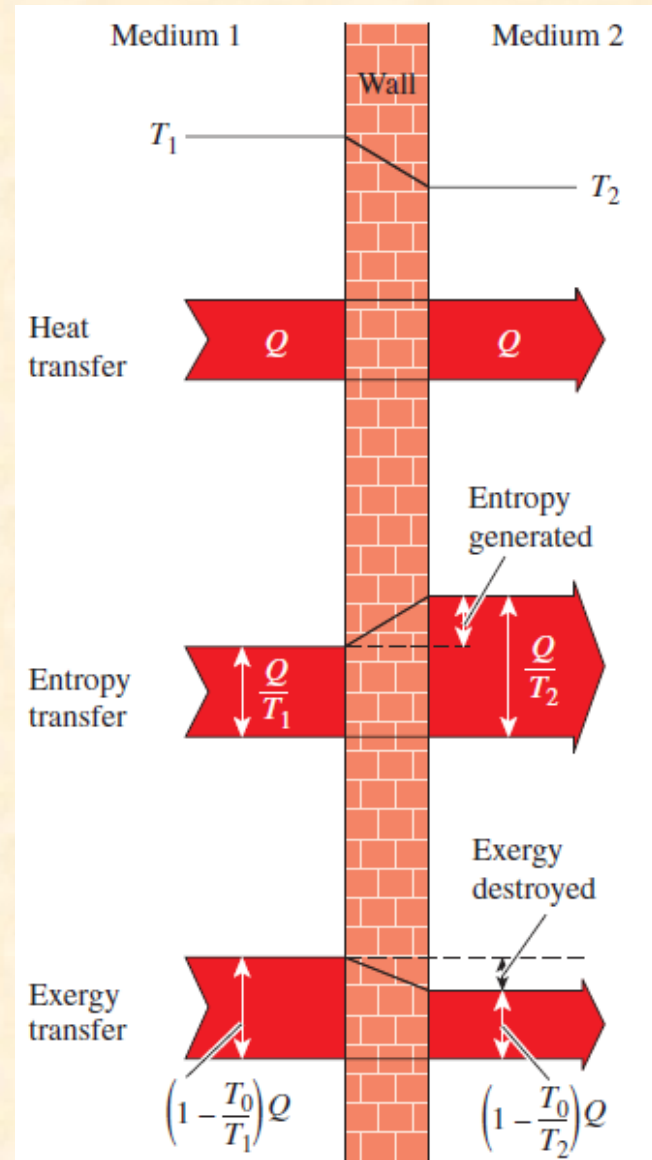
FIGURE 8–26

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

Exergy Transfer by Work, *W*

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

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

Exergy Transfer by Mass, *m*

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

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

FIGURE 8–28

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

FIGURE 8–27

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

THE DECREASE OF EXERGY PRINCIPLE AND EXERGY DESTRUCTION

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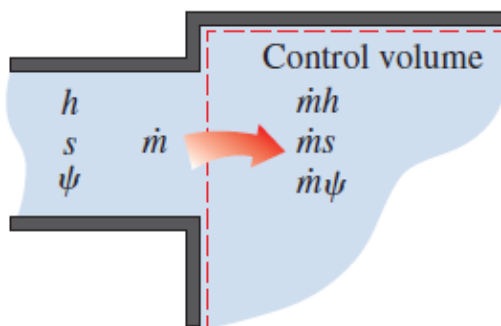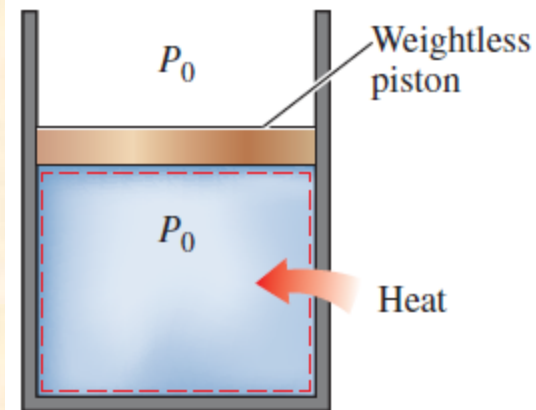$$E_{in}^{\nearrow 0} - E_{out}^{\nearrow 0} = \Delta E_{system} \rightarrow 0 = E_2 - E_1$$

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

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

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

From Eq. 8–17 we have

$$X_2 - X_1 = (E_2 - E_1) + P_0(V_2 - V_1)^{\nearrow 0} - T_0(S_2 - S_1) \qquad (8\text{–}30)$$
$$= (E_2 - E_1) - T_0(S_2 - S_1)$$

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

$$-T_0 S_{gen} = X_2 - X_1 \le 0 \qquad (8\text{–}31)$$

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

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

No heat, work or mass transfer

Isolated system
$\Delta X_{isolated} \le 0$
(or $X_{destroyed} \ge 0$)
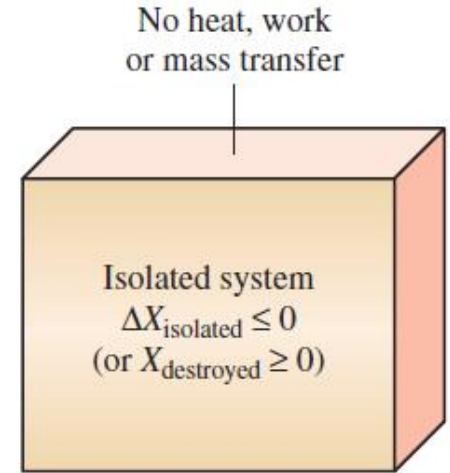
FIGURE 8–29
The isolated system considered in the development of the decrease of exergy principle.

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**.

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*.

Can the exergy change of a system during a process be negative?

Consider heat transfer from a system to its surroundings. How do you compare exergy changes of the system and the surroundings?
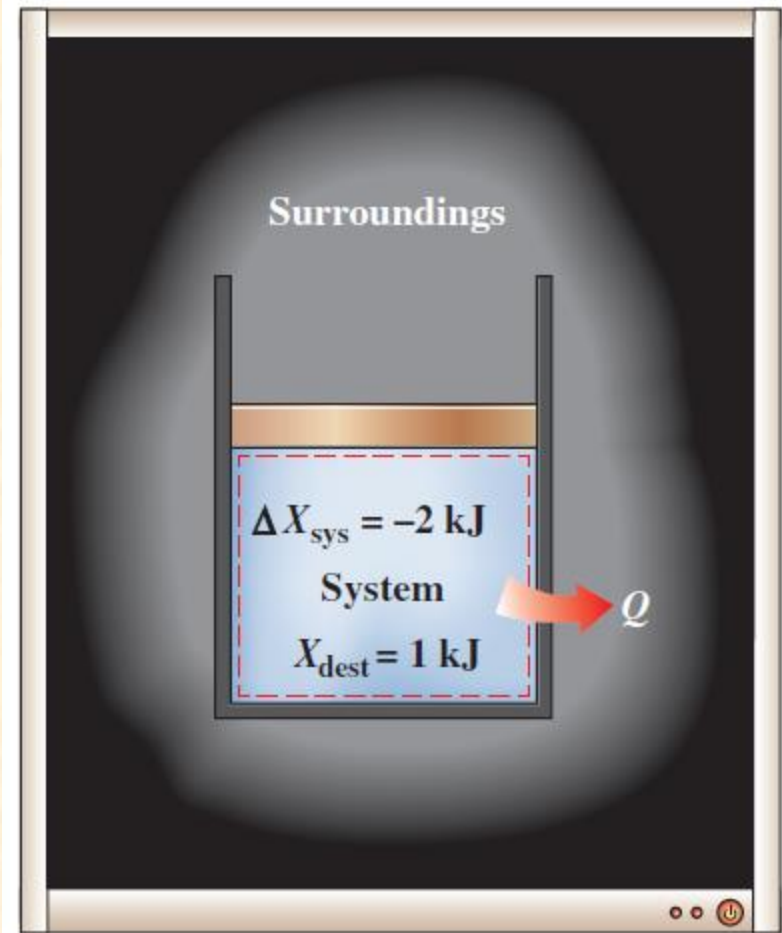
Surroundings

$$\Delta X_{\text{sys}} = -2 \text{ kJ}$$

System

Q

$$X_{\text{dest}} = 1 \text{ kJ}$$

FIGURE 8–30
The exergy change of a system can be negative, but the exergy destruction cannot.

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EXERGY BALANCE: CLOSED SYSTEMS

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

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

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

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

General, unit-mass basis: $\quad (x_{in} - x_{out}) - x_{destroyed} = \Delta x_{system} \quad \text{(kJ/kg)}$

$$X_{destroyed} = T_0 S_{gen} \quad \text{or} \quad \dot{X}_{destroyed} = T_0 \dot{S}_{gen}$$

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.
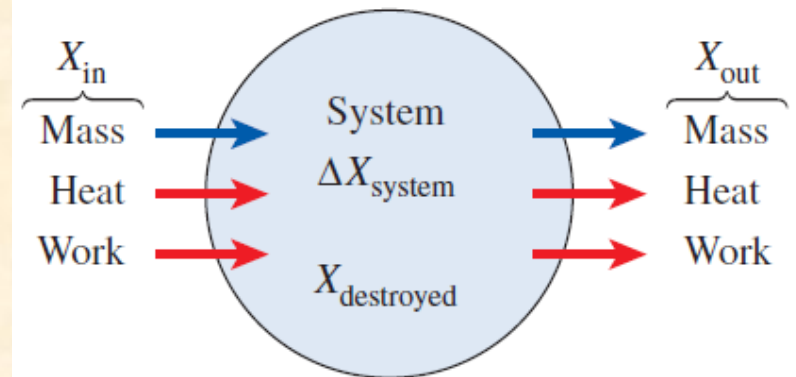

FIGURE 8–31

Mechanisms of exergy transfer.

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

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

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

The heat transfer to a system and work done by the system are taken to be positive quantities.

Q_k is the heat transfer through the boundary at temperature T_k at location *k*.

X_{work}

W

ΔX_{system}
$X_{\text{destroyed}}$

Q

X_{heat}

$$X_{\text{heat}} - X_{\text{work}} - X_{\text{destroyed}} = \Delta X_{\text{system}}$$
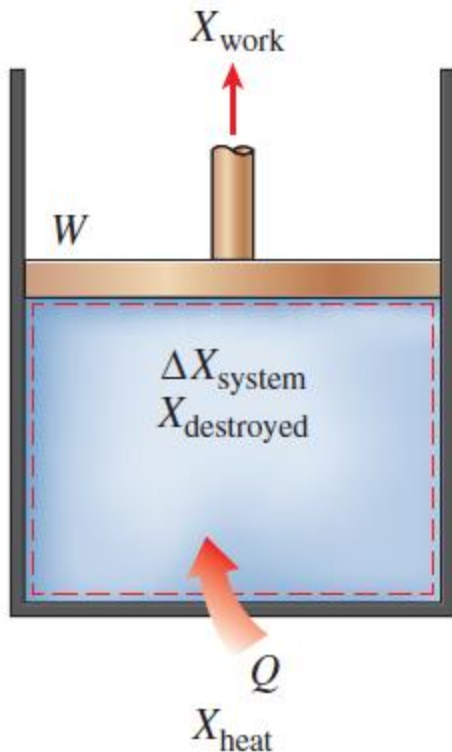
Exergy balance for a closed system when heat transfer is to the system and the work is from the system.

Exergy destroyed outside system boundaries can be accounted for by writing an exergy balance on the extended system that includes the system and its immediate surroundings.

Outer surroundings (environment)
T_0

T_0

Immediate surroundings

System

Q
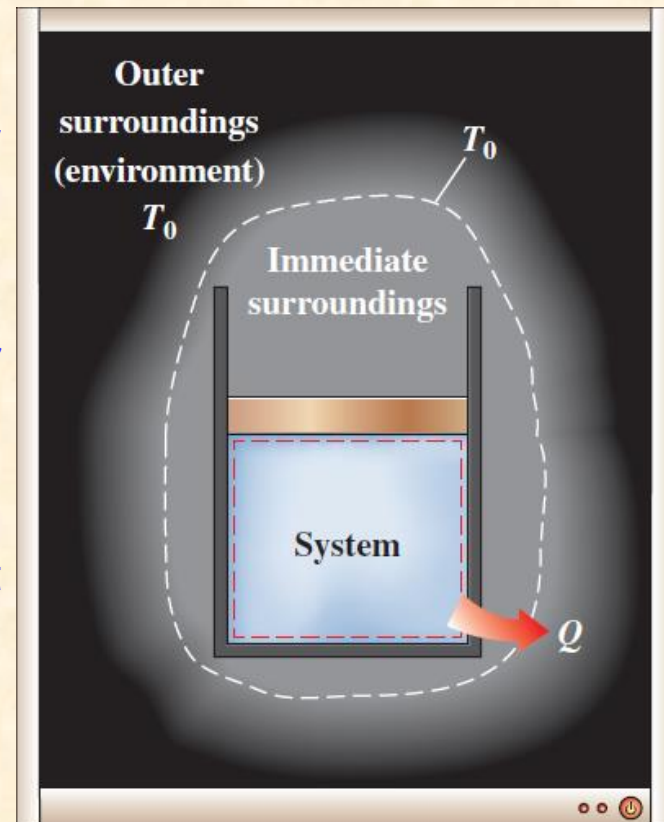
General Exergy Balance for Closed Systems

$$\textit{Energy balance:} \quad E_{\text{in}} - E_{\text{out}} = \Delta E_{\text{system}} \rightarrow Q - W = E_2 - E_1$$

$$\textit{Entropy balance:} \quad S_{\text{in}} - S_{\text{out}} + S_{\text{gen}} = \Delta S_{\text{system}} \rightarrow \int_1^2 \left(\frac{\delta Q}{T}\right)_{\text{boundary}} + S_{\text{gen}} = S_2 - S_1$$
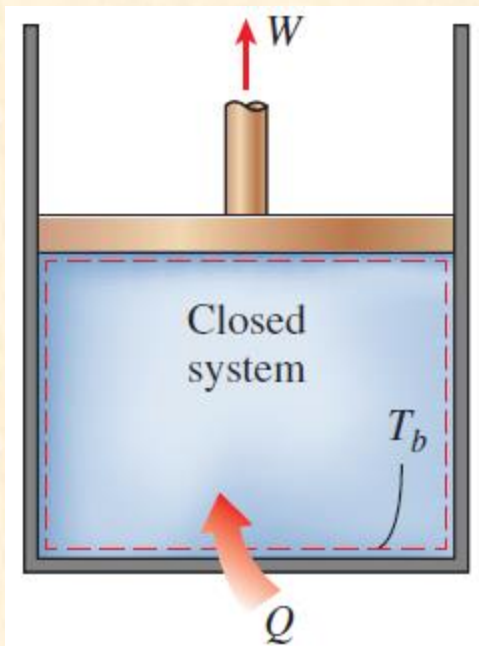
$$Q - T_0 \int_1^2 \left(\frac{\delta Q}{T}\right)_{\text{boundary}} - W - T_0 S_{\text{gen}} = E_2 - E_1 - T_0(S_2 - S_1)$$

$$\int_1^2 \delta Q - T_0 \int_1^2 \left(\frac{\delta Q}{T}\right)_{\text{boundary}} - W - T_0 S_{\text{gen}} = X_2 - X_1 - P_0(V_2 - V_1)$$

$$\int_1^2 \left(1 - \frac{T_0}{T_b}\right) \delta Q - [W - P_0(V_2 - V_1)] - T_0 S_{\text{gen}} = X_2 - X_1$$

W

Closed system

T_b

Q

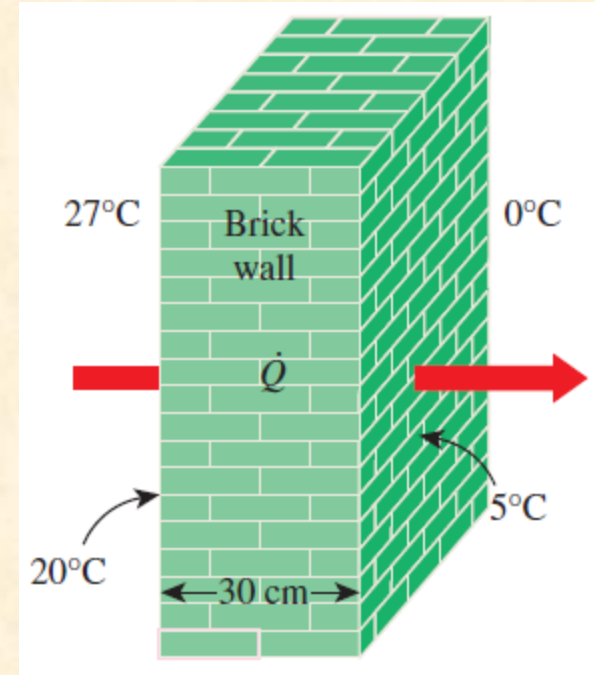# Exergy Destruction during Heat Conduction

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

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

$$(1035 \text{ W})\left(1 - \frac{273 \text{ K}}{293 \text{ K}}\right) - (1035 \text{ W})\left(1 - \frac{273 \text{ K}}{278 \text{ K}}\right) - \dot{X}_{destroyed} = 0$$

$$\dot{X}_{destroyed} = \textbf{52.0 W}$$

27°C Brick wall 0°C

$\dot{Q}$

20°C   5°C

←30 cm→

To determine the rate of total exergy destruction during this heat transfer process, we extend the system to include the regions on both sides of the wall that experience a temperature change. Then one side of the system boundary becomes room temperature while the other side, the temperature of the outdoors. The exergy balance for this *extended system* (system + immediate surroundings) is the same as that given above, except the two boundary temperatures are 300 and 273 K instead of 293 and 278 K, respectively. Then the rate of total exergy destruction becomes

$$\dot{X}_{destroyed,total} = (1035 \text{ W})\left(1 - \frac{273 \text{ K}}{300 \text{ K}}\right) - (1035 \text{ W})\left(1 - \frac{273 \text{ K}}{273 \text{ K}}\right) = \textbf{93.2 W}$$
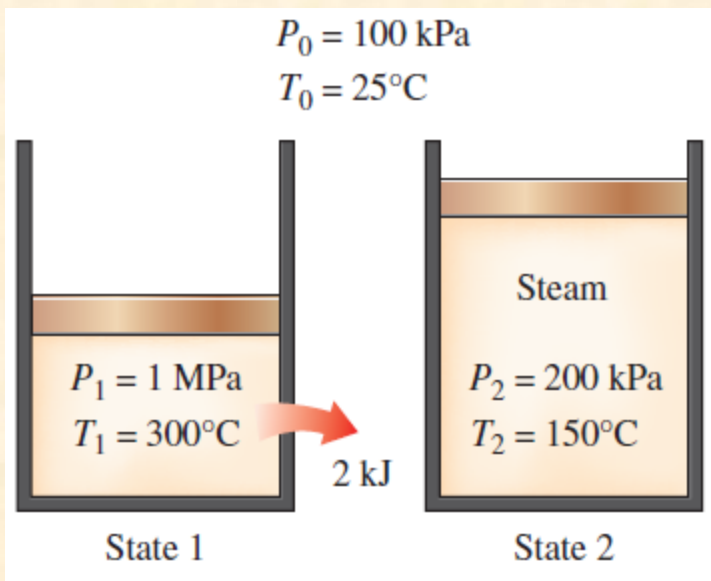
Exergy Destruction During Expansion of Steam

$P_0 = 100$ kPa
$T_0 = 25°C$

Steam

$P_1 = 1$ MPa
$T_1 = 300°C$

$P_2 = 200$ kPa
$T_2 = 150°C$

2 kJ

State 1   State 2

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

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

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

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

$$X_1 = m[(u_1 - u_0) - T_0(s_1 - s_0) + P_0(v_1 - v_0)]$$

$$X_2 = m[(u_2 - u_0) - T_0(s_2 - s_0) + P_0(v_2 - v_0)]$$

$$\Delta X = X_2 - X_1$$

$$W_u = W - W_{surr} = W_{b,out} - P_0(V_2 - V_1) = W_{b,out} - P_0 m(v_2 - v_1)$$

$$\eta_{II} = \frac{\text{Exergy recovered}}{\text{Exergy expended}} = \frac{W_u}{X_1 - X_2}$$

Alternative method of exergy destruction calculation:

$$X_{destroyed} = T_0 S_{gen} = T_0\left[m(s_2 - s_1) + \frac{Q_{surr}}{T_0}\right]$$

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

$$-Q_{out} - W_{b,out} = \Delta U$$

$$W_{b,out} = -Q_{out} - \Delta U = -Q_{out} - m(u_2 - u_1)$$

Dropping a Hot Iron Block into Water
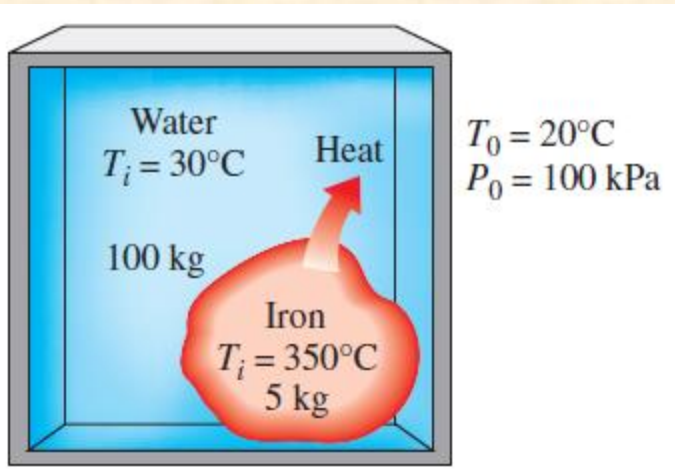
Water
$T_i = 30°C$
Heat

100 kg

Iron
$T_i = 350°C$
5 kg

$T_0 = 20°C$
$P_0 = 100$ kPa

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

$$0 = \Delta U$$

$$0 = (\Delta U)_{iron} + (\Delta U)_{water}$$

$$0 = [mc(T_f - T_i)]_{iron} + [mc(T_f - T_i)]_{water}$$

$$X = (U - U_0) - T_0(S - S_0) + P_0(V \overset{0}{\nearrow} V_0)$$

$$= mc(T - T_0) - T_0 mc \ln \frac{T}{T_0} + 0$$
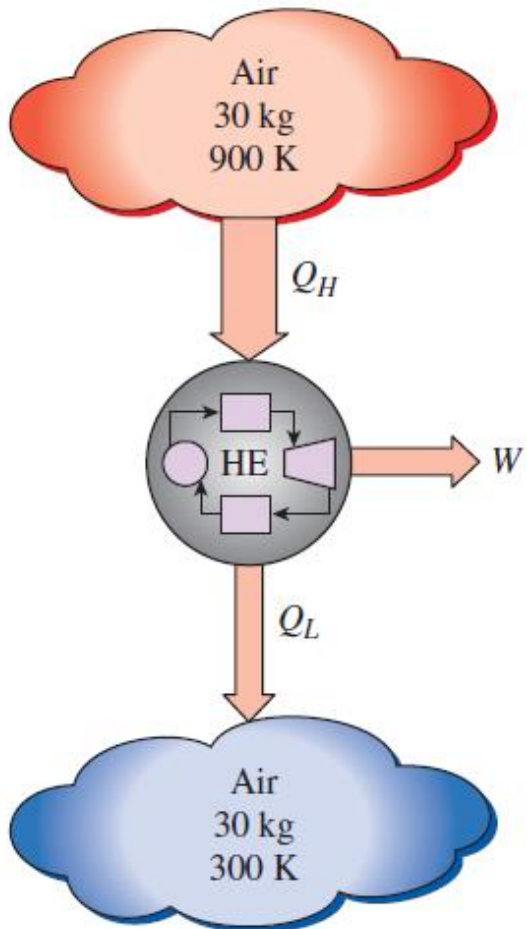
$$= mc\left(T - T_0 - T_0 \ln \frac{T}{T_0}\right)$$

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

$$0 - X_{destroyed} = X_2 - X_1$$

$$X_{destroyed} = X_1 - X_2$$

27

Work Potential of Heat Transfer Between Two Tanks

$$\underbrace{S_{in} - S_{out}}_{\substack{\text{Net entropy transfer} \\ \text{by heat and mass}}} + \underbrace{S_{gen}\!\!\nearrow^{0}}_{\substack{\text{Entropy} \\ \text{generation}}} = \underbrace{\Delta S_{system}}_{\substack{\text{Change} \\ \text{in entropy}}}$$

$$0 + S_{gen}\!\!\nearrow^{0} = \Delta S_{tank,source} + \Delta S_{tank,sink} + \Delta S_{heat\ engine}\!\!\nearrow^{0}$$

$$\Delta S_{tank,source} + \Delta S_{tank,sink} = 0$$

$$\left(mc_v \ln \frac{T_2}{T_1} + mR \ln \frac{V_2}{V_1}\!\!\nearrow^{0} \right)_{source} + \left(mc_v \ln \frac{T_2}{T_1} + mR \ln \frac{V_2}{V_1}\!\!\nearrow^{0} \right)_{sink} = 0$$

$$\ln \frac{T_2}{T_{1,A}} \frac{T_2}{T_{1,B}} = 0 \rightarrow T_2^2 = T_{1,A} T_{1,B}$$

$$T_2 = \sqrt{T_{1,A} T_{1,B}}$$

$$Q_{source,out} = mc_v (T_{1,A} - T_2)$$

$$Q_{sink,in} = mc_v (T_2 - T_{1,B})$$

$$W_{max,out} = Q_H - Q_L = Q_{source,out} - Q_{sink,\,in}$$

EXERGY BALANCE: CONTROL VOLUMES

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

$$\sum \left(1 - \frac{T_0}{T_k}\right)Q_k - [W - P_0(\mathcal{V}_2 - \mathcal{V}_1)] + \sum_{in} m\psi - \sum_{out} m\psi - X_{destroyed} = (X_2 - X_1)_{CV}$$

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

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.
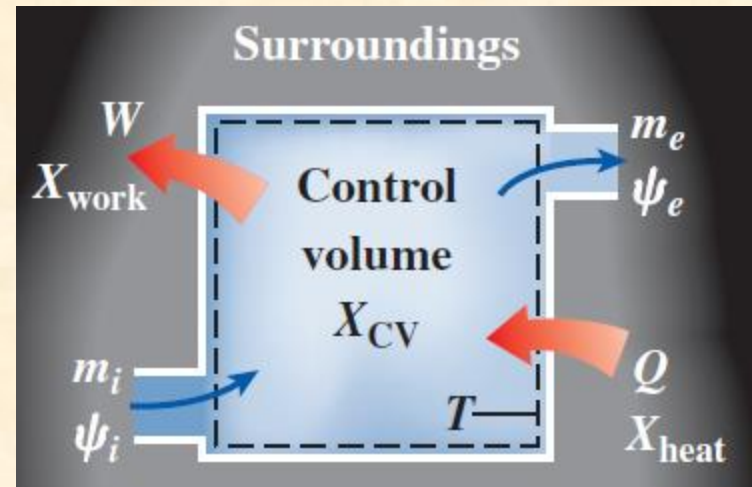

FIGURE 8–41

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

Exergy Balance for Steady-Flow Systems

Most control volumes encountered in practice such as turbines, compressors, nozzles, diffusers, heat exchangers, pipes, and ducts operate steadily, and thus they experience no changes in their mass, energy, entropy, and exergy contents as well as their volumes. Therefore, $dV_{CV}/dt = 0$ and $dX_{CV}/dt = 0$ for such systems.

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

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

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

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

FIGURE 8–42

The exergy transfer to a steady-flow system is equal to the exergy transfer from it plus the exergy destruction within the system.
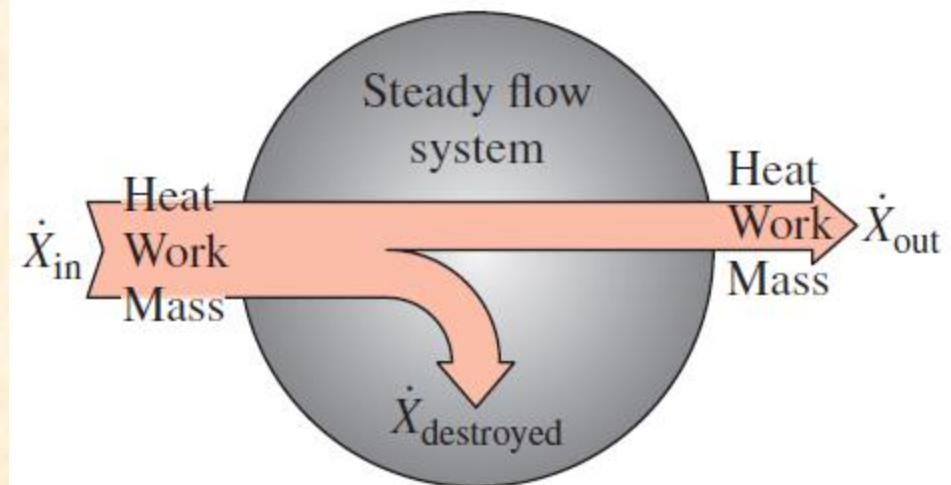
Reversible Work

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

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

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

Adiabatic, single stream: $\qquad\qquad \dot{W}_{rev} = \dot{m}(\psi_1 - \psi_2)$

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

The *second-law efficiency* of various steady-flow devices can be determined from its general definition, η_{II} = (Exergy recovered)/(Exergy expended). When the changes in kinetic and potential energies are negligible and the devices are adiabatic:

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

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

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

$$\eta_{II,\text{HX}} = \frac{\dot{m}_{\text{cold}}(\psi_4 - \psi_3)}{\dot{m}_{\text{hot}}(\psi_1 - \psi_2)}$$ Heat exchanger

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

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

$$\eta_{II,\text{mix}} = \frac{\dot{m}_3 \psi_3}{\dot{m}_1 \psi_1 + \dot{m}_2 \psi_2}$$ Mixing chamber

$$\eta_{II,\text{mix}} = 1 - \frac{T_0 \dot{S}_{\text{gen}}}{\dot{m}_1 \psi_1 + \dot{m}_2 \psi_2} \quad \dot{S}_{\text{gen}} = \dot{m}_3 s_3 - \dot{m}_2 s_2 - \dot{m}_1 s_1$$
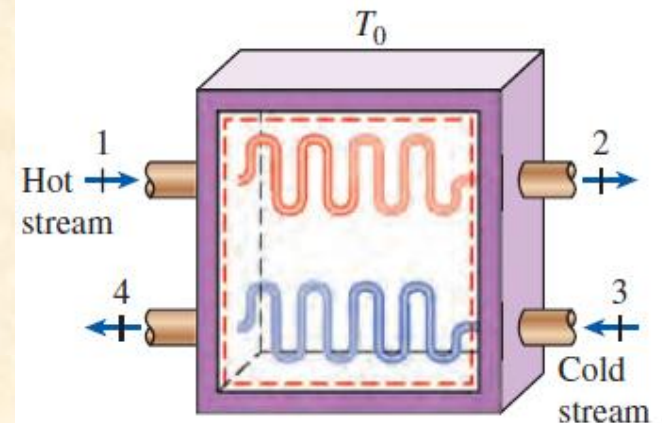

FIGURE 8–43
A heat exchanger with two unmixed fluid streams.

Second-law analysis of a steam turbine

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

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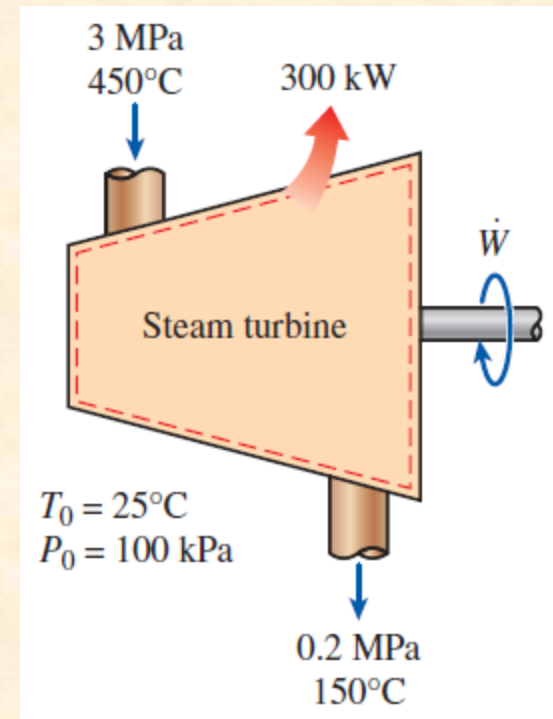
$$\dot{m}\psi_1 = \dot{W}_{rev,out} + \dot{X}_{heat}\nearrow^{0} + \dot{m}\psi_2$$

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

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

$$\eta_{II} = \frac{\dot{W}_{out}}{\dot{W}_{rev,out}} \qquad \dot{X}_{destroyed} = \dot{W}_{rev,out} - \dot{W}_{out}$$

3 MPa
450°C   **300 kW**

Steam turbine $\dot{W}$

$T_0 = 25°C$
$P_0 = 100$ kPa

0.2 MPa
150°C

$$\underbrace{\dot{E}_{in} - \dot{E}_{out}}_{\substack{\text{Rate of net energy transfer} \\ \text{by heat, work, and mass}}} = \underbrace{dE_{system}/dt}_{\substack{\text{Rate of change in internal, kinetic,} \\ \text{potential, etc., energies}}}\nearrow^{0\,(steady)} = 0$$

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

$$\dot{m}h_1 = \dot{W}_{out} + \dot{Q}_{out} + \dot{m}h_2 \qquad (\text{since ke} \cong \text{pe} \cong 0)$$

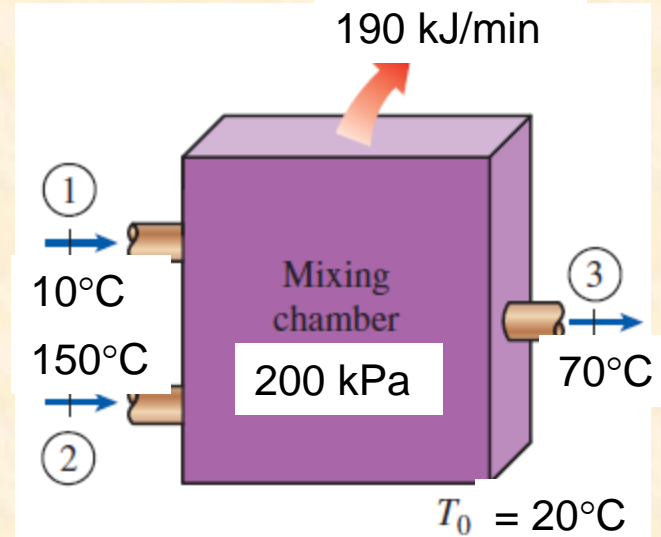$$\dot{W}_{out} = \dot{m}(h_1 - h_2) - \dot{Q}_{out}$$

Exergy Destroyed During Mixing of Fluid Streams

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

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

$$\dot{m}_1\psi_1 + \dot{m}_2\psi_2 = \dot{W}_{rev,out} + \dot{X}_{heat}^{\nearrow 0} + \dot{m}_3\psi_3$$

$$\dot{W}_{rev,out} = \dot{m}_1\psi_1 + \dot{m}_2\psi_2 - \dot{m}_3\psi_3$$

$$\dot{X}_{destroyed} = \dot{W}_{rev,out} - \dot{W}_u^{\nearrow 0} = T_0\dot{S}_{gen}$$

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

Mass balance: $\dot{m}_{in} - \dot{m}_{out} = dm_{system}/dt^{\nearrow 0\,(\text{steady})} = 0 \rightarrow \dot{m}_1 + \dot{m}_2 = \dot{m}_3$

Energy balance: $\underbrace{\dot{E}_{in} - \dot{E}_{out}}_{\substack{\text{Rate of net energy transfer} \\ \text{by heat, work, and mass}}} = \underbrace{dE_{system}/dt^{\nearrow 0\,(\text{steady})}}_{\substack{\text{Rate of change in internal, kinetic,} \\ \text{potential, etc., energies}}} = 0$

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

$$\dot{m}_1 h_1 + \dot{m}_2 h_2 = \dot{m}_3 h_3 + \dot{Q}_{out} \ (\text{since } \dot{W} = 0, \text{ ke} \cong \text{pe} \cong 0)$$

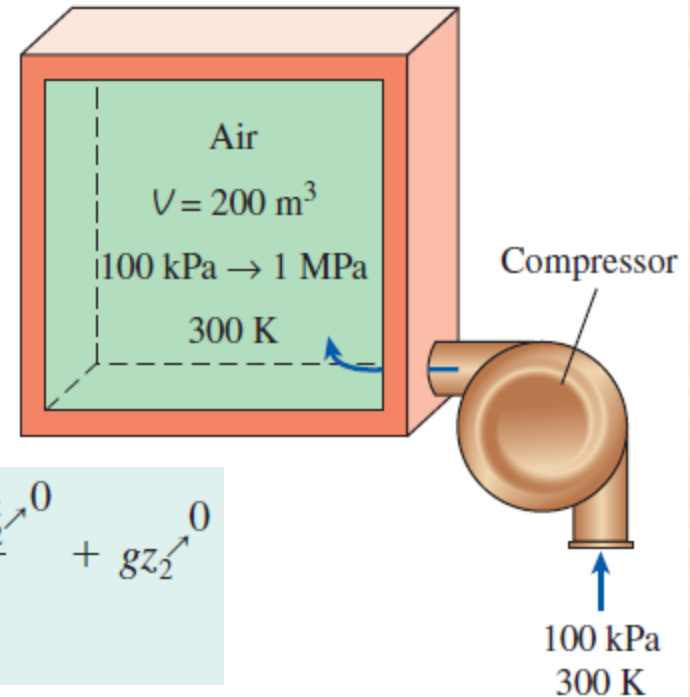$$\dot{Q}_{out} = \dot{m}_1 h_1 + \dot{m}_2 h_2 - (\dot{m}_1 + \dot{m}_2)h_3$$

Charging a Compressed Air Storage System

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

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

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

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

Air
$V = 200 \text{ m}^3$
$100 \text{ kPa} \to 1 \text{ MPa}$
300 K

Compressor

100 kPa
300 K

$$\phi_2 = (u_2 - u_0) \nearrow^{0 \, \text{(since } T_2 = T_0\text{)}} + P_0(v_2 - v_0) - T_0(s_2 - s_0) + \frac{V_2^2}{2} \nearrow^0 + gz_2 \nearrow^0$$

$$= P_0(v_2 - v_0) - T_0(s_2 - s_0)$$

$$P_0(v_2 - v_0) = P_0\left(\frac{RT_2}{P_2} - \frac{RT_0}{P_0}\right) = RT_0\left(\frac{P_0}{P_2} - 1\right) \quad \text{(since } T_2 = T_0\text{)}$$

$$T_0(s_2 - s_0) = T_0\left(c_p \ln\frac{T_2}{T_0} \nearrow^0 - R \ln\frac{P_2}{P_0}\right) = -RT_0 \ln\frac{P_2}{P_0} \quad \text{(since } T_2 = T_0\text{)}$$

$$\phi_2 = RT_0\left(\frac{P_0}{P_2} - 1\right) + RT_0 \ln\frac{P_2}{P_0} = RT_0\left(\ln\frac{P_2}{P_0} + \frac{P_0}{P_2} - 1\right)$$

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