Thermodynamics: An Engineering Approach
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CHAPTER 8
EXERGY: A MEASURE OF WORK POTENTIAL

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Adapted from the 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 of a system at some specified state is called *exergy*, which is also called the *availability* or *available energy*

- The *useful work potential* of the energy contained in a system at a specified state is simply the *maximum useful work* that can be obtained

- Work done during a process depends on the initial state, the final state, and the process path:

  Work = *f*(*initial state*, *process path*, *final state*)

- In an exergy analysis, *initial state is specified*. The *final state is the dead state*. The work output is maximized when the *process* between two specified states is executed in a *totally reversible* manner.

DEAD STATE

- A system is said to be in the ***dead state*** when it is in thermodynamic equilibrium with the environment it is in.
- 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*)
- There are no unbalanced magnetic, electrical, and surface tension effects between the system and the surroundings, if these are relevant to the situation in 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
- Unless specified otherwise, the *dead-state temperature and pressure are taken to be T_0 = 25°C and P_0 = 1 atm (101.325 kPa)*
- *A system has zero exergy at the dead state*

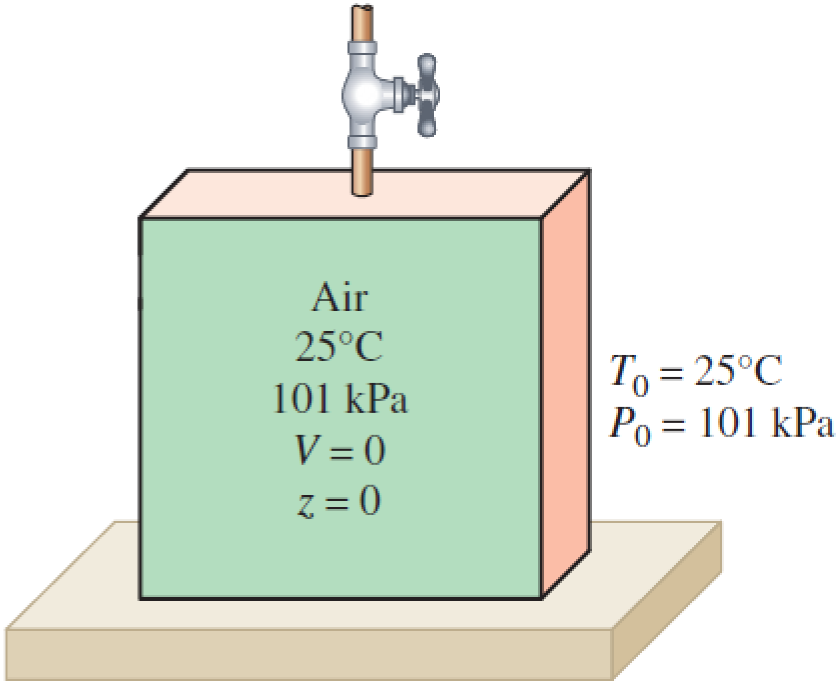


FIGURE 8–1
A system that is in equilibrium with its environment is said to be at the dead state.

Surroundings, Immediate Surroundings, and the Environment

- ***Surroundings:*** Everything outside the system boundaries
- ***Immediate Surroundings:*** The portion of the surroundings that is affected by the process
- ***Environment:*** Region beyond the immediate surroundings whose properties are not affected by the process at any point
- *Any irreversibilities during a process occur within the system and its immediate surroundings*
- *Environment is free of any irreversibilities*

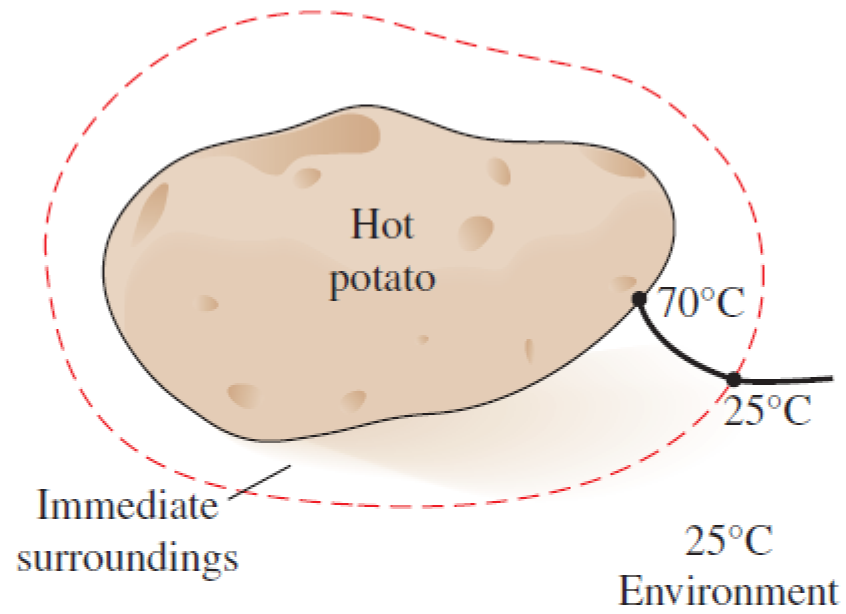


FIGURE 8–2
The immediate surroundings of a hot potato are simply the temperature gradient zone of the air next to the potato.

- A system must go to the dead state at the end of the process to maximize the work output
- No work can be produced from a system that is initially at the dead state

FIGURE 8–3
The atmosphere contains a tremendous amount of energy, but no exergy.

EXERGY

- *Maximum possible work is delivered as a system undergoes a **totally 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
- Exergy is a property of the ***system-environment combination*** and not the system alone

Unavailable Energy

Unavailable energy is simply the difference between the total energy of a system at a specified state and the exergy of that energy

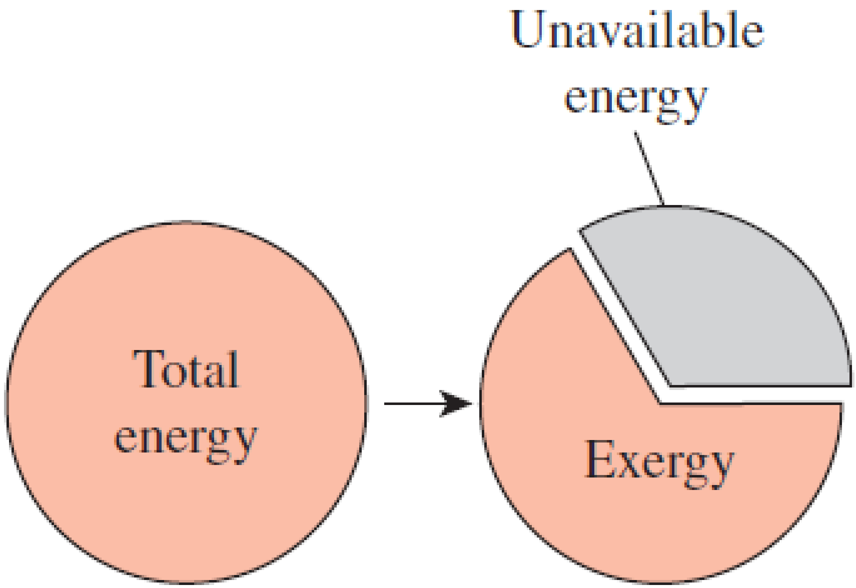


FIGURE 8–6

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

Exergy (Work Potential) Associated with Kinetic and Potential Energy

- *Kinetic and potential energies* are forms of mechanical energy, and thus they *can be converted to work entirely*
- The **exergy** of the *kinetic* or *potential* energy of a system is equal to the *kinetic or potential energy themselves*, respectively, regardless of the temperature and pressure of the environment

Exergy of kinetic energy:

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

Exergy of potential energy:

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

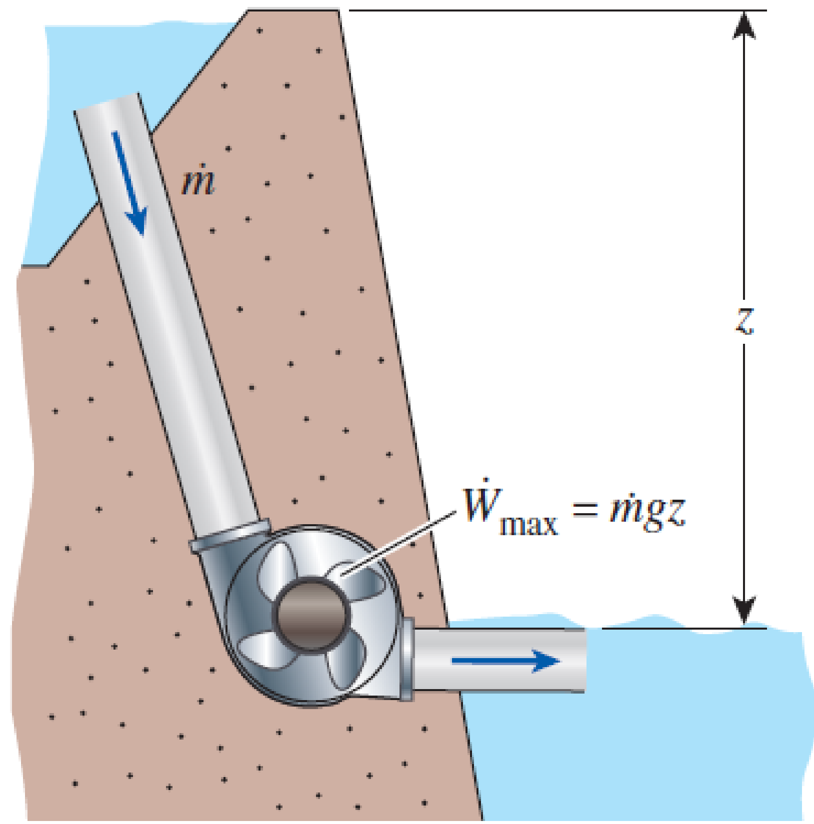
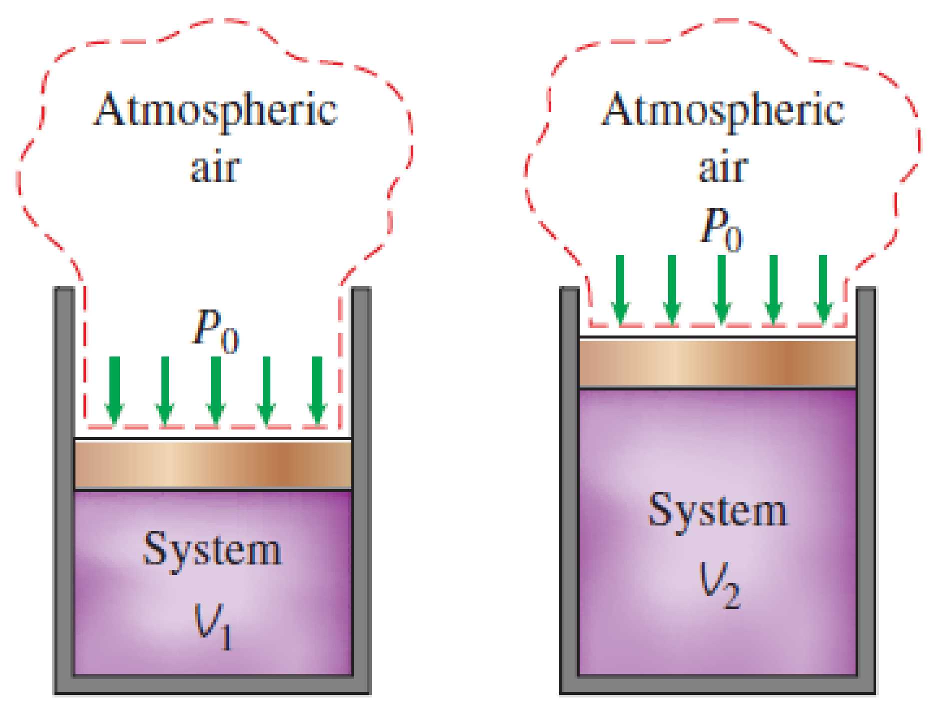


FIGURE 8–4
The *work potential* or *exergy* of potential energy is equal to the potential energy itself.

SURROUNDINGS WORK AND USEFUL WORK

- ***Surroundings work W_{surr}:*** Work done by or against the surroundings during a process
- As a closed system expands, some work (W_{surr}) needs to be done to push the atmospheric air (at P_0) out of the way



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

- The difference between the actual work W and the surroundings work (W_{surr}) is called the ***useful work W_u***

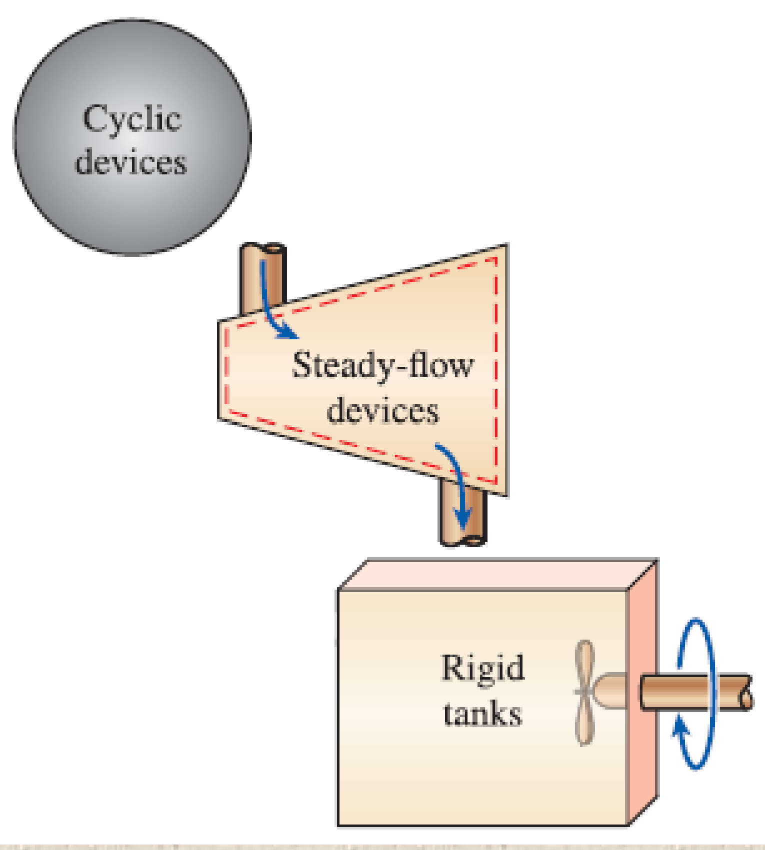
$$W_u = W - W_{\text{surr}} = W - P_0(V_2 - V_1)$$

- When a system is *expanding* and doing work, ***W_{surr}*** *represents a loss ($W_u < W$)*. Whereas when a system is *compressed* and work is being done on the system ***W_{surr}*** *represents a gain ($W_u > W$)*

SURROUNDINGS WORK AND USEFUL WORK

- Work done by or against the atmospheric air *(W_{surr}) has significance only for systems whose volume changes* during the process (i.e. systems that involve moving boundary work)

- It has *no significance* for *cyclic devices* and *systems whose boundaries remain fixed* during a process such as rigid tanks and steady flow devices (turbines, compressors, nozzles, heat exchangers, etc..)



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

REVERSIBLE WORK

- **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*
- ***W_{rev}*** is the ***useful work*** output (or input) obtained (or expended) when the process between the initial and final states is executed in a ***totally reversible manner***
- ***When the final state is the dead state, the reversible work equals exergy***

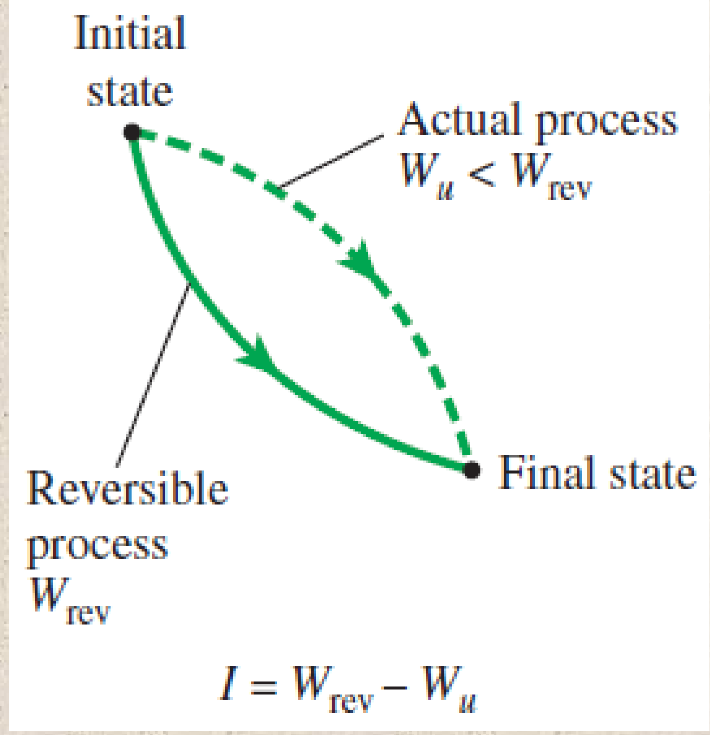
IRREVERSIBILITY

- Any *difference between the reversible work W_{rev} and the useful work W_u* is due to irreversibilities present during the process, and this difference is called ***irreversibility I***

$$I = W_{\text{rev,out}} - W_{u,\text{out}}$$

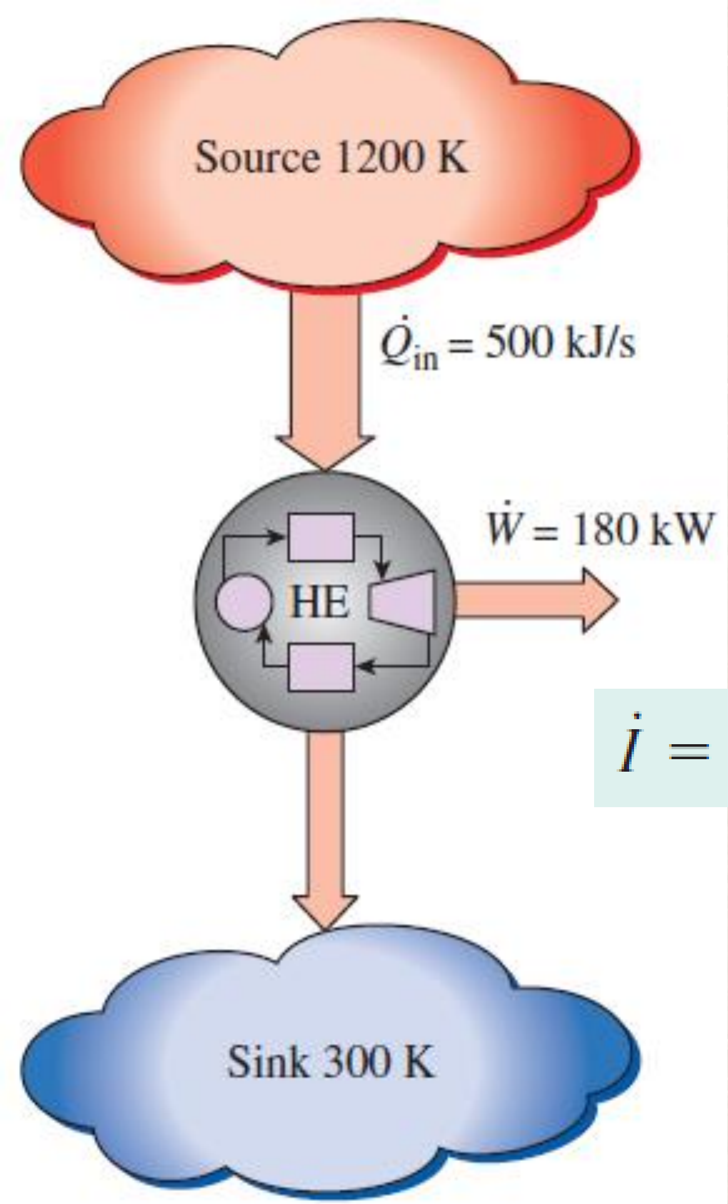
$$I = W_{u,\text{in}} - W_{\text{rev,in}}$$

- For a *totally reversible process*, the actual and reversible work terms are identical, and thus *irreversibility is zero*
- *Irreversibility is a positive quantity for all actual (irreversible) processes*
- Irreversibility can be viewed as the *wasted work potential* or the *lost opportunity to do work*. It represents the energy that could have been converted to work but was not



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

Example: The Rate of Irreversibility of a Heat Engine



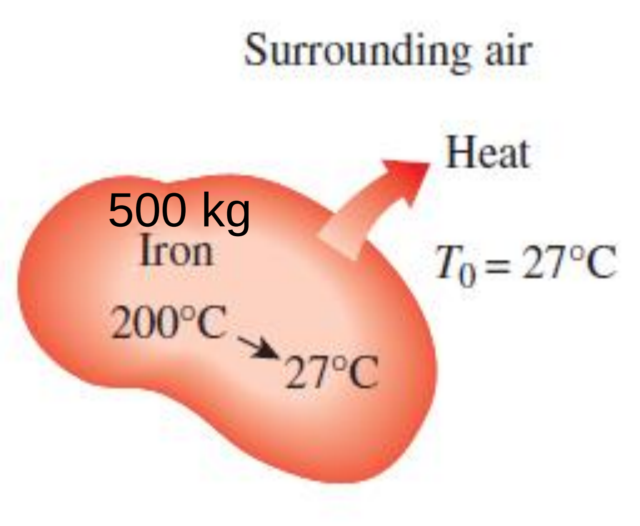
Determine the reversible power and the irreversibility rate for this process

$$\dot{W}_{\text{rev,out}} = \eta_{\text{th,rev}}\,\dot{Q}_{\text{in}} = \left(1 - \frac{T_{\text{sink}}}{T_{\text{source}}}\right)\dot{Q}_{\text{in}}$$

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

$$\dot{I} = \dot{W}_{\text{rev,out}} - \dot{W}_{u,\text{out}} = 375 - 180 = \mathbf{195\ kW}$$

Example: Irreversibility during the Cooling of an Iron Block



Determine the reversible work and the irreversibility for this process

Analysis: we take *iron block* as the system

Reversible work in this case is determined by considering a series of imaginary reversible heat engines operating between the source (at a variable temperature T) and the sink (at a constant temperature T_0)

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

$$W_{rev} = \int \left(1 - \frac{T_0}{T}\right)\delta Q_{in}$$

The source temperature changes from T_1 = 200°C = 473 K to T_0 = 27°C = 300 K during this process

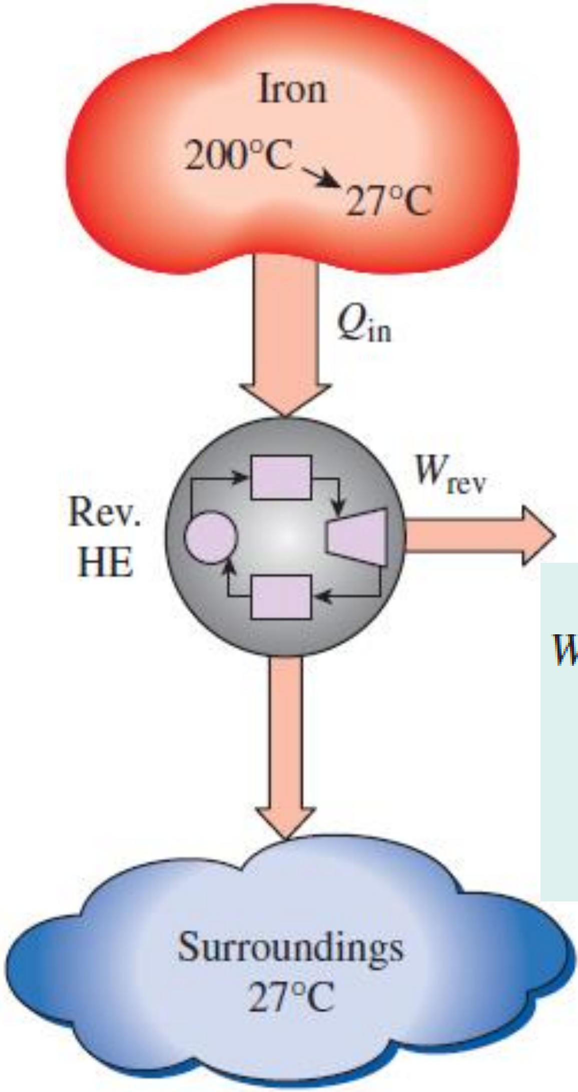


FIGURE 8–12
An irreversible heat transfer process can be made reversible by the use of a reversible heat engine.

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

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

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

Specific heat from Table A-3

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

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

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

$mc_{avg}(T_1 – T_0)$ = 38,925 kJ, is the total heat transfer from the iron block to the heat engine, 21% (8,191 kJ) of which could have been converted to work

$$I = W_{rev} - W_u = 8191 - 0 = \mathbf{8191\ kJ}$$

SECOND-LAW EFFICIENCY

- *Thermal efficiency (η_{th})* and *coefficient of performance (COP)* are *first-law efficiencies*
- *Second-law efficiency (η_{II}) is a measure of the performance of a device relative to its performance under reversible conditions*
- Note that the second law efficiency cannot exceed 100%

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

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

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

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

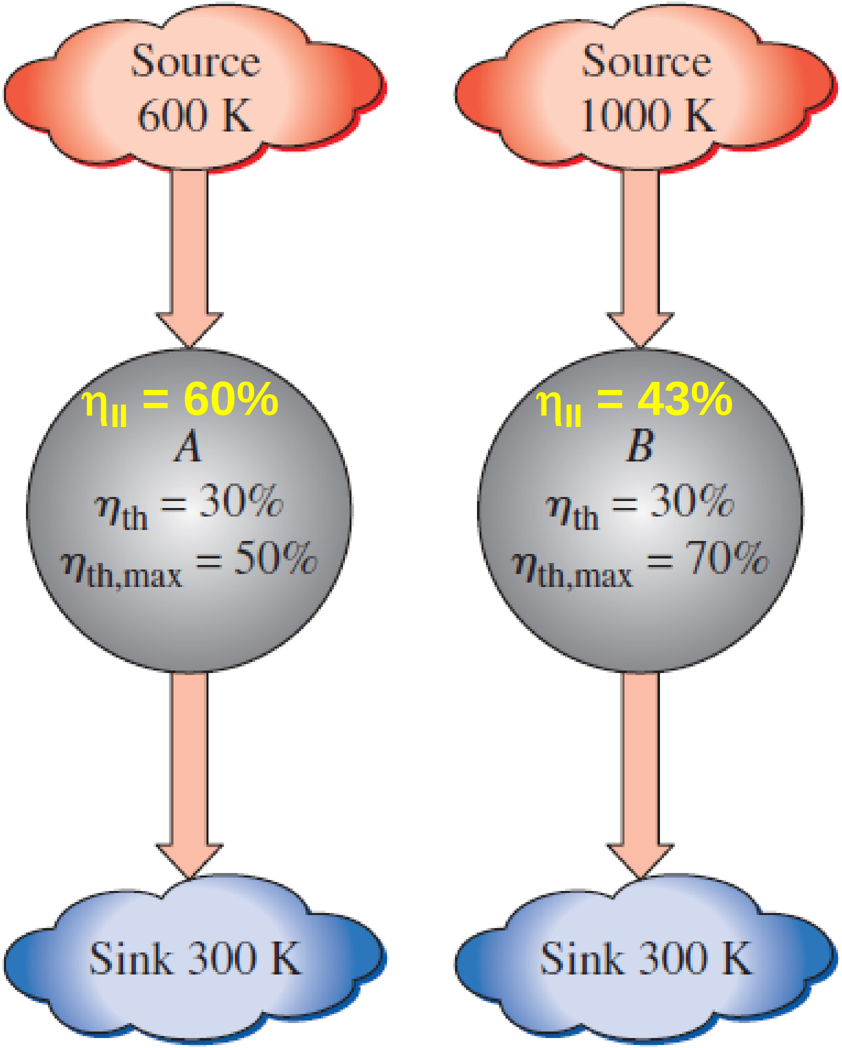


FIGURE 8–14
Two heat engines that have the same thermal efficiency, but different maximum thermal efficiencies.

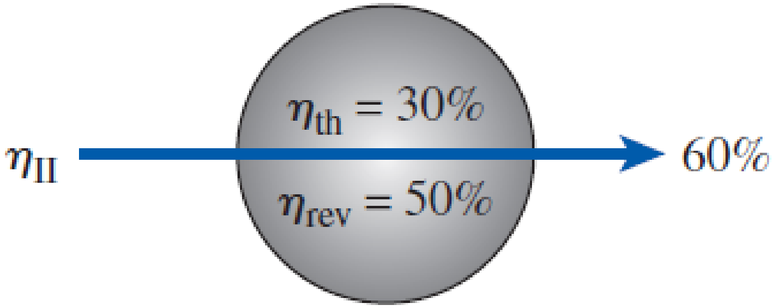


FIGURE 8–15
Second-law efficiency is a measure of the performance of a device relative to its performance under reversible conditions.

General definition of second law efficiency:

$$\eta_{II} = \frac{\text{Exergy recovered}}{\text{Exergy expended}} = 1 - \frac{\text{Exergy destroyed}}{\text{Exergy expended}}$$

- For a ***heat engine***, the *exergy expended* is the difference between the exergy of the heat supplied and the exergy of the heat rejected. (The exergy of heat rejected at the temperature of the surroundings is zero). The net work output is the *recovered exergy*.

- For a ***refrigerator*** or ***heat pump***, the *exergy expended* is the work input since the work supplied to a cyclic device is entirely consumed. The *recovered exergy* is the exergy of the heat transferred to the high-temperature medium for a *heat pump*, and the exergy of the heat transferred from the low-temperature medium for a refrigerator.

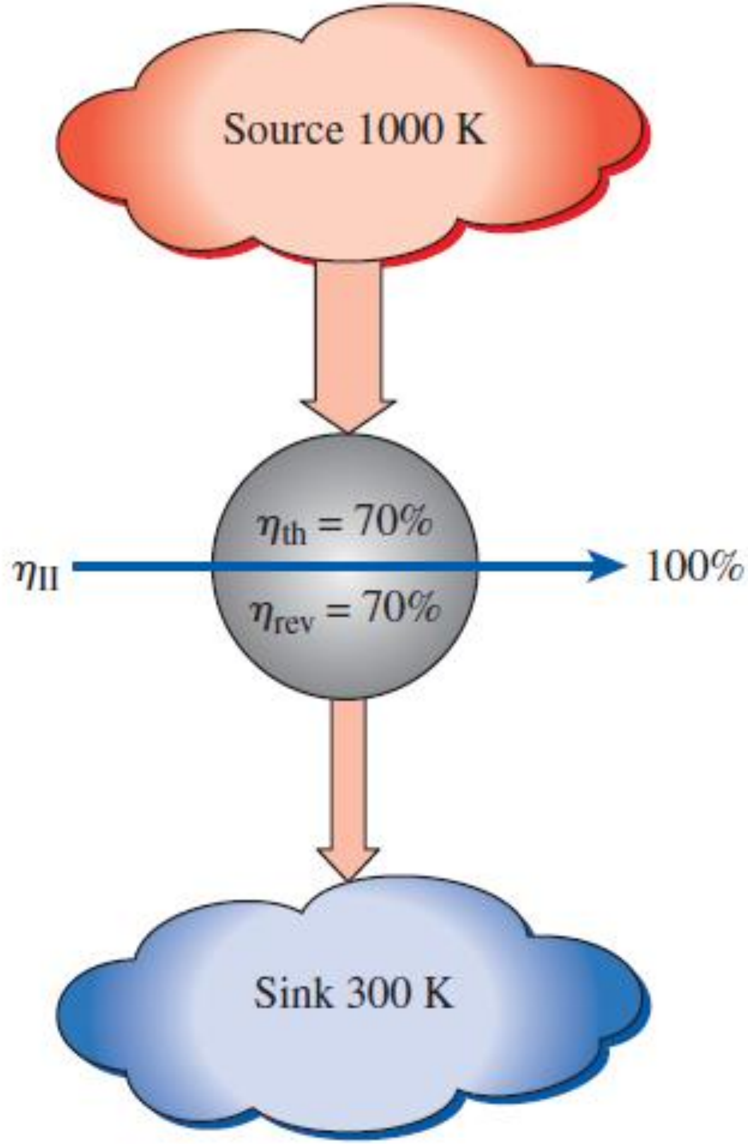


FIGURE 8–16
Second-law efficiency of all reversible devices is 100 percent.

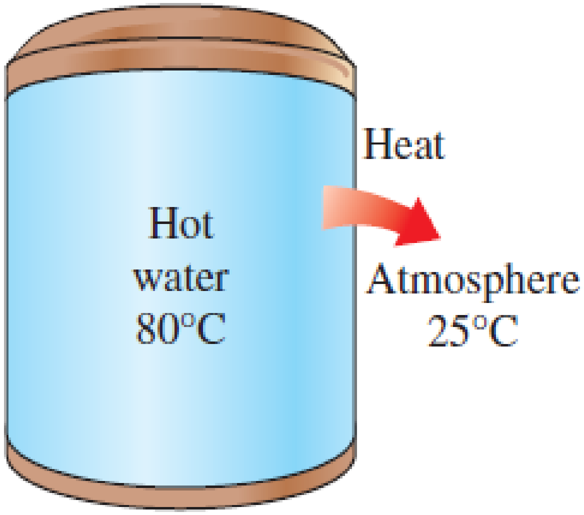


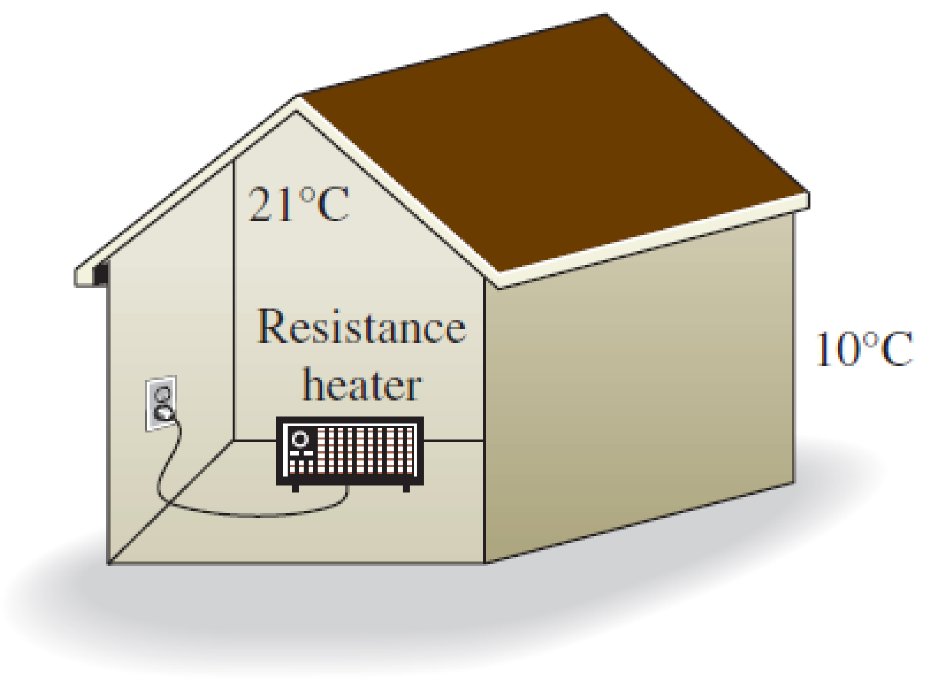
FIGURE 8–17
The second-law efficiency of naturally occurring processes is zero if none of the work potential is recovered.

Example: Second-Law Efficiency of Resistance Heaters

Determine the second-law efficiency of this heater

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

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



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

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

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

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

EXERGY OF A CLOSED SYSTEM

- Unlike energy, the *value of exergy depends on the state of the **environment** as well as the state of the **system***
- The exergy of a system that is in equilibrium with its environment is zero (i.e. system in *dead state*)
- Here, we limit our discussion to ***thermo-mechanical exergy***, and thus disregarded any mixing and chemical reactions. Hence, the system in the (restricted) dead state may have a different chemical composition than the environment.

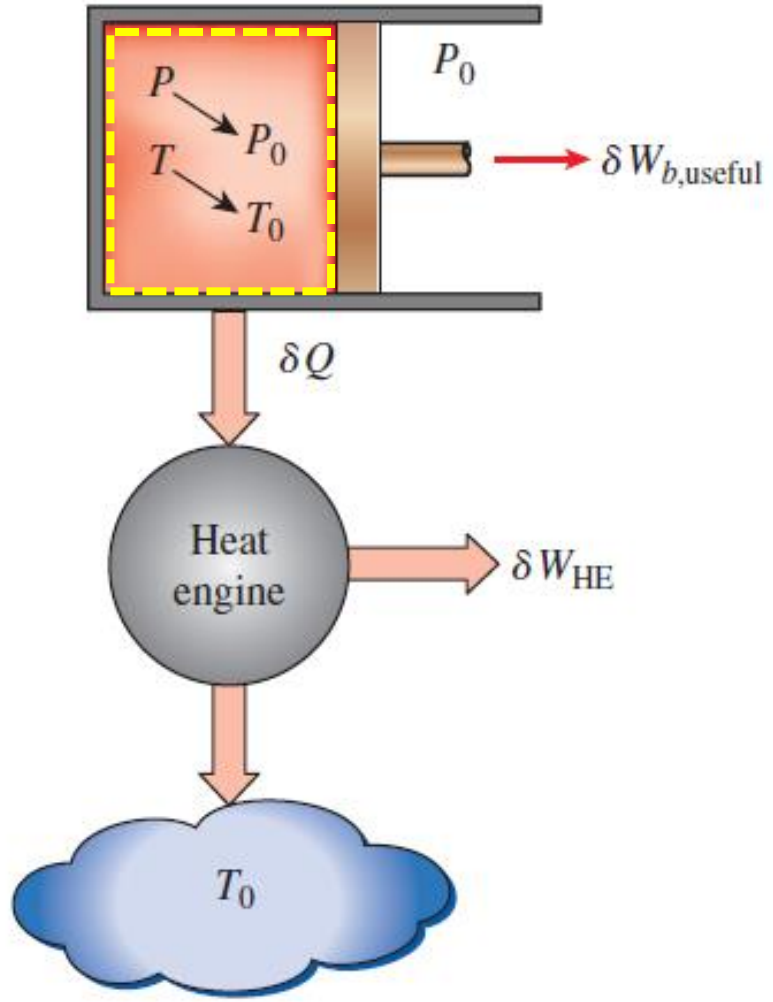


FIGURE 8–19
The *exergy* of a specified mass at a specified state is the useful work that can be produced as the mass undergoes a reversible process to the state of the environment.

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

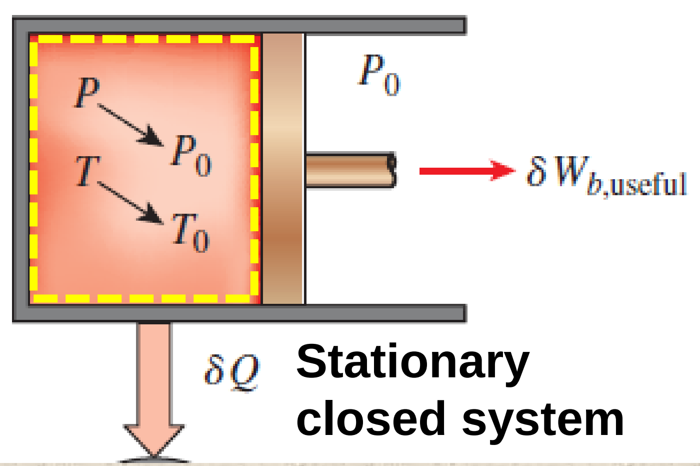
- In general, *internal energy* consist consists of *sensible*, *latent*, *chemical*, and *nuclear* energies
- In absence of any chemical or nuclear reactions, the chemical and nuclear energies can be disregarded and the *internal energy* can be considered to consist of only *sensible* and *latent* energies (i.e. *thermal* energy) that can be transferred as *heat* whenever there is a temperature difference across the system boundary
- The second law of thermodynamics states that *heat cannot be converted to work entirely*, and thus the ***work potential of internal energy must be less than the internal energy itself***
- Note that the ***exergy*** of the *kinetic* or *potential* energy of a system is equal to the kinetic or potential energy themselves

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

- Consider a *stationary closed system* at a specified state that undergoes a *totally reversible process* to the state of the environment (that is, the final temperature and pressure of the system should be T_0 and P_0, respectively)
- The **useful work delivered** during this process is the ***exergy*** of the system at its initial state
- Taking the direction of heat transferred ***from*** the system as positive (note that this sign convention is opposite of what we have used elsewhere, and *this is done only for this derivation*) and work done ***by*** the system as positive (this sign convention is same as that used elsewhere)

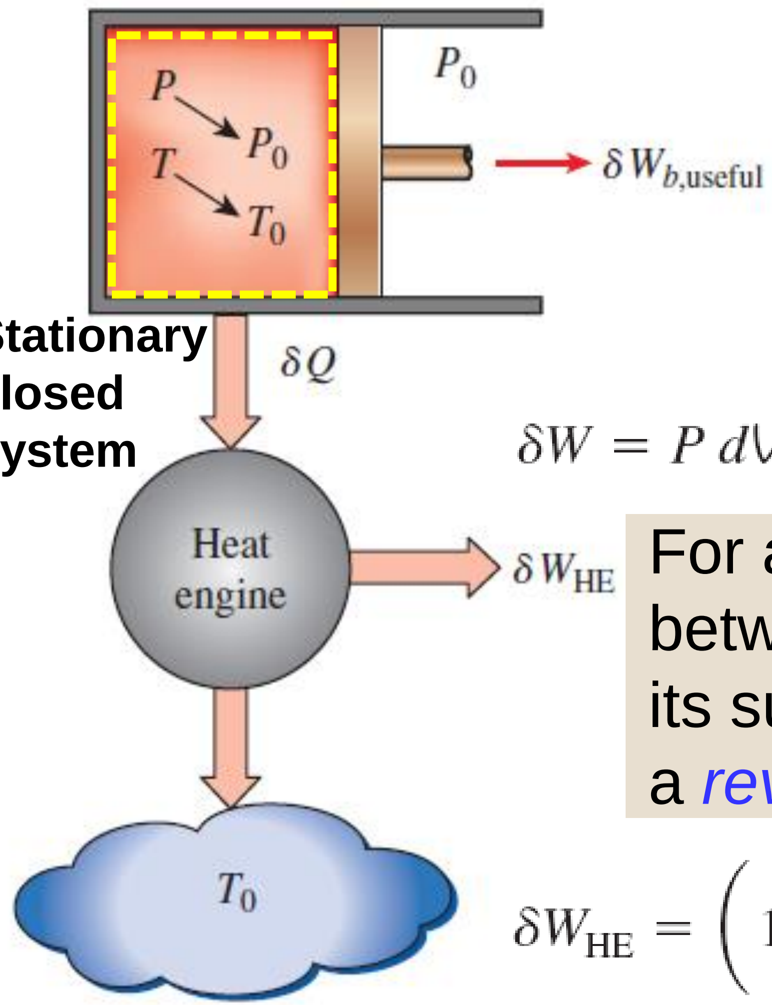
$$\underbrace{\delta E_{in} - \delta E_{out}}_{\substack{\text{Net energy transfer} \\ \text{by heat, work, and mass}}} = \underbrace{dE_{system}}_{\substack{\text{Change in internal, kinetic,} \\ \text{potential, etc., energies}}}$$

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



Stationary closed system

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



Stationary closed system

The only form of work a simple compressible system can involve during a *reversible process (which is also internally reversible)* is the *boundary work*

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

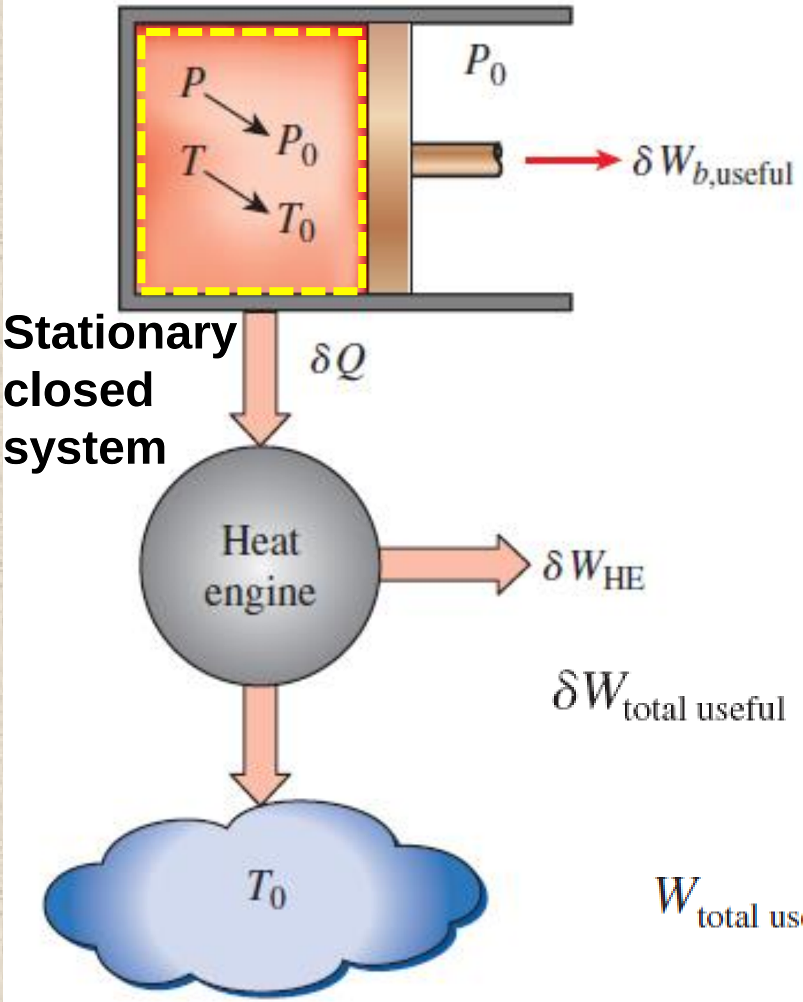
For a *reversible process*, any heat transfer between the system at temperature T and its surroundings at T_0 must occur through a *reversible heat engine*

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

Note that a reversible process is also internally reversible, and we can use the definition of entropy: $dS = \delta Q/T$

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

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



Note that the ***total useful work*** is the addition of useful work from the ***system*** and the work from the ***reversible heat engine***

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

Stationary closed system

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

A closed system in general may posses kinetic and potential energies, and ***exergy*** of a closed system of mass *m* is:

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

Closed system exergy per unit mass

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

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

Exergy change of a closed system

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

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

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

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

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 of a closed system is either positive or zero. ***It is never negative***
- Even a medium at *low temperature ($T < T_0$)* and/or *low pressure ($P < P_0$)* contains exergy since a cold medium can serve as the heat sink to a heat engine that absorbs heat from the environment at T_0, and an evacuated space makes it possible for the atmospheric pressure to move a piston and do useful work.

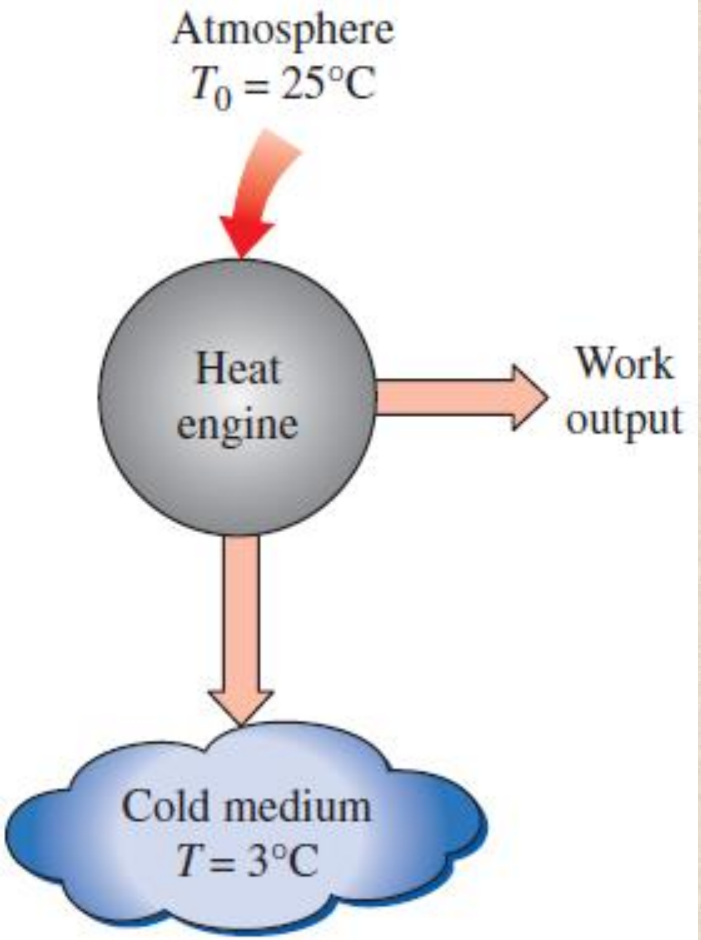


FIGURE 8–20
The *exergy* of a cold medium is also a *positive* quantity since work can be produced by transferring heat to it.

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

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

Exergy of non flowing fluid energy

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

Exergy of flow energy

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

Exergy of (non flowing fluid energy + flow energy)

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

Exergy of flowing fluid (flow exergy)

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

Exergy change of fluid stream

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

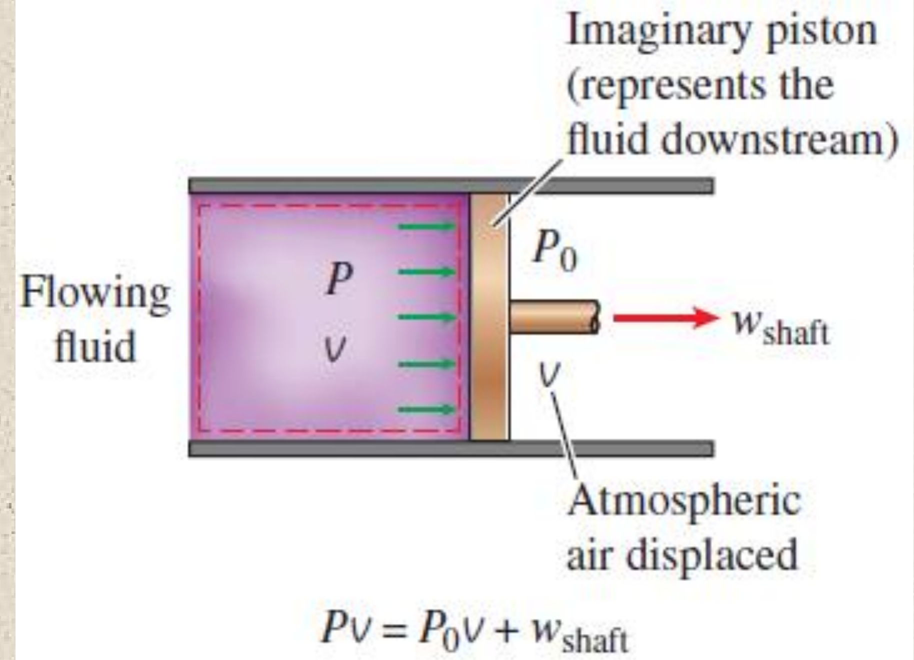


FIGURE 8–21

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

Exergy Change, Reversible Work, Exergy of Flow Stream

- The ***exergy change*** of a closed system or a fluid stream represents the maximum amount of useful work that can be done (or the minimum amount of useful work that needs to be supplied if it is negative) as the system (or the fluid packet) changes from state 1 to state 2 in a specified environment, and represents the ***reversible work*** W_{rev}
- *Exergy of a closed system cannot be negative*, but the *exergy of a flow stream can be negative* at pressures below the environment pressure P_0

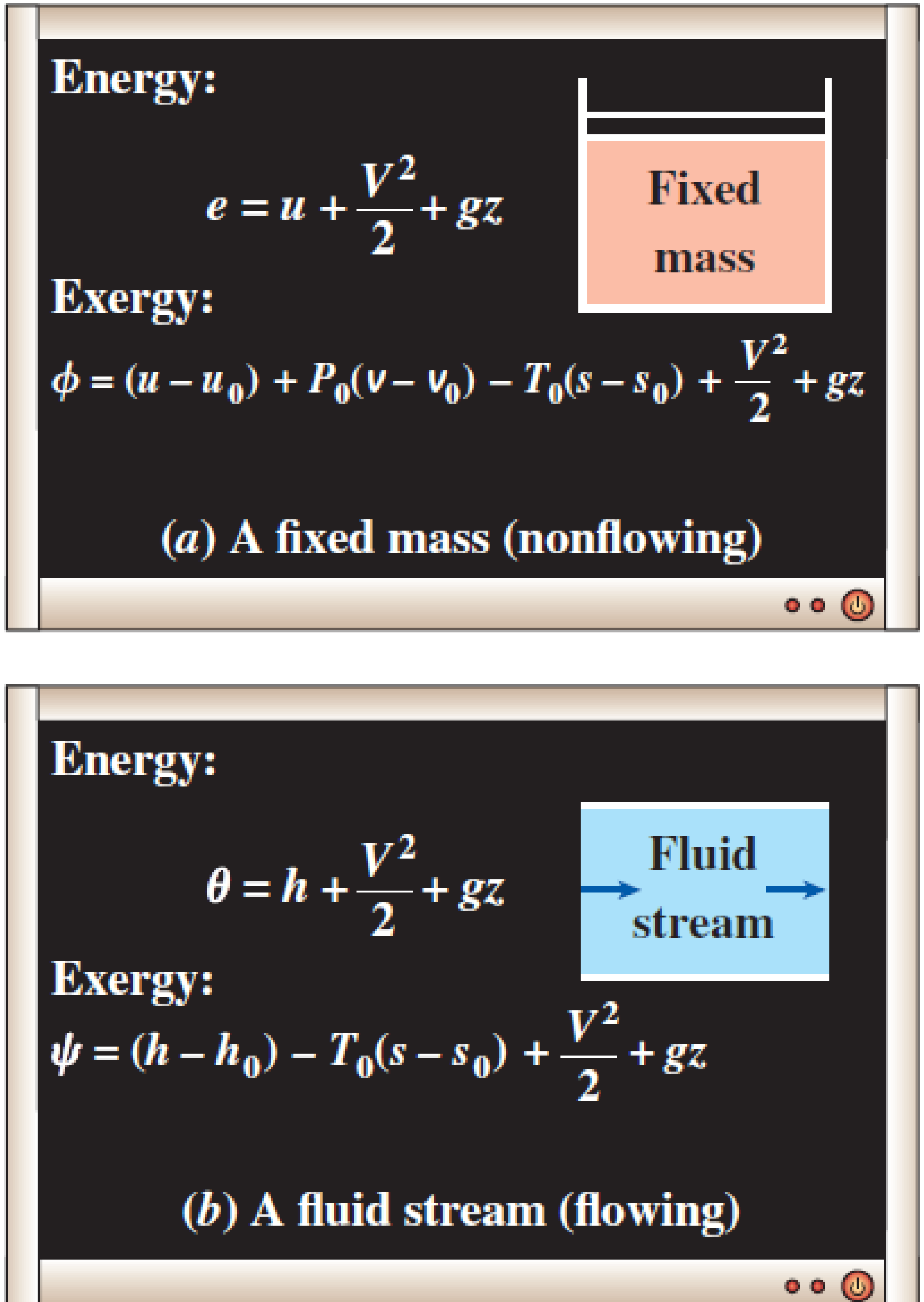
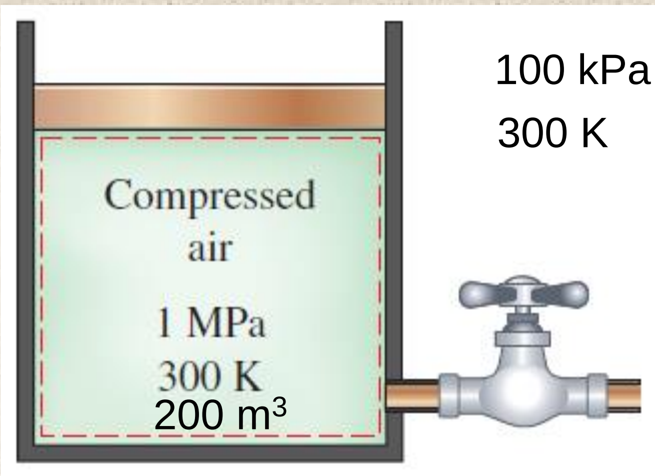


FIGURE 8–22
The *energy* and *exergy* contents of (*a*) a fixed mass and (*b*) a fluid stream.



Example: Work Potential of Compressed Air in a Tank

Determine the exergy of the compressed air stored in the tank at the given state and in the specified environment

$$X_1 = m\phi_1 \qquad m_1 = \frac{P_1 V}{RT_1} = 2323 \text{ kg}$$

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

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

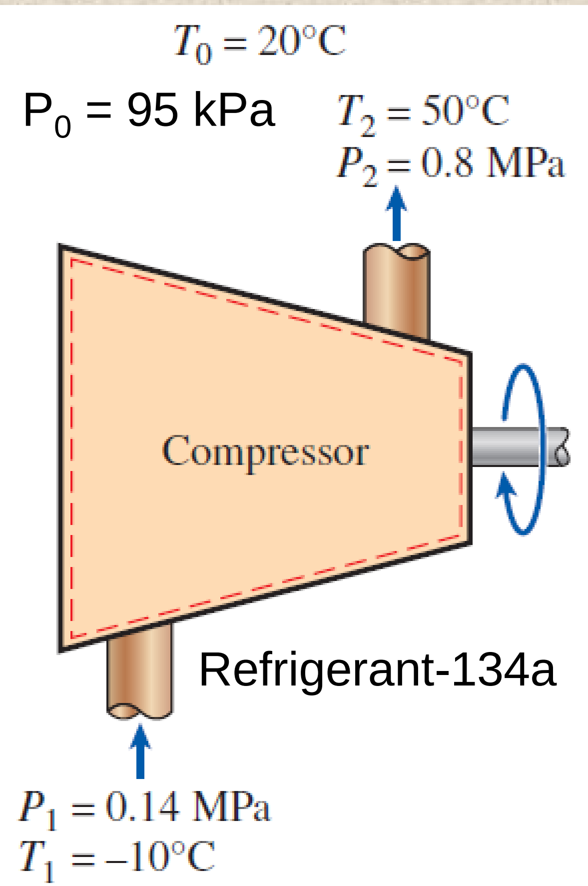
$$P_0(v_1 - v_0) = P_0\left(\frac{RT_1}{P_1} - \frac{RT_0}{P_0}\right) = RT_0\left(\frac{P_0}{P_1} - 1\right) \quad (\text{since } T_1 = T_0)$$

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

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

$$X_1 = m_1\phi_1 \cong \mathbf{281\ MJ}$$

Example: Exergy Change During a Compression Process



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 refrigerant

Analysis: we take *compressor* as the system (control volume)

$$\text{Inlet state:}\quad \left.\begin{aligned} P_1 &= 0.14 \text{ MPa} \\ T_1 &= -10°C \end{aligned}\right\} \quad \begin{aligned} h_1 &= 246.37 \text{ kJ/kg} \\ s_1 &= 0.9724 \text{ kJ/kg·K} \end{aligned}$$

$$\text{Exit state:}\quad \left.\begin{aligned} P_2 &= 0.8 \text{ MPa} \\ T_2 &= 50°C \end{aligned}\right\} \quad \begin{aligned} h_2 &= 286.71 \text{ kJ/kg} \\ s_2 &= 0.9803 \text{ kJ/kg·K} \end{aligned}$$

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

$$= (h_2 - h_1) - T_0(s_2 - s_1) = \mathbf{38.0\ kJ/kg}$$

$$w_{\text{in,min}} = \psi_2 - \psi_1 = \mathbf{38.0\ kJ/kg}$$

EXERGY TRANSFER BY HEAT, WORK, AND MASS

Exergy by Heat Transfer, *Q*

- Heat is a form of disorganized energy, and thus only a portion of it can be converted to work, which is a form of organized energy

Exergy transfer by heat

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

When temperature is not constant

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

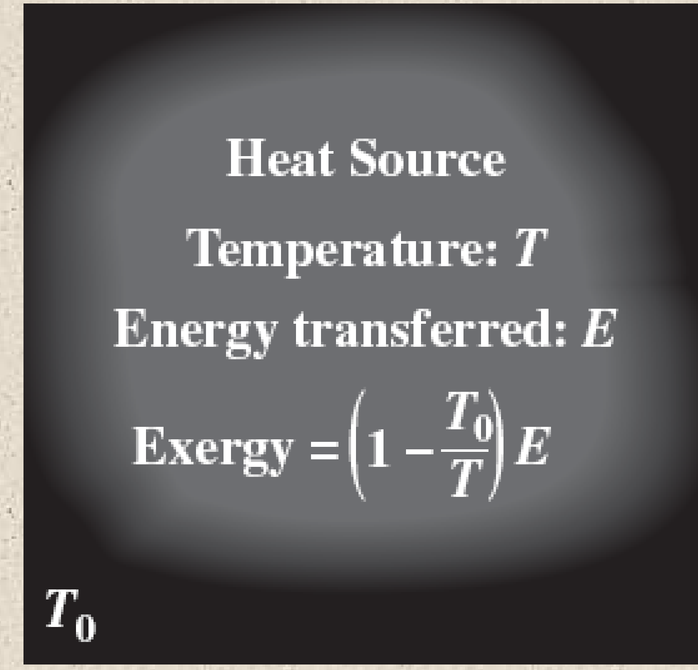
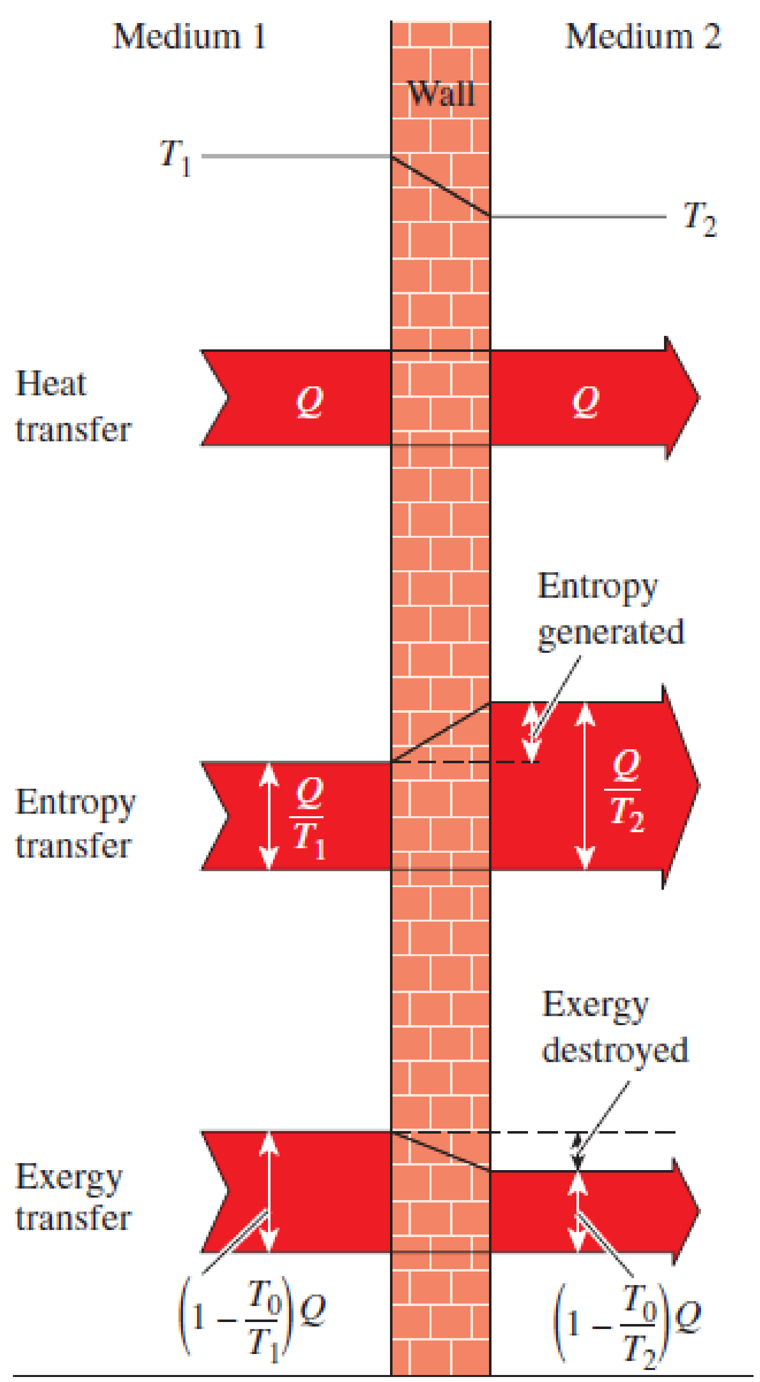


FIGURE 8–25
The Carnot efficiency $\eta_C = 1 - T_0/T$ represents the fraction of the energy transferred from a heat source at temperature T that can be converted to work in an environment at temperature T_0.



- Heat transfer through a finite temperature difference is irreversible, and some entropy is generated as a result.
- The *entropy generation is always accompanied by exergy destruction*

FIGURE 8–26
The transfer and destruction of exergy during a heat transfer process through a finite temperature difference.

Exergy Transfer by Work, *W*

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

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

- Exergy transfer with work such as shaft and electrical work is equal to the work *W* itself.
- In the case of a system that involves boundary work, such as piston cylinder device, the work done to push the atmospheric air out of the way during expansion cannot be transferred, and thus it must be subtracted

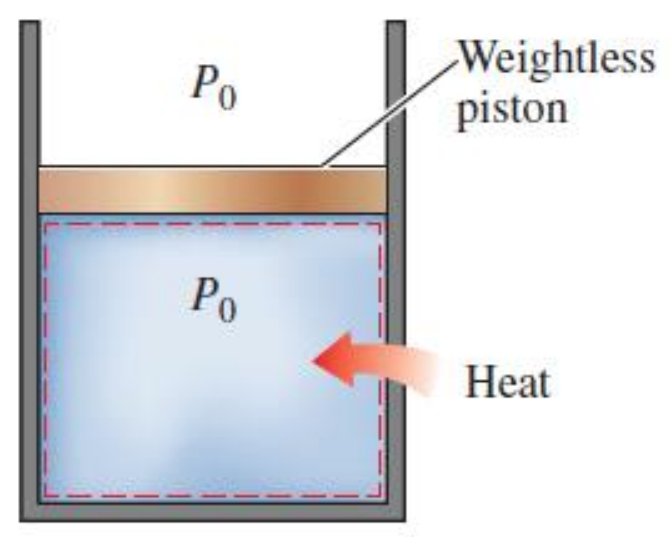


FIGURE 8–27
There is no useful work transfer associated with boundary work when the pressure of the system is maintained constant at atmospheric pressure.

Exergy Transfer by Mass, *m*

$$X_{\text{mass}} = m\psi$$

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

- Mass contains ***exergy*** as well as energy and entropy
- When mass enters or leaves a system, it carries exergy ***in*** or ***out*** of the system

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

$$\dot{X}_{\text{mass}} = \int_{A_c} \psi \rho V_n\, dA_c$$

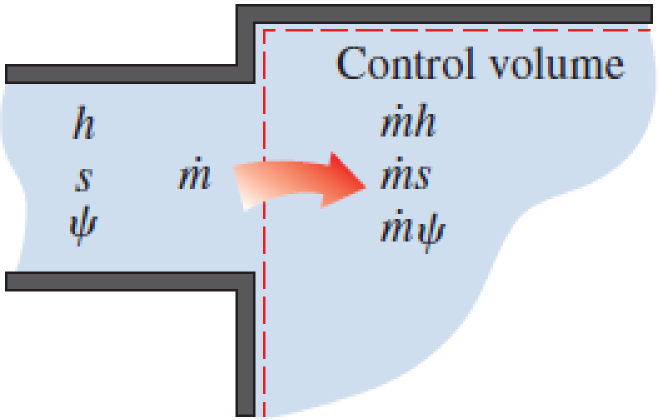


FIGURE 8–28
Mass contains energy, entropy, and exergy, and thus mass flow into or out of a system is accompanied by energy, entropy, and exergy transfer.

THE DECREASE OF EXERGY PRINCIPLE

For an isolated system

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

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

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

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

We know,

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

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

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

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

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

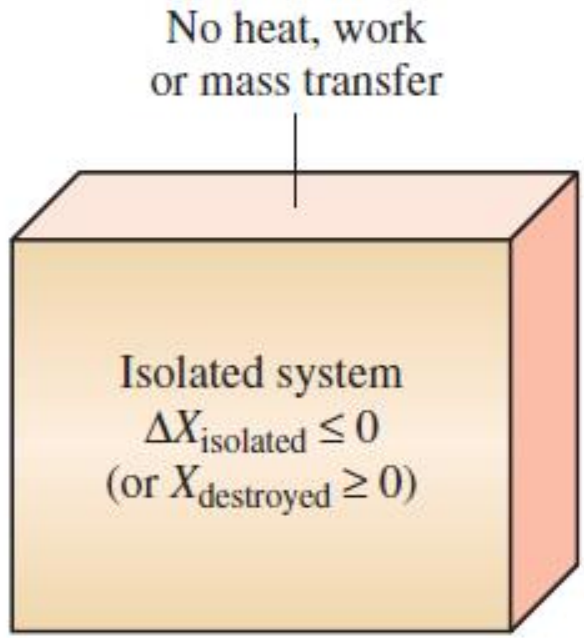


FIGURE 8–29
The isolated system considered in the development of the decrease of exergy principle.

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***
- *Irreversibilities* such as friction, mixing, chemical reactions, heat transfer through a finite temperature difference, unrestrained expansion, nonquasi-equilibrium compression or expansion always *generate entropy*, and *anything that generates entropy always destroys exergy*

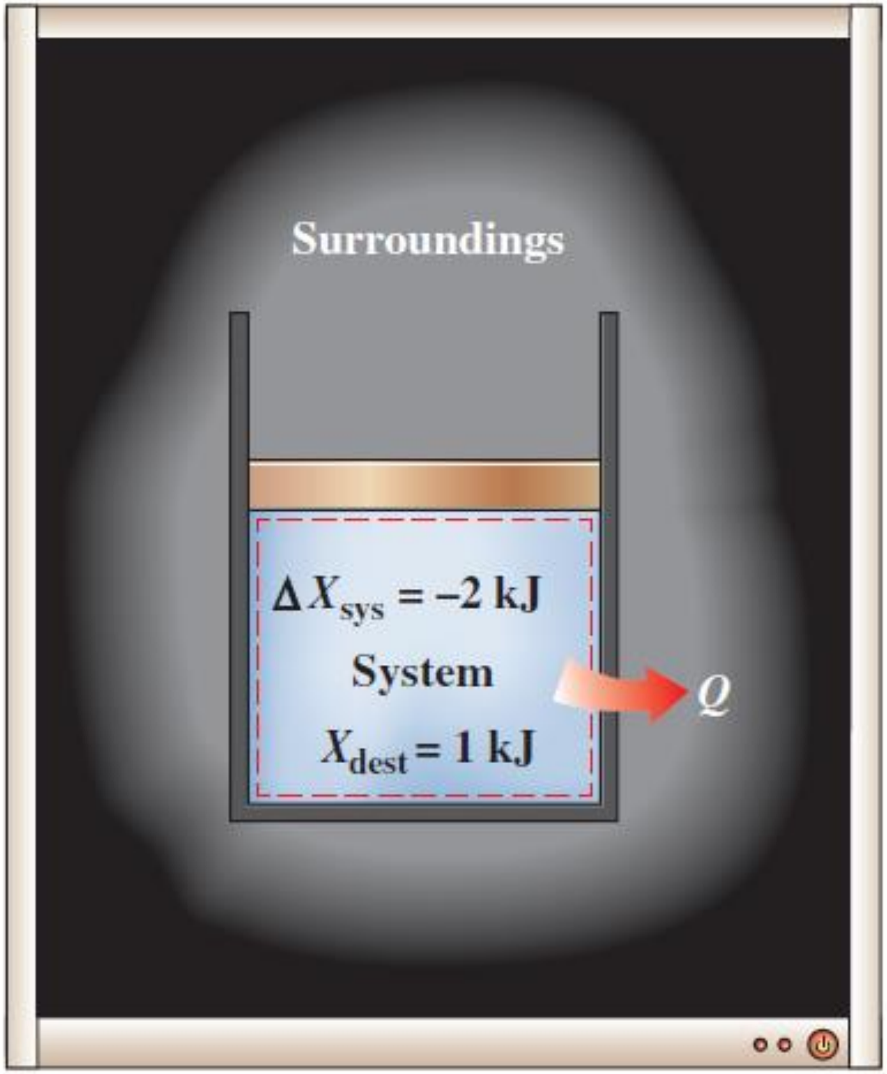


FIGURE 8–30

The exergy change of a system can be negative, but the exergy destruction cannot.

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:

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

General, rate form:

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

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

General, unit-mass basis:

$$(x_{\text{in}} - x_{\text{out}}) - x_{\text{destroyed}} = \Delta x_{\text{system}} \quad (\text{kJ/kg})$$

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

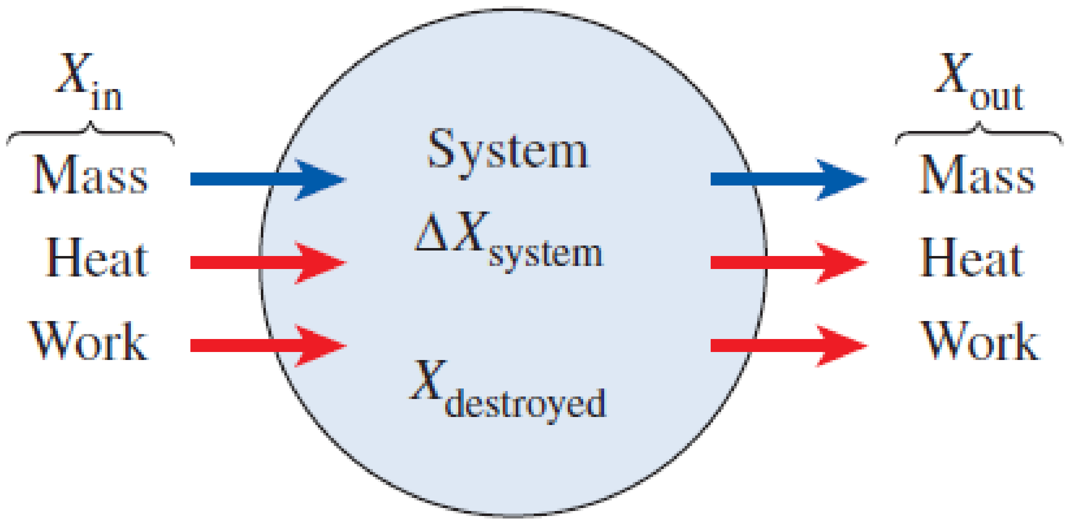


FIGURE 8–31

Mechanisms of exergy transfer.

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.

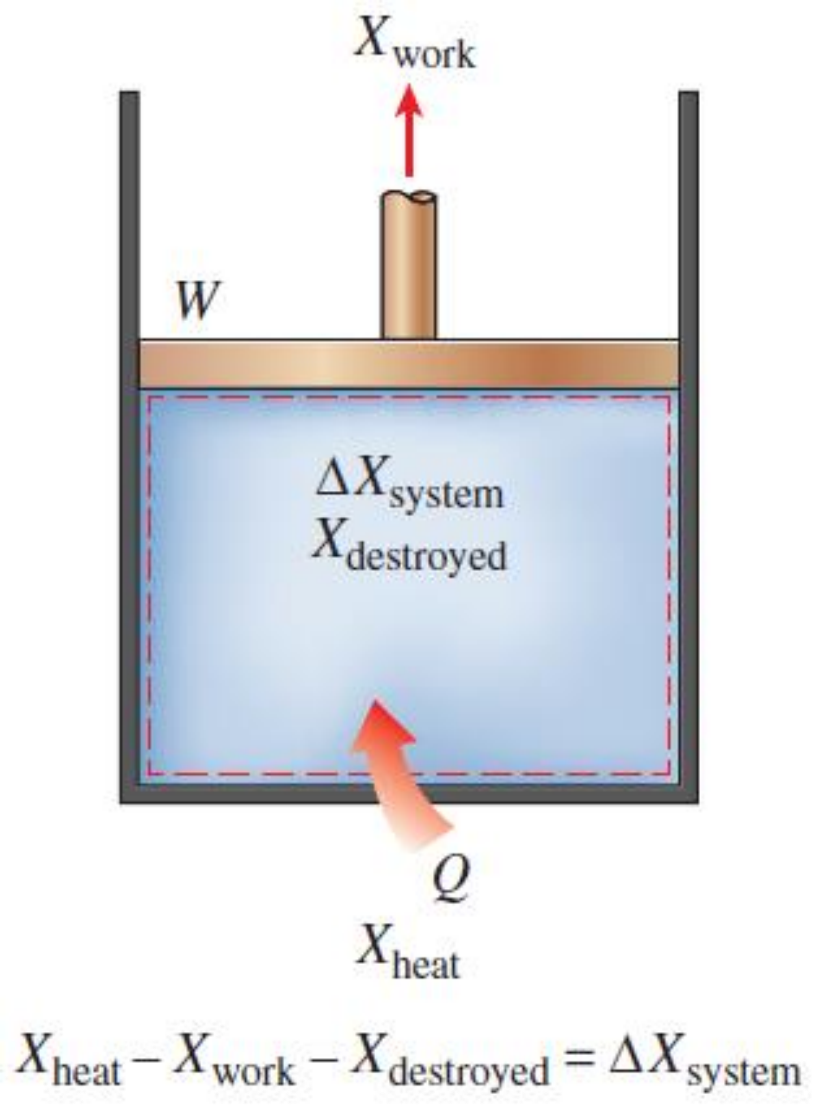
Closed system: $$X_{\text{heat}} - X_{\text{work}} - X_{\text{destroyed}} = \Delta X_{\text{system}}$$

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

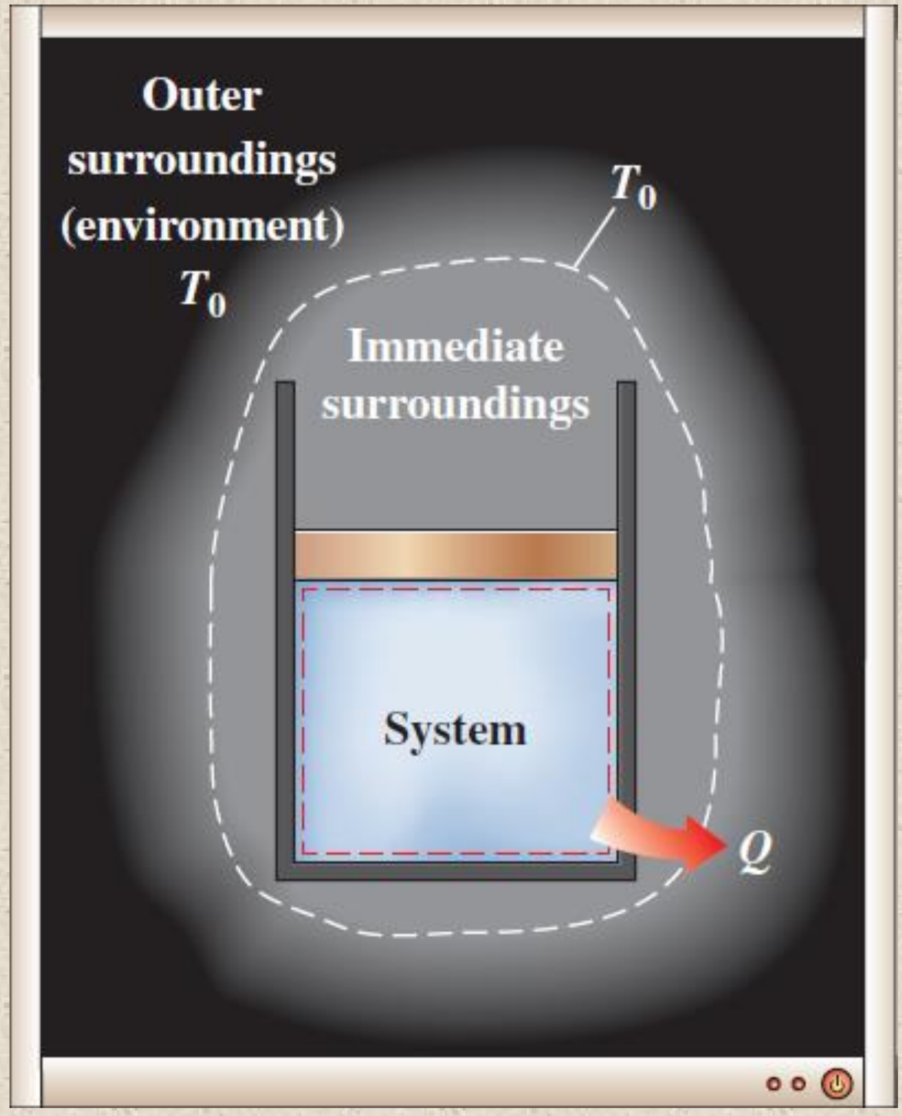
Closed system: $$\sum \left(1 - \frac{T_0}{T_k}\right) Q_k - [W - P_0(V_2 - V_1)] - T_0 S_{\text{gen}} = X_2 - X_1$$

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

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



Exergy balance for a closed system when heat transfer ***to*** the system is positive and the work done ***by*** the system is positive.



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

General Exergy Balance for Closed Systems

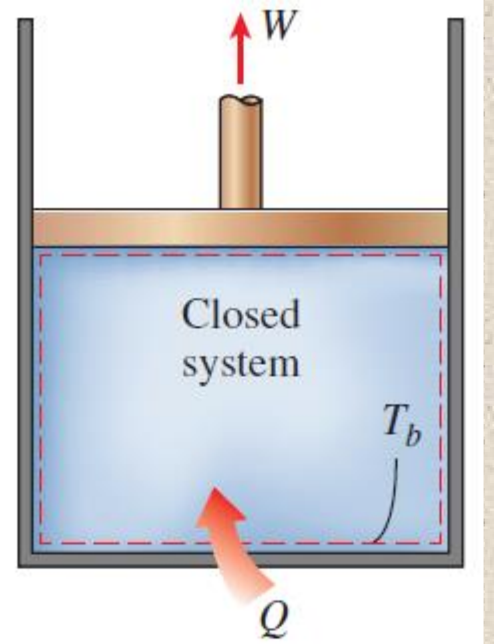
Energy balance: $E_{\text{in}} - E_{\text{out}} = \Delta E_{\text{system}} \rightarrow Q - W = E_2 - E_1$

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

$$Q - T_0 \int_1^2 \left(\frac{\delta Q}{T}\right)_{\text{boundary}} - W - T_0 S_{\text{gen}} = E_2 - E_1 - T_0(S_2 - S_1)$$

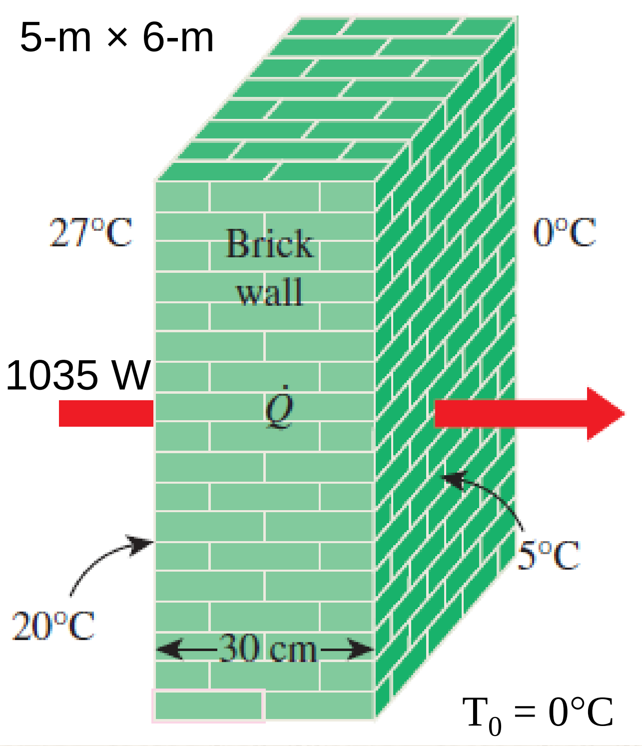
$$\int_1^2 \delta Q - T_0 \int_1^2 \left(\frac{\delta Q}{T}\right)_{\text{boundary}} - W - T_0 S_{\text{gen}} = X_2 - X_1 - P_0(V_2 - V_1)$$

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



Example: Exergy Destruction during Heat Conduction

Determine the rate of exergy destruction in the wall, and the rate of total exergy destruction associated with this heat transfer process



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

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

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

$\dot{X}_{destroyed} = \mathbf{52.0\ W}$ Also: $\dot{X}_{destroyed} = T_0\,\dot{S}_{gen}$ $\dot{S}_{gen} = \mathbf{0.191\ W/K}$ $T_0 = 273$ K

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

$$\dot{X}_{destroyed,total} = (1035\text{ W})\left(1 - \frac{273\text{ K}}{300\text{ K}}\right) - (1035\text{ W})\left(1 - \frac{273\text{ K}}{273\text{ K}}\right) = \mathbf{93.2\ W}$$

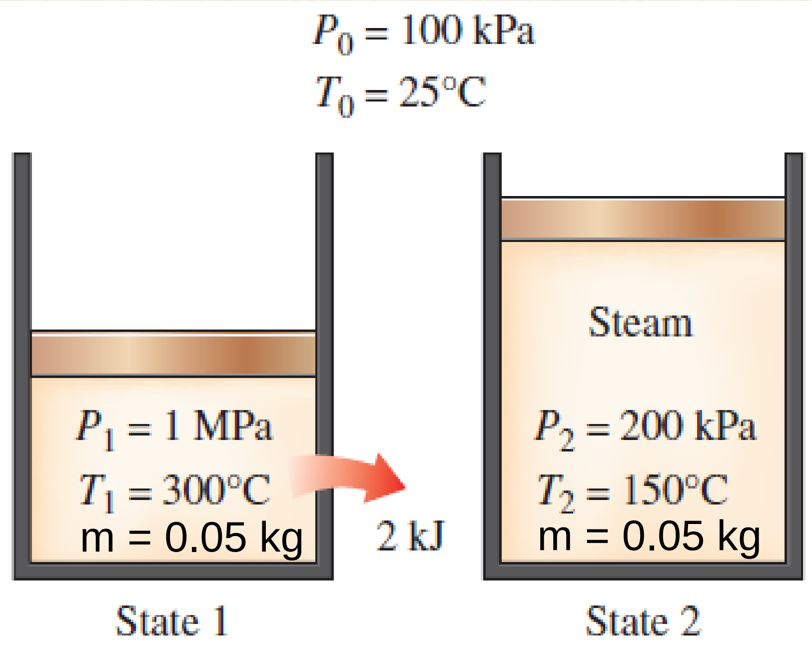
Also:

$\dot{X}_{destroyed,total} = T_0\,\dot{S}_{gen,total}$

$\dot{S}_{gen,total} = \mathbf{0.341\ W/K}$

$T_0 = 273$ K

Example: Exergy Destruction During Expansion



Determine (a) the exergy of the system at the initial and the final states, (b) exergy change of the system, (c) the exergy destroyed, and (d) the second law efficiency for the process

Analysis: We take the *steam* contained within the piston-cylinder device as the system

$$X_1 = m[(u_1 - u_0) - T_0(s_1 - s_0) + P_0(v_1 - v_0)] = \mathbf{35.0\ kJ}$$

$$X_2 = m[(u_2 - u_0) - T_0(s_2 - s_0) + P_0(v_2 - v_0)] = \mathbf{25.4\ kJ}$$

$$\Delta X = X_2 - X_1 = \mathbf{-9.6\ kJ}$$

State 1: $\left.\begin{aligned} P_1 &= 1 \text{ MPa} \\ T_1 &= 300°\text{C} \end{aligned}\right\} \begin{aligned} u_1 &= 2793.7 \text{ kJ/kg} \\ v_1 &= 0.25799 \text{ m}^3\text{/kg} \\ s_1 &= 7.1246 \text{ kJ/kg·K} \end{aligned}$ (Table A–6)

State 2: $\left.\begin{aligned} P_2 &= 200 \text{ kPa} \\ T_2 &= 150°\text{C} \end{aligned}\right\} \begin{aligned} u_2 &= 2577.1 \text{ kJ/kg} \\ v_2 &= 0.95986 \text{ m}^3\text{/kg} \\ s_2 &= 7.2810 \text{ kJ/kg·K} \end{aligned}$ (Table A–6)

Dead state: $\left.\begin{aligned} P_0 &= 100 \text{ kPa} \\ T_0 &= 25°\text{C} \end{aligned}\right\} \begin{aligned} u_0 &\cong u_{f @ 25°\text{C}} = 104.83 \text{ kJ/kg} \\ v_0 &\cong v_{f @ 25°\text{C}} = 0.00103 \text{ m}^3\text{/kg} \\ s_0 &\cong s_{f @ 25°\text{C}} = 0.3672 \text{ kJ/kg·K} \end{aligned}$ (Table A–4)

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

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

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

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

$W_{u,out}$ is the useful boundary work delivered as the system expands

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

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

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

$$W_u = W - W_{\text{surr}} = W_{b,\text{out}} - P_0(V_2 - V_1) = W_{b,\text{out}} - P_0 m(v_2 - v_1) = 5.3 \text{ kJ}$$

$$X_{\text{destroyed}} = X_1 - X_2 - W_{u,\text{out}} = 35.0 - 25.4 - 5.3 = \mathbf{4.3\ kJ}$$

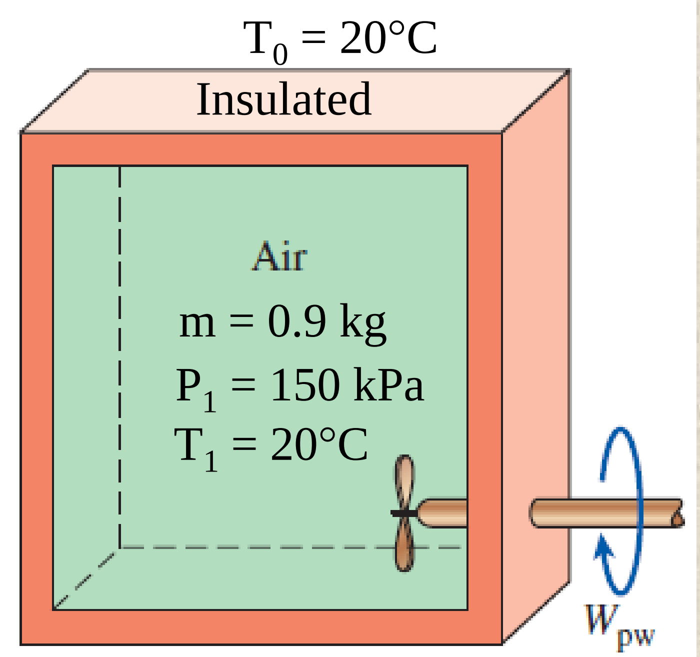
Alternately: $X_{\text{destroyed}} = T_0 S_{\text{gen}} = T_0\left[m(s_2 - s_1) + \frac{Q_{\text{surr}}}{T_0}\right] = 4.3 \text{ kJ}$

$$\eta_{\text{II}} = \frac{\text{Exergy recovered}}{\text{Exergy expended}} = \frac{W_u}{X_1 - X_2} = \frac{5.3}{35.0 - 25.4} = \mathbf{0.552} \text{ or } \mathbf{55.2\%}$$

Example: Exergy Destroyed During Stirring of a Gas

Determine (a) the exergy destroyed and (b) the reversible work for the process

Analysis: We take *air* contained within the tank as the system



$T_1 = 20°C \rightarrow T_2 = 55°C$

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

$$0 + S_{\text{gen}} = \Delta S_{\text{system}} = m\left(c_v \ln\frac{T_2}{T_1} + R\ln\frac{V_2}{V_1}\nearrow^{0}\right)$$

$$S_{\text{gen}} = mc_v \ln\frac{T_2}{T_1}$$

$$X_{\text{destroyed}} = T_0 S_{\text{gen}} = T_0 mc_v \ln\frac{T_2}{T_1}$$ **= 21.4 kJ**

Example: Exergy Destroyed During Stirring of a Gas

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

$$\begin{aligned} W_{rev,in} &= X_2 - X_1 \\ &= (E_2 - E_1) + P_0(V_2 - V_1)\nearrow^{0} - T_0(S_2 - S_1) \\ &= (U_2 - U_1) - T_0(S_2 - S_1) \end{aligned}$$

$$W_{rev,in} = mc_v(T_2 - T_1) - T_0(S_2 - S_1) = 1.2 \text{ kJ}$$

Actual work (the paddle wheel work W_{pw})

$$W_{pw,in} = \Delta U = 22.6 \text{ kJ}$$

Exergy of the system as a result of 22.6 kJ of paddle-wheel work done on it has increased by 1.2 kJ only, that is, by the amount of reversible work. In other words, if the system were returned to its initial state, it would produce, at most, 1.2 kJ of work.

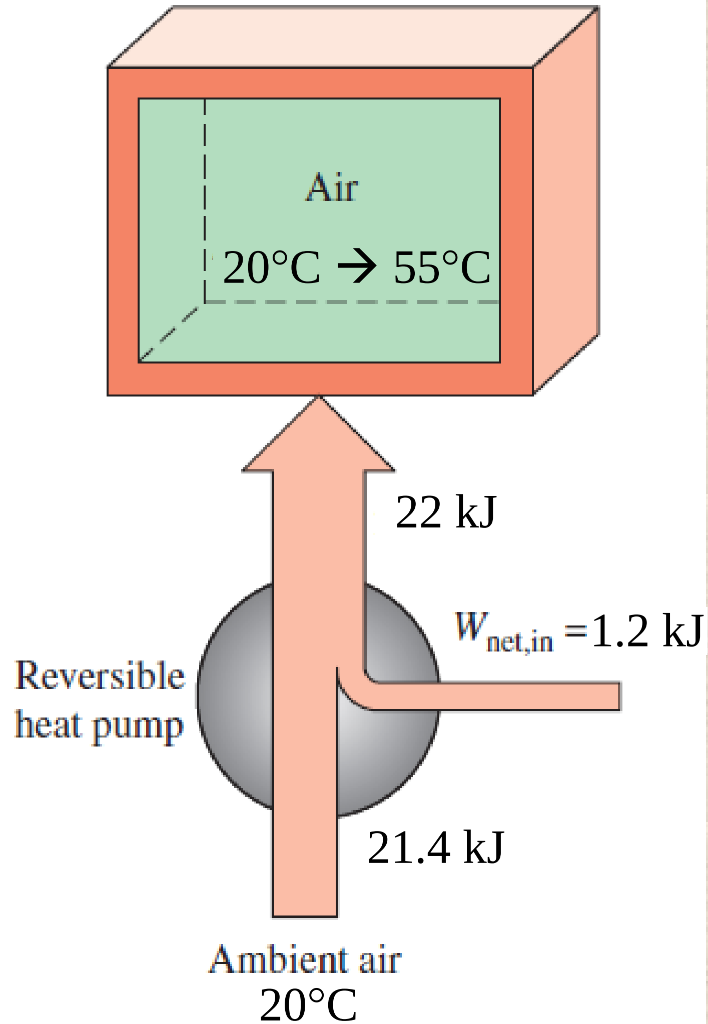
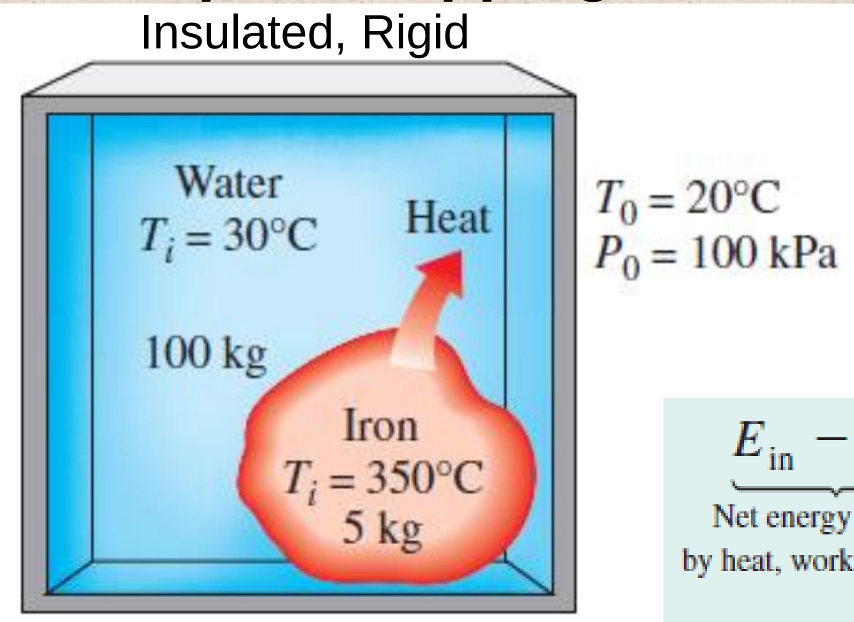


FIGURE 8–38

The same effect on the system can be accomplished by a reversible heat pump that consumes only 1.2 kJ of work.

Example: Dropping a Hot Iron Block into Water



Determine (a) the final equilibrium temperature, (b) exergy of the combined system at the initial and the final states, (c) the wasted work potential during the process

Analysis: We take the entire contents of the tank, *water + iron block,* as the system

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

$$0 = \Delta U$$

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

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

$$T_f = \mathbf{31.7°C}$$

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

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

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

$$X_{1,total} = X_{1,iron} + X_{1,water} = \mathbf{315\ kJ}$$

$$X_{2,total} = X_{2,iron} + X_{2,water} = \mathbf{95.6\ kJ}$$

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

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

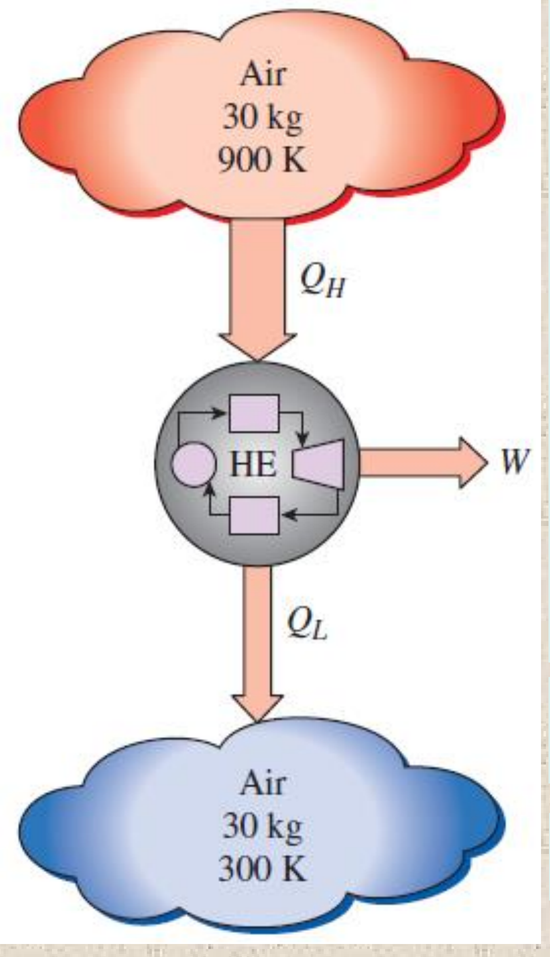
$$X_{destroyed} = X_1 - X_2$$

$$X_{destroyed} = X_1 - X_2 = 315 - 95.6 = \mathbf{219.4\ kJ}$$

Note that 219.4 kJ of work could have been produced as the iron was cooled from 350 = 31.7°C and water was heated from 30 to 31.7°C, but was not

Examples: Work Potential of Heat Transfer Between Two Tanks

Determine the maximum work that can be produced by the heat engine and the final temperatures of the tanks.



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

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

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

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

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

$$T_2 = \sqrt{T_{1,A}T_{1,B}} = \sqrt{(900\,\text{K})(300\,\text{K})} = \mathbf{519.6\,K}$$

$$Q_{source,out} = mc_v(T_{1,A} - T_2) = 8193\ \text{kJ}$$

$$Q_{sink,in} = mc_v(T_2 - T_{1,B}) = 4731\ \text{kJ}$$

$$W_{max,out} = Q_H - Q_L = Q_{source,out} - Q_{sink,\ in} = 8193 - 4731 = \mathbf{3463\,kJ}$$

EXERGY BALANCE: CONTROL VOLUMES

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

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

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

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

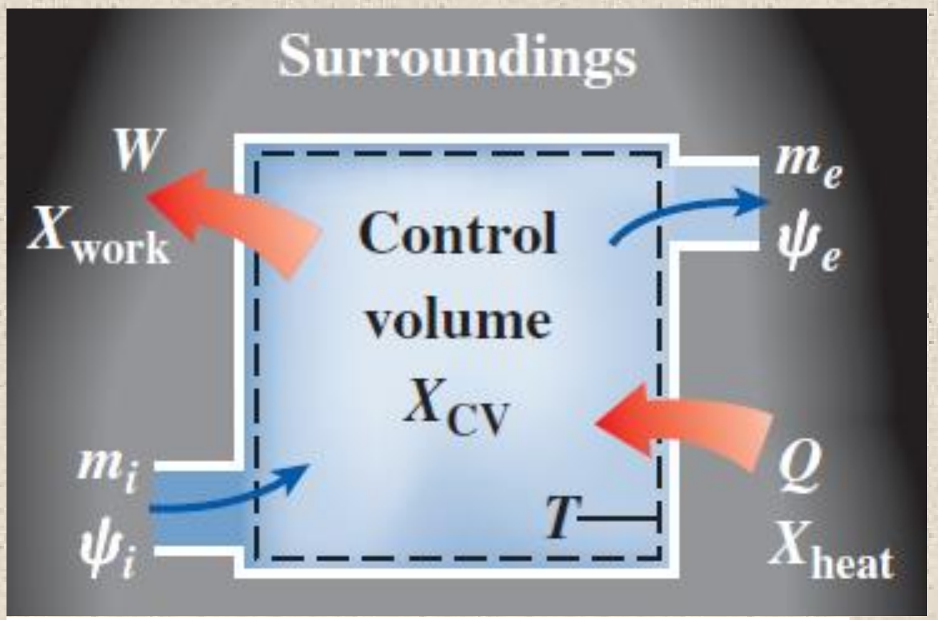


FIGURE 8–41
Exergy is transferred into or out of a control volume by mass as well as heat and work transfer.

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.

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

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

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

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

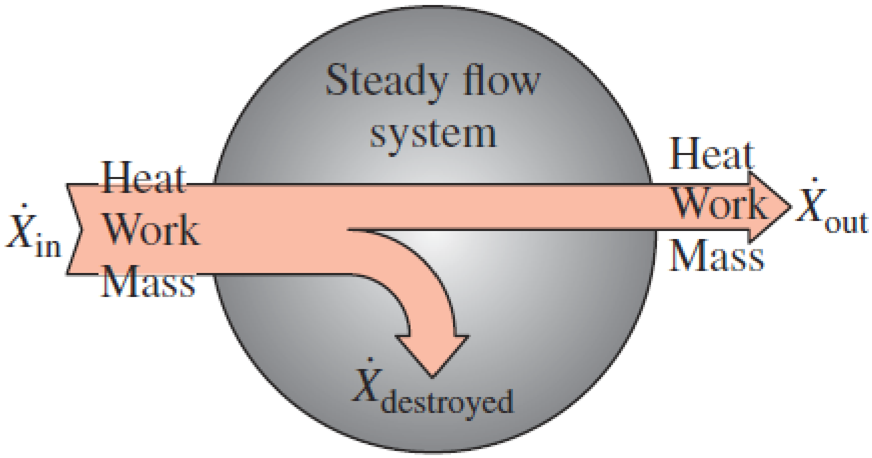


FIGURE 8–42
The exergy transfer to a steady-flow system is equal to the exergy transfer from it plus the exergy destruction within the system.

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

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

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

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:

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

Turbine

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

Compressor

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

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:

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

Heat exchanger

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

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

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

Mixing chamber

$$\eta_{II,mix} = 1 - \frac{T_0 \dot{S}_{gen}}{\dot{m}_1\psi_1 + \dot{m}_2\psi_2}$$

$$\dot{S}_{gen} = \dot{m}_3 s_3 - \dot{m}_2 s_2 - \dot{m}_1 s_1$$

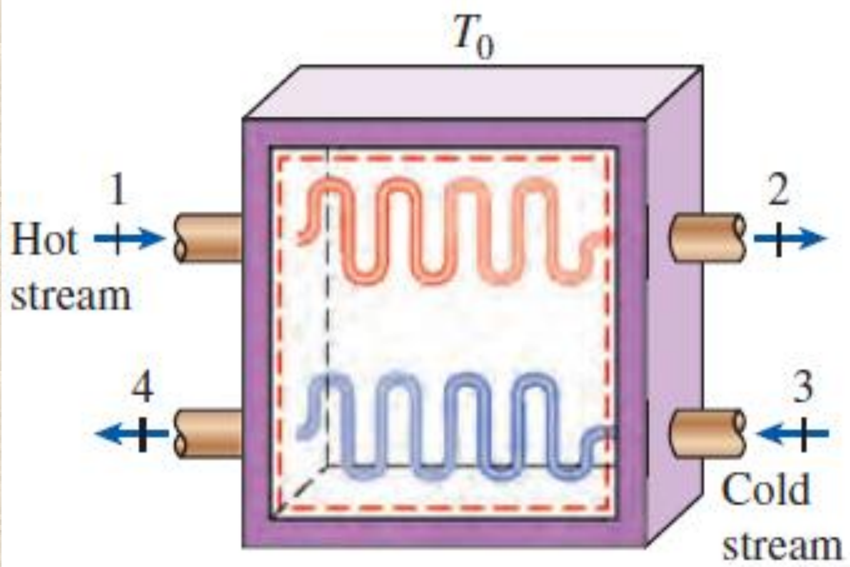
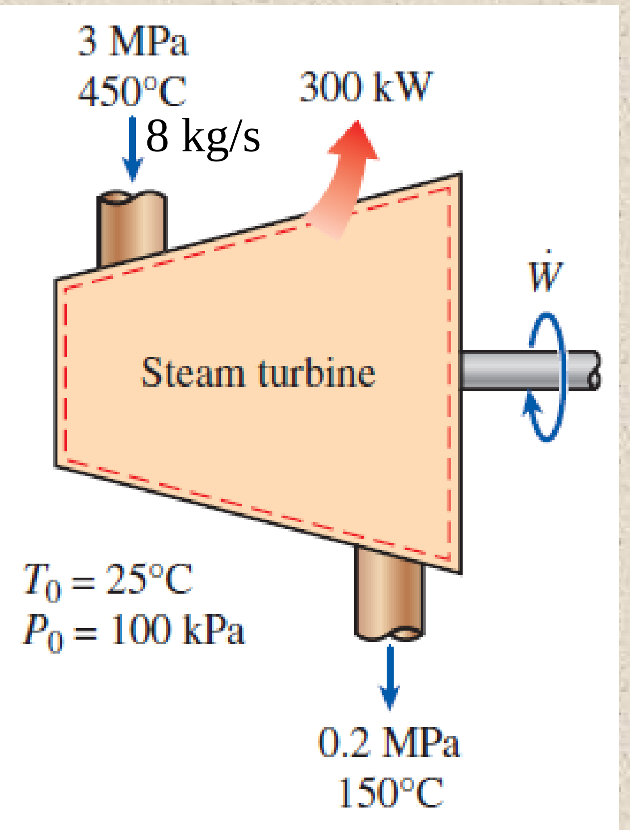


FIGURE 8–43
A heat exchanger with two unmixed fluid streams.

Example: Second-law analysis of a steam turbine

Determine (a) actual power output, (b) maximum possible power output, (c) the second-law efficiency, (d) the exergy destroyed, and (e) the exergy of the steam at the inlet conditions



Inlet state: $\left.\begin{aligned} P_1 &= 3\text{MPa} \\ T_1 &= 450°\text{C} \end{aligned}\right\} \begin{aligned} h_1 &= 3344{\cdot}9 \text{ kJ/kg} \\ s_1 &= 7.0856 \text{ kJ/kg·K} \end{aligned}$

Exit state: $\left.\begin{aligned} P_2 &= 0.2 \text{ MPa} \\ T_2 &= 150°\text{C} \end{aligned}\right\} \begin{aligned} h_2 &= 2769.1 \text{ kJ/kg} \\ s_2 &= 7.2810 \text{ kJ/kg·K} \end{aligned}$

Dead state: $\left.\begin{aligned} P_0 &= 100 \text{ kPa} \\ T_0 &= 25°\text{C} \end{aligned}\right\} \begin{aligned} h_0 &\cong h_{f @ 25°\text{C}} = 104.83 \text{ kJ/kg} \\ s_0 &\cong s_{f @ 25°\text{C}} = 0.3672 \text{ kJ/kg·K} \end{aligned}$

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

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

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

$$\dot{W}_{out} = \dot{m}(h_1 - h_2) - \dot{Q}_{out} = \mathbf{4306\ kW}$$

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

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

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

$$\dot{W}_{rev,out} = \dot{m}(\psi_1 - \psi_2) = \mathbf{5072\ kW}$$

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

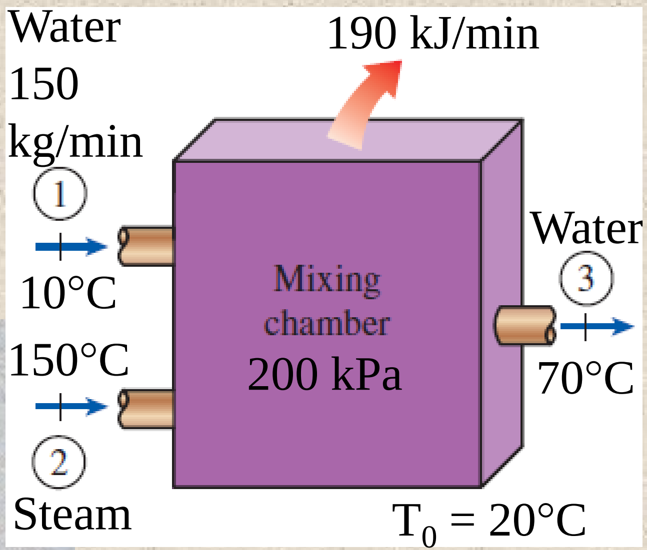
$$\eta_{II} = \frac{\dot{W}_{out}}{\dot{W}_{rev,out}} = \frac{4306 \text{ kW}}{5072 \text{ kW}} = \mathbf{0.849} \text{ or } \mathbf{84.9\%}$$

$$\dot{X}_{destroyed} = \dot{W}_{rev,out} - \dot{W}_{out} = 5072 - 4306 = \mathbf{776 \text{ kW}}$$

$$\begin{aligned}
\psi_1 &= (h_1 - h_0) - T_0(s_1 - s_0) + \frac{V_1^2}{2}^{\nearrow 0} + gz_1^{\nearrow 0} \\
&= (h_1 - h_0) - T_0(s_1 - s_0) \\
&= (3344.9 - 104.83)\text{kJ/kg} - (298 \text{ K})(7.0856 - 0.3672) \text{ kJ/kg·K} \\
&= \mathbf{1238 \text{ kJ/kg}}
\end{aligned}$$

Example: Exergy Destroyed During Mixing of Fluid Streams

Determine the reversible power and the rate of exergy destruction for the process



State 1: $\left.\begin{array}{l} P_1 = 200 \text{ kPa} \\ T_1 = 10°\text{C} \end{array}\right\}$ $\begin{array}{l} h_1 = h_{f @ 10°C} = 42.022 \text{ kJ/kg} \\ s_1 = s_{f @ 10°C} = 0.1511 \text{ kJ/kg·K} \end{array}$

State 2: $\left.\begin{array}{l} P_2 = 200 \text{ kPa} \\ T_2 = 150°\text{C} \end{array}\right\}$ $\begin{array}{l} h_2 = 2769.1 \text{ kJ/kg} \\ s_2 = 7.2810 \text{ kJ/kg·K} \end{array}$

State 3: $\left.\begin{array}{l} P_3 = 200 \text{ kPa} \\ T_3 = 70°\text{C} \end{array}\right\}$ $\begin{array}{l} h_3 = h_{f @ 70°C} = 293.07 \text{ kJ/kg} \\ s_3 = s_{f @ 70°C} = 0.9551 \text{ kJ/kg·K} \end{array}$

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

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

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

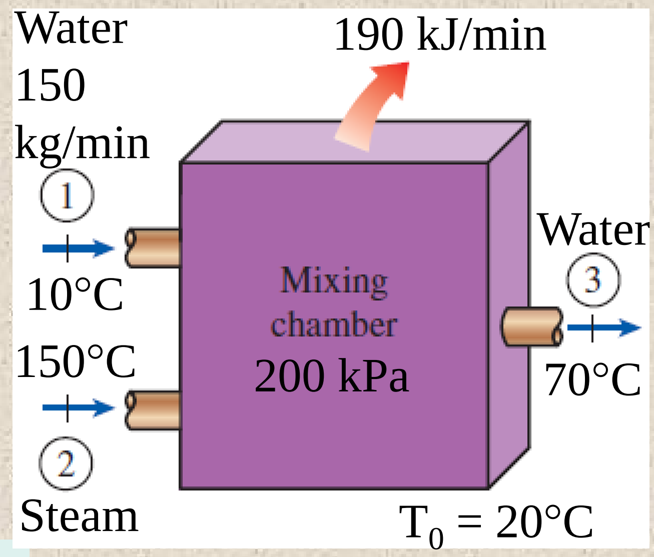
$$\dot{m}_1 h_1 + \dot{m}_2 h_2 = \dot{m}_3 h_3 + \dot{Q}_{out} \text{ (since } \dot{W} = 0, \text{ ke} \cong \text{pe} \cong 0)$$

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

$$\dot{m}_2 = \mathbf{15.29 \text{ kg/min}}$$

Exergy Destroyed During Mixing of Fluid Streams

The maximum power output (reversible power) is determined from the rate form of the exergy balance applied to the ***extended system*** *(system + immediate surroundings),* whose boundary is at the environment temperature of T_0, and by setting the exergy destruction term equal to zero



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

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

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

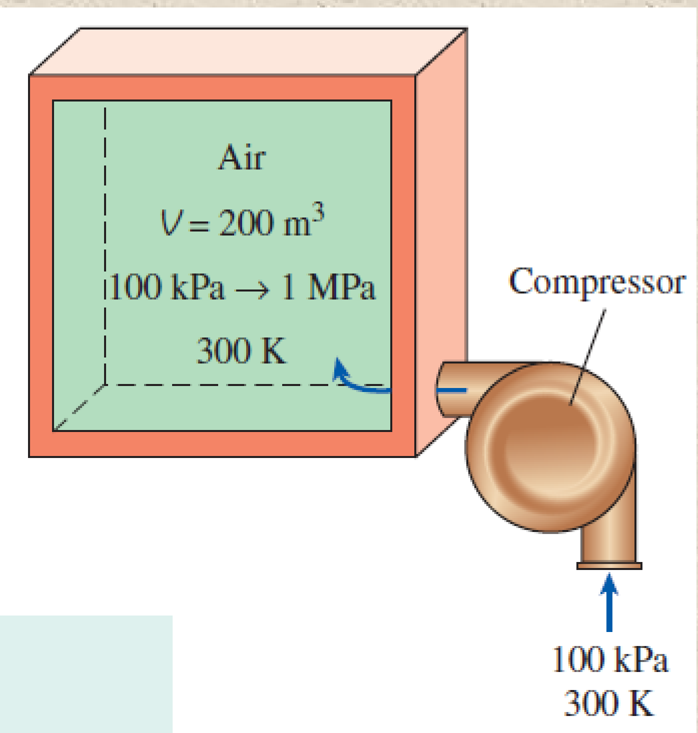
$$\dot{W}_{rev,out} = \dot{m}_1\psi_1 + \dot{m}_2\psi_2 - \dot{m}_3\psi_3$$ **= 7197 kJ/min**

$$\dot{X}_{destroyed} = \dot{W}_{rev,out} - \dot{W}_u^{\nearrow 0} = \dot{X}_{destroyed} = \dot{W}_{rev,out}$$ **= 7197 kJ/min**

$$\dot{X}_{destroyed} = T_0\,\dot{S}_{gen}$$ = (293 K)(24.53 kJ/min-K) **= 7197 kJ/min**

Example: Charging a Compressed Air Storage System

Determine the minimum work requirement for this process



The minimum work required for this process is the *reversible work,* which can be determined from the exergy balance applied to the ***extended system*** *(system + immediate surroundings),* whose boundary is at the environment temperature of T_0 (so that there is no exergy transfer accompanying heat transfer to or from the environment), and by setting the exergy destruction term equal to zero

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

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

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

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

$$m_2 = \frac{P_2V}{RT_2}$$

Example: Charging a Compressed Air Storage System

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

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

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

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

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

$$W_{\text{rev,in}} = m_2\phi_2 = (2323 \text{ kg})(120.76 \text{ kJ/kg}) = 280{,}525 \text{ kJ} \cong \mathbf{281\ MJ}$$

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