Thermodynamics: An Engineering Approach, 5th Edition
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McGraw-Hill, 2008

# Chapter 8
# EXERGY: A MEASURE OF WORK POTENTIAL

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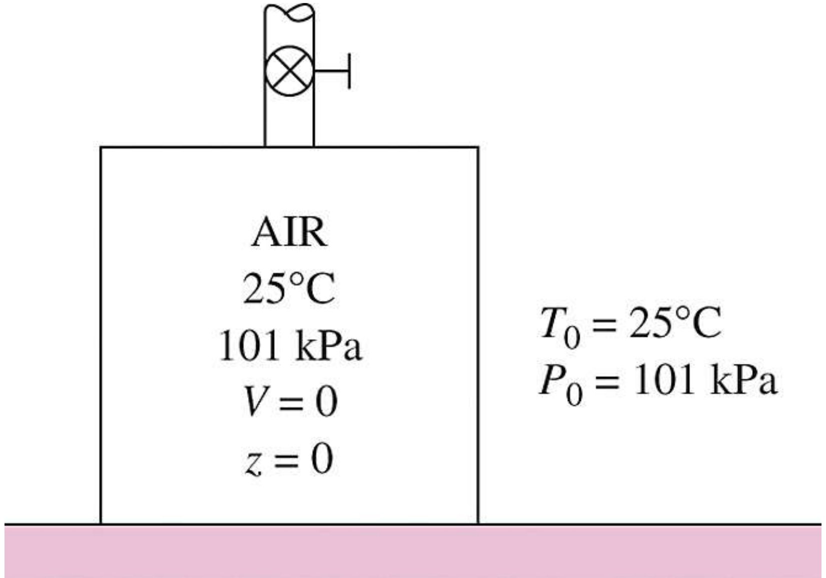
# Objectives

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

# EXERGY: WORK POTENTIAL OF ENERGY

The useful work potential of a given amount of energy at some specified state is called *exergy*, which is also called the *availability* or *available energy*.
A system is said to be in the dead state when it is in thermodynamic equilibrium with the environment it is in.



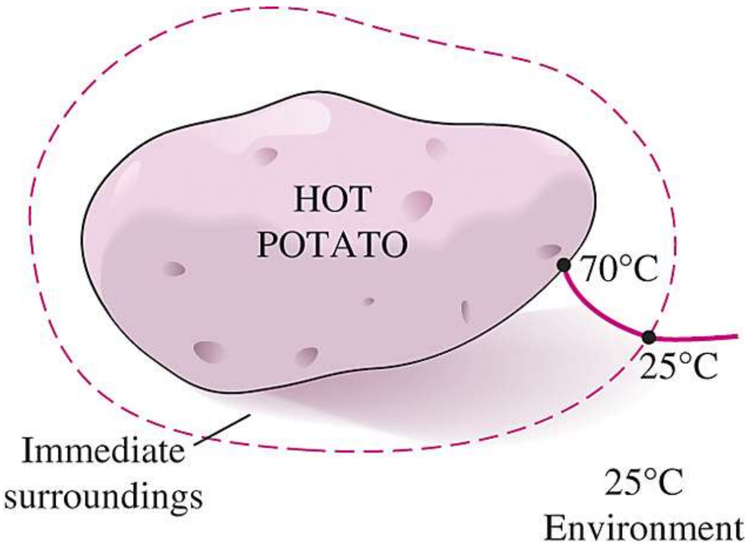

A system that is in equilibrium with its environment is said to be at the dead state.


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

*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.




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

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

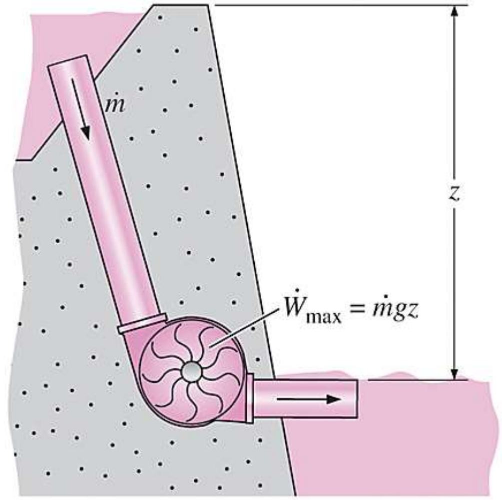
# Exergy (Work Potential) Associated with Kinetic and Potential Energy

*Exergy of kinetic energy:*

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

*Exergy of potential energy:*

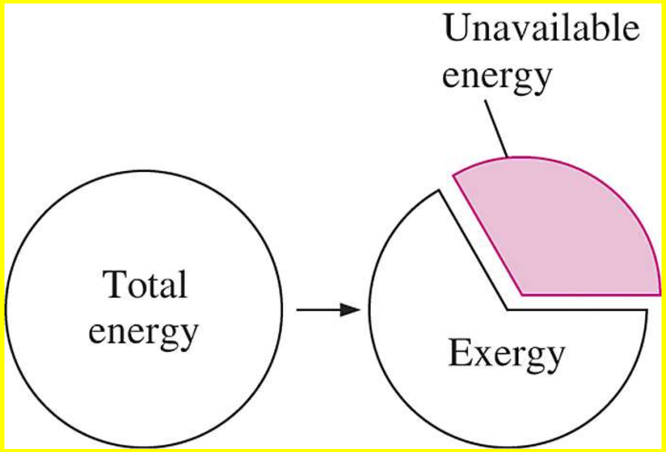
$$x_{pe} = pe = gz \qquad (kJ/kg)$$




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

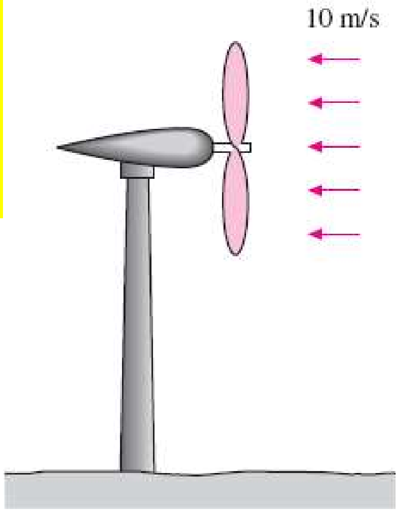
The *work potential* or *exergy* of potential energy is equal to the potential energy itself.

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



## EXAMPLE 8-1

A wind turbine with a 12-m-diameter rotor, is to be installed at a location where the wind is blowing steadily at an average velocity of 10 m/s. Determine the maximum power that can be generated by the wind turbine.




**Solution** A wind turbine is being considered for a specified location. The maximum power that can be generated by the wind turbine is to be determined.

***Assumptions*** Air is at standard conditions of 1 atm and 25°C, and thus its density is 1.18 kg/m³.

$$\mathrm{ke}_1 = \frac{V_1^2}{2} = \frac{(10\ \mathrm{m/s})^2}{2}\left(\frac{1\ \mathrm{kJ/kg}}{1000\ \mathrm{m^2/s^2}}\right) = 0.05\ \mathrm{kJ/kg}$$

$$\dot{m} = \rho A V_1 = \rho \frac{\pi D^2}{4} V_1 = (1.18\ \mathrm{kg/m^3}) \frac{\pi (12\ \mathrm{m})^2}{4} (10\ \mathrm{m/s}) = 1335\ \mathrm{kg/s}$$

$$\text{Maximum power} = \dot{m}(\mathrm{ke}_1) = (1335\ \mathrm{kg/s})(0.05\ \mathrm{kJ/kg}) = \mathbf{66.7\ kW}$$

A conversion efficiency of 25 %, an actual wind turbine will convert 16.7 kW to electricity.

***Discussion*** Betz's law states that the power output of a wind machine will be at maximum when the wind is slowed to one-third of its initial velocity. Therefore, for maximum power the highest efficiency of a wind turbine is about 59 %. In practice, the actual efficiency ranges between 20 and 40 % and is about 35 % for most wind turbines.

**EXAMPLE 8–2**

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

**Solution** Heat is being supplied by a large furnace at a specified temperature. The rate of exergy flow is to be determined.

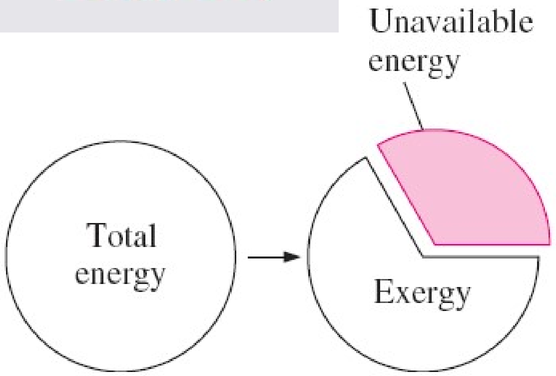
***Analysis*** The furnace supplies heat indefinitely at a constant temperature. The exergy of this heat energy is its useful work potential, that is, the maximum possible amount of work that can be extracted from it. This corresponds to the amount of work that a reversible heat engine operating between the furnace and the environment can produce.

The thermal efficiency of this reversible heat engine is

$$\eta_{\text{th,max}} = \eta_{\text{th,rev}} = 1 - \frac{T_L}{T_H} = 1 - \frac{T_0}{T_H} = 1 - \frac{298\text{ K}}{1100\text{ K}} = 0.729\ (\text{or } 72.9\%)$$

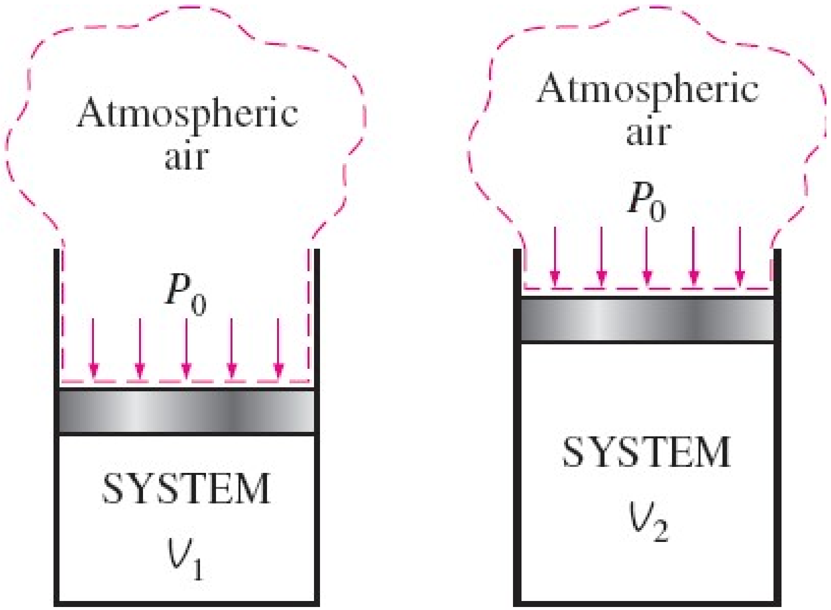
$$\dot{W}_{\text{max}} = \dot{W}_{\text{rev}} = \eta_{\text{th,rev}}\,\dot{Q}_{\text{in}} = (0.729)(3000\text{ kW}) = \mathbf{2187\ kW}$$

***Discussion*** Notice that 26.8 percent of the heat transferred from the furnace is not available for doing work. The portion of energy that cannot be converted to work is called **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.

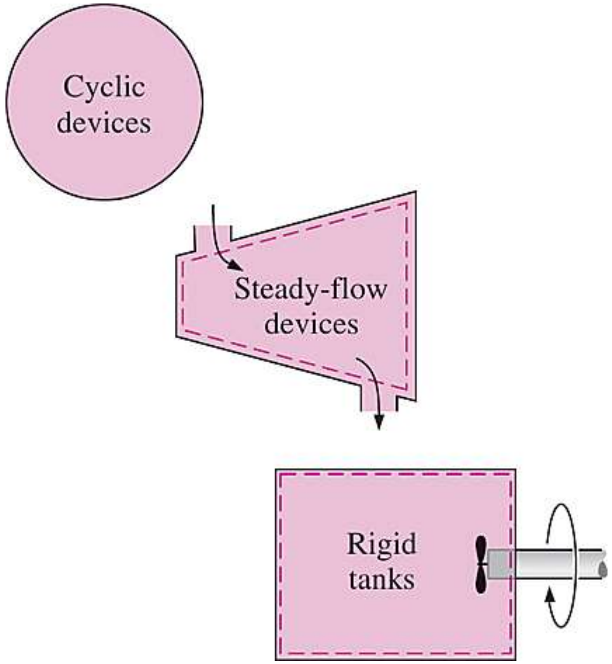


# REVERSIBLE WORK AND IRREVERSIBILITY

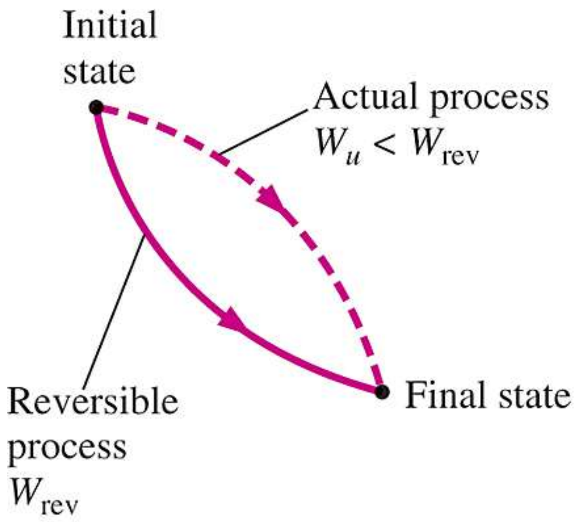
**Reversible work $W_{rev}$:** The maximum amount of useful work that can be produced (or the minimum work that needs to be supplied) as a system undergoes a process between the specified initial and final states.




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




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




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

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

**surroundings work**

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

**Useful work $W_u$**

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

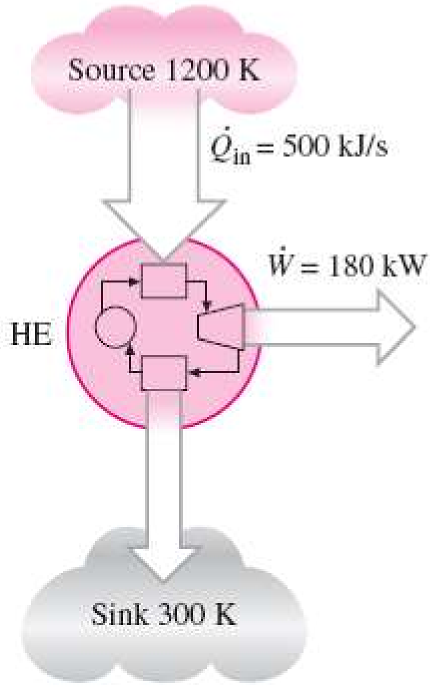
**irreversibility $I$**

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

**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 smaller the irreversibility associated with a process, the greater the work that will be produced (or the smaller the work that will be consumed). The performance of a system can be improved by minimizing the irreversibility associated with it.

## EXAMPLE 8–3

A heat engine receives heat from a source at 1200 K at a rate of 500 kJ/s and rejects the waste heat to a medium at 300 K. The power output of the heat engine is 180 kW. Determine the reversible power and the irreversibility rate for this process.




**Solution** A heat engine operating between a specified source and a specified sink. The reversible power and the irreversibility rate associated with this operation are to be determined.

***Analysis*** The reversible power for this process is the amount of power that a reversible heat engine, such as a Carnot heat engine would produce when operating between the same temperature limits.

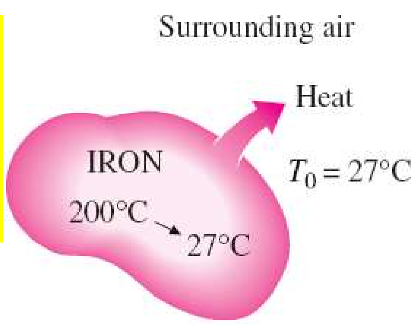
$$\dot{W}_{rev} = \eta_{th,\,rev}\,\dot{Q}_{in} = \left(1 - \frac{T_{sink}}{T_{source}}\right)\dot{Q}_{in} = \left(1 - \frac{300\text{ K}}{1200\text{ K}}\right)(500\text{ kW}) = \mathbf{375\ kW}$$

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

***Discussion*** Note that 195 kW of power potential is wasted during this process as a result of irreversibilities. Also, the 500  375  125 kW of heat rejected to the sink is not available for converting to work and thus is not part of the irreversibility.

## EXAMPLE 8–4

A 500-kg iron block is initially at 200°C and is allowed to cool to 27°C by transferring heat to the surrounding air at 27°C. Determine the reversible work and the irreversibility for this process.




**Solution** A hot iron block is allowed to cool in air. The reversible work and irreversibility associated with this process are to be determined.

***Assumptions*** **1** The kinetic and potential energies are negligible. **2** The process involves no work interactions.

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

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

$$-\delta Q_{out} = dU = mC_{av}\,dT$$

$$\delta Q_{in,\,heat\ engine} = \delta Q_{out,\,system} = -mC_{av}\,dT$$

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

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

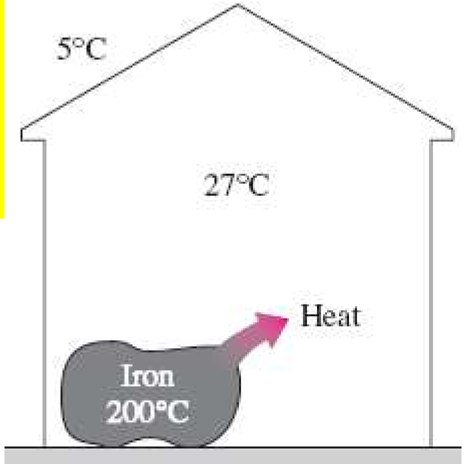
$$= \mathbf{8191\ kJ}$$

The irreversibility for this process is determined from its definition,

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

# EXAMPLE 8-5

The iron block discussed in Example 8–4 is to be used to maintain a house at 27°C when the outdoor temperature is 5°C. Determine the maximum amount of heat that can be supplied to the house as the iron cools to 27°C.




**Solution** The iron block discussed before is considered for heating a house. The maximum amount of heating this block can provide is to be determined.

$$\text{COP}_{\text{HP}} = \frac{1}{1 - T_L/T_H} = \frac{1}{1 - (278\text{ K})/(300\text{ K})} = 13.6$$

This heat pump can supply the house with 13.6 times the energy it consumes as work. In our case, it will consume the 8191 kJ of work and deliver 8191x13.6=111,398 kJ of heat to the house. Therefore, the hot iron block has the potential to supply of heat to the house.

$$(30{,}734 + 111{,}398)\text{ kJ} = 142{,}132\text{ kJ} \cong \mathbf{142\ MJ}$$

# SECOND-LAW EFFICIENCY, $\eta_{II}$

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

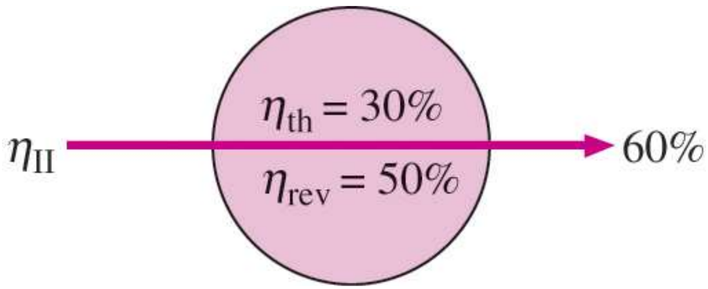
$$\eta_{II} = \frac{W_u}{W_{rev}} \qquad \text{(work-producing devices)}$$

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

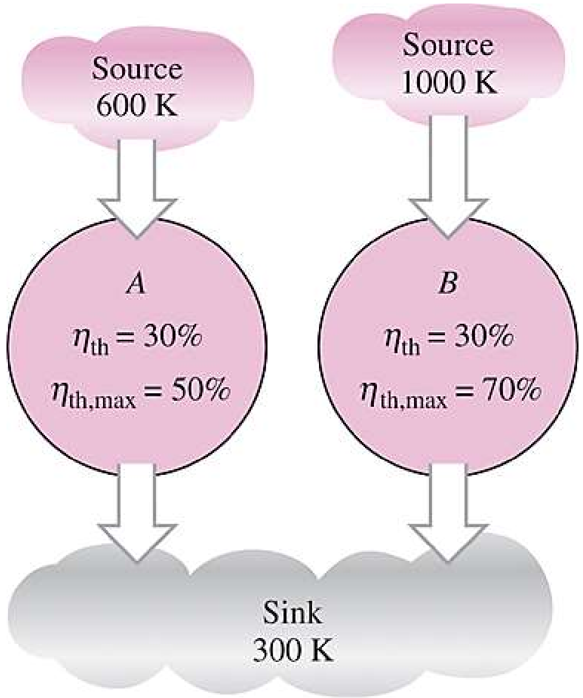
$$\eta_{II} = \frac{\text{COP}}{\text{COP}_{rev}} \qquad \text{(refrigerators and heat pumps)}$$

$$\eta_{rev,\,A} = \left(1 - \frac{T_L}{T_H}\right)_A = 1 - \frac{300\text{ K}}{600\text{ K}} = 50\%$$

$$\eta_{rev,\,B} = \left(1 - \frac{T_L}{T_H}\right)_B = 1 - \frac{300\text{ K}}{1000\text{ K}} = 70\%$$




$$\eta_{II,B} = \frac{0.30}{0.70} = 0.43$$

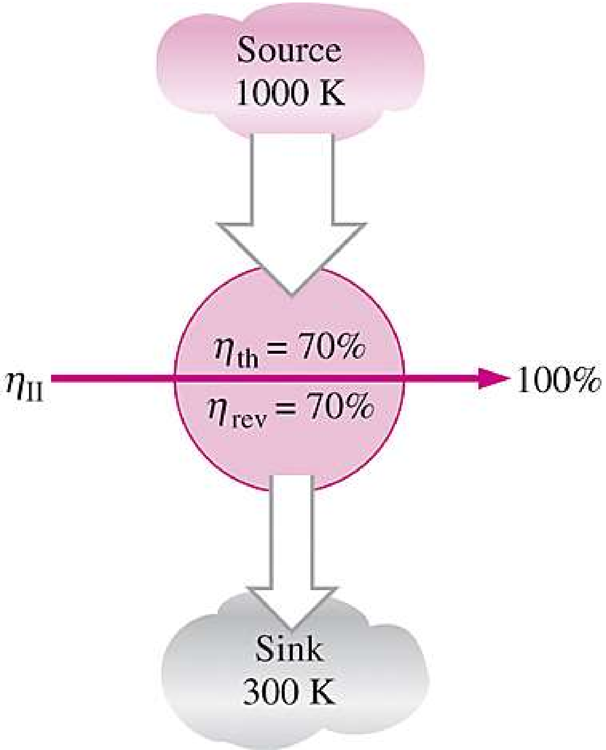



Second-law efficiency is a measure of the performance of a device relative to its performance under reversible conditions.

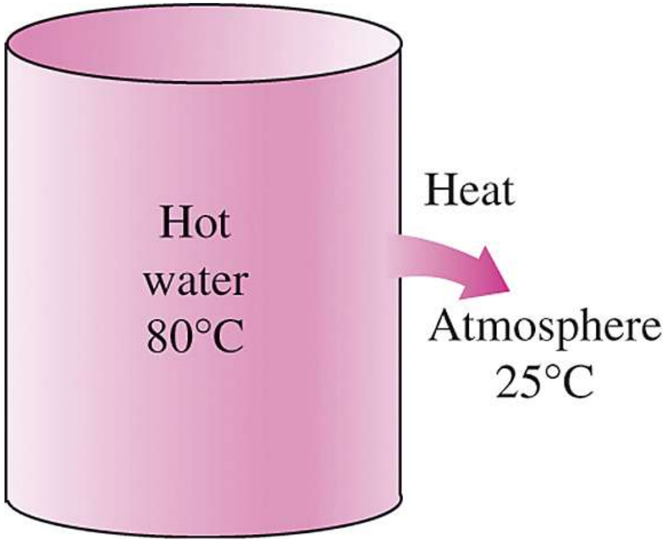
Two heat engines that have the same thermal efficiency, but different maximum thermal efficiencies.

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

General definition of exergy efficiency



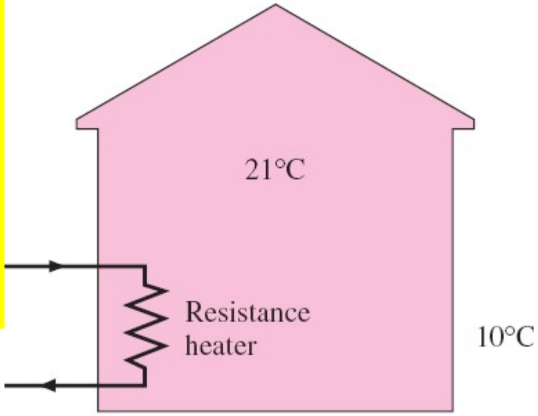

Second-law efficiency of all reversible devices is 100%.




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

## EXAMPLE 8–6

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




**Solution** Electric resistance heaters are being considered for residential buildings. The second-law efficiency of these heaters is to be determined.

***Analysis*** Obviously the efficiency that the dealer is referring to is the first law efficiency, meaning that for each unit of electric energy consumed, the heater will supply the house with 1 unit of energy (heat). That is, the advertised heater has a COP of 1.

A reversible heat pump would have a coefficient of the performance of

$$\mathrm{COP}_{\mathrm{HP,\,rev}} = \frac{1}{1 - T_L/T_H} = \frac{1}{1 - (283\ \mathrm{K})/(294\ \mathrm{K})} = 26.7$$

The second-law efficiency of this resistance heater is

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

The dealer will not be happy to see this value. Considering the high price of electricity, a consumer will probably be better off with a “less” efficient gas heater.

# EXERGY CHANGE OF A SYSTEM

## Exergy of a Fixed Mass: Non flow (or Closed System) Exergy

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

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

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

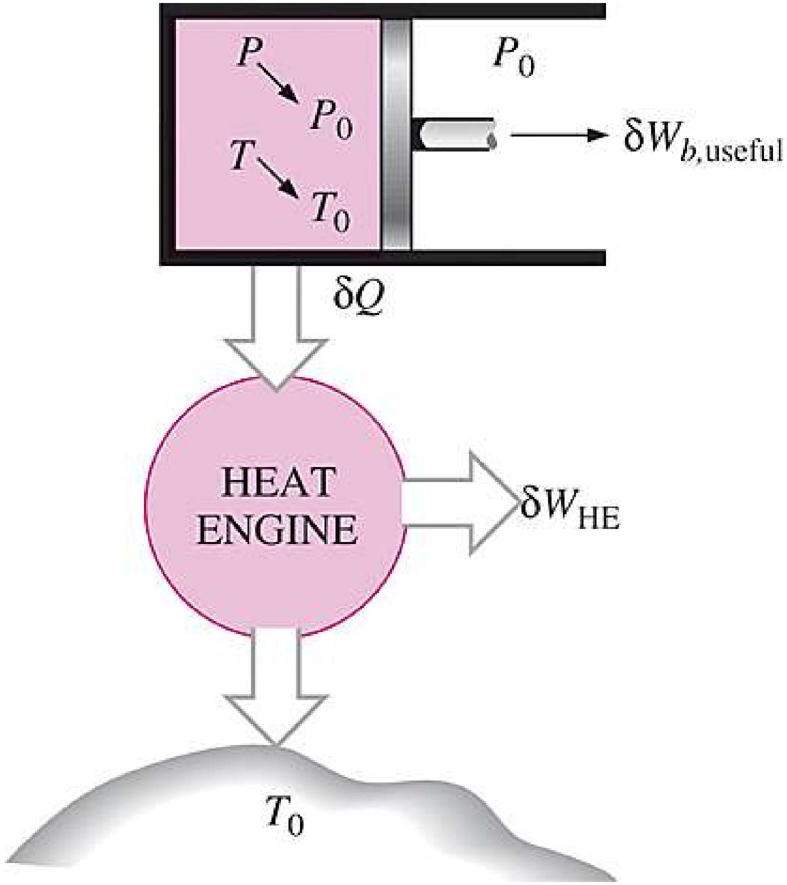
$$\delta W_{\text{HE}} = \left(1 - \frac{T_0}{T}\right)\delta Q = \delta Q - \frac{T_0}{T}\delta Q = \delta Q - (-T_0\,dS) \rightarrow \delta Q$$

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

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

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

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




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.

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

Closed system exergy per unit mass

Exergy change of a closed system

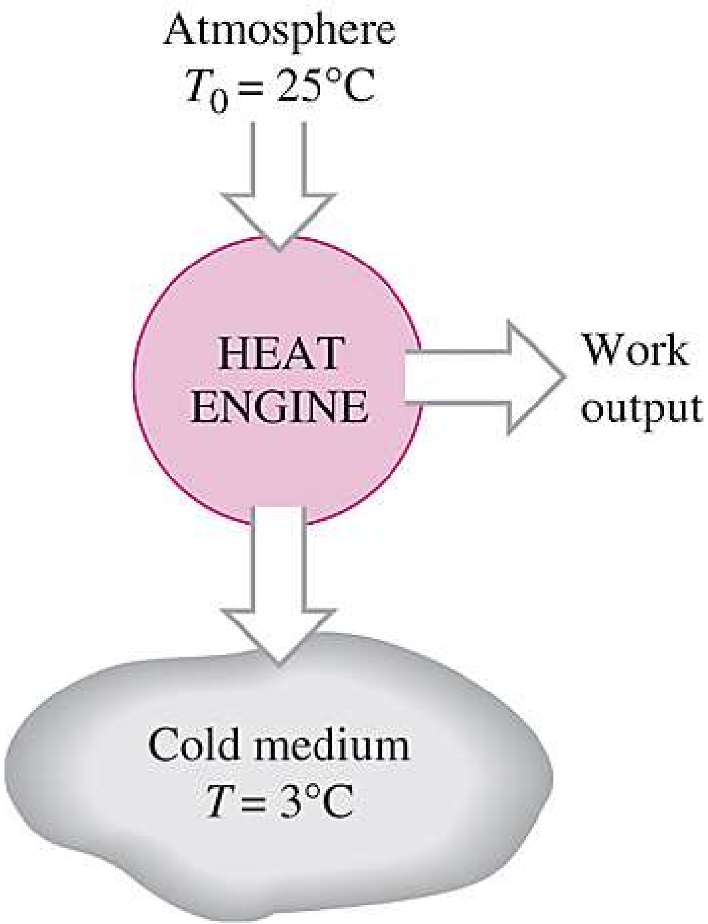
$$\Delta X = X_2 - X_1 = m(\phi_2 - \phi_1) = (E_2 - E_1) + P_0(V_2 - V_1) - T_0(S_2 - S_1)$$

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

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

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

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




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

Exergy of flow energy

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

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

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

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

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

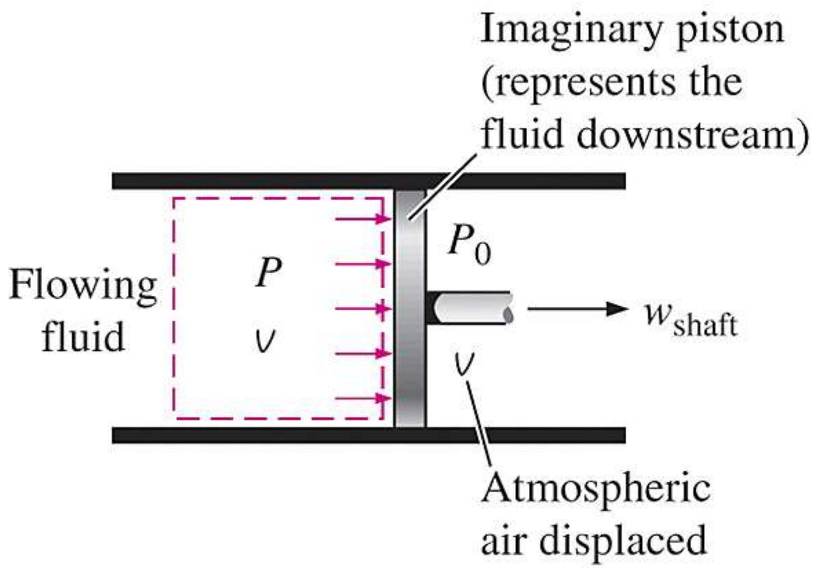
Flow exergy

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

## Exergy change of flow

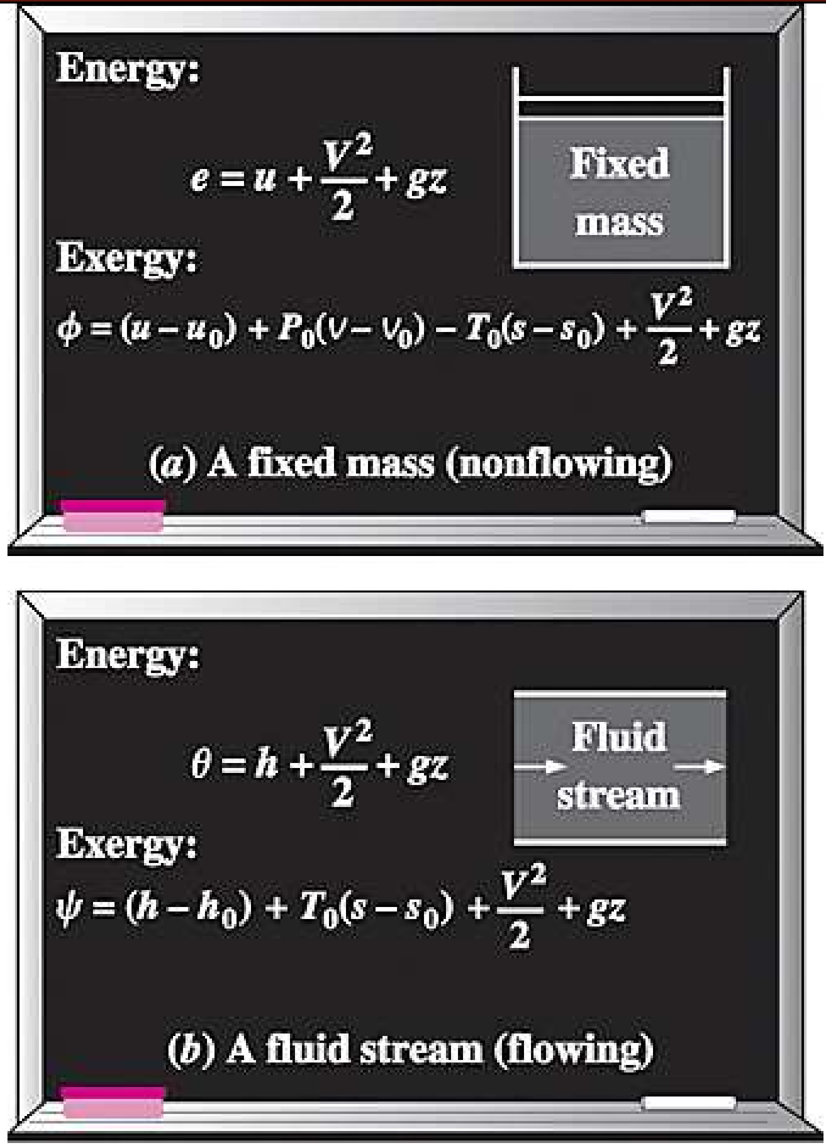
$$\Delta\psi = \psi_2 - \psi_1$$

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




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

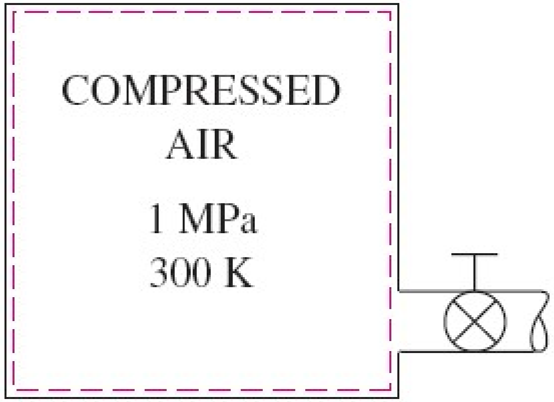
The *exergy* associated with *flow energy* is the useful work that would be delivered by an imaginary piston in the flow section.




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

## EXAMPLE 8–7

A 200-$m^3$ rigid tank contains compressed air at 1 MPa and 300 K. Determine how much work can be obtained from this air if the environment conditions are 100 kPa and 300 K.




**Solution** Compressed air stored in a large tank is considered. The work potential of this air is to be determined.

***Assumptions*** **1** Air is an ideal gas since it is at a high temperature and low pressure relative to its critical point values. **2** The kinetic and potential energies are negligible.

$$m_1 = \frac{P_1 V}{RT_1} = \frac{(1000\ \text{kPa})(200\ \text{m}^3)}{(0.287\ \text{kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(300\ \text{K})} = 2323\ \text{kg}$$

The exergy content of the compressed air can be determined from

$$\begin{aligned} X_1 &= m\phi_1 \\ &= m\left[(u_1 - u_0)^{\nearrow 0} + P_0(v_1 - v_0) - T_0(s_1 - s_0) + \frac{V_1^2}{2}^{\nearrow 0} + gz_1^{\nearrow 0}\right] \\ &= m[P_0(v_1 - v_0) - T_0(s_1 - s_0)] \end{aligned}$$

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

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

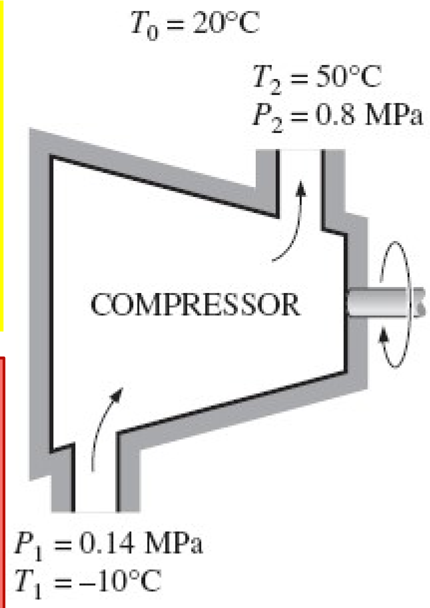
$$\begin{aligned}
\phi_1 &= RT_0\left(\frac{P_0}{P_1} - 1\right) + RT_0 \ln\frac{P_1}{P_0} = RT_0\left(\ln\frac{P_1}{P_0} + \frac{P_0}{P_1} - 1\right) \\
&= (0.287 \text{ kJ/kg}\cdot\text{K})(300 \text{ K})\left(\ln\frac{1000 \text{ kPa}}{100 \text{ kPa}} + \frac{100 \text{ kPa}}{1000 \text{ kPa}} - 1\right) \\
&= 120.76 \text{ kJ/kg}
\end{aligned}$$

$$X_1 = m_1\phi_1 = (2323 \text{ kg})(120.76 \text{ kJ/kg}) = \mathbf{280{,}525 \text{ kJ}}$$

***Discussion*** The work potential of the system is 280,525 kJ, and thus a maximum of 280,525 kJ of useful work can be obtained from the compressed air stored in the tank in the specified environment.

## EXAMPLE 8–8

Refrigerant-134a is to be compressed from 0.14 MPa and 10°C to 0.8 MPa and 50°C steadily by a compressor. Taking the environment conditions to be 20°C and 95 kPa, determine the exergy change of the refrigerant during this process and the minimum work input that needs to be supplied to the compressor per unit mass of the refrigerant.




**Solution** Refrigerant-134a is being compressed from a specified inlet state to a specified exit state. The exergy change of the refrigerant and the minimum compression work per unit mass are to be determined.

***Assumptions*** **1** Steady operating conditions exist. **2** The kinetic and potential energies are negligible.

$$\textit{Inlet state:} \quad \left.\begin{aligned} P_1 &= 0.14 \text{ MPa} \\ T_1 &= -10°\text{C} \end{aligned}\right\} \quad \begin{aligned} h_1 &= 246.36 \text{ kJ/kg} \\ s_1 &= 0.9724 \text{ kJ/kg} \cdot \text{K} \end{aligned}$$

$$\textit{Exit state:} \quad \left.\begin{aligned} P_2 &= 0.8 \text{ MPa} \\ T_2 &= 50°\text{C} \end{aligned}\right\} \quad \begin{aligned} h_2 &= 286.69 \text{ kJ/kg} \\ s_2 &= 0.9802 \text{ kJ/kg} \cdot \text{K} \end{aligned}$$

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

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

$$= (286.69 - 246.36)\ \text{kJ/kg} - (293\ \text{K})[(0.9802 - 0.9724)\text{kJ/kg}\cdot\text{K}]$$

$$= \mathbf{38.0\ kJ/kg}$$

The exergy change of a system in a specified environment represents the reversible work in that environment, which is the minimum work input required for work-consuming devices such as compressors. Therefore, the increase in exergy of the refrigerant is equal to the minimum work that needs to be supplied to the compressor:

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

***Discussion*** *Note that if the compressed refrigerant at 0.8 MPa and 50°C* were to be expanded to 0.14 MPa and -10°C in a turbine in the same environment in a reversible manner, 38.0 kJ/kg of work would be produced.

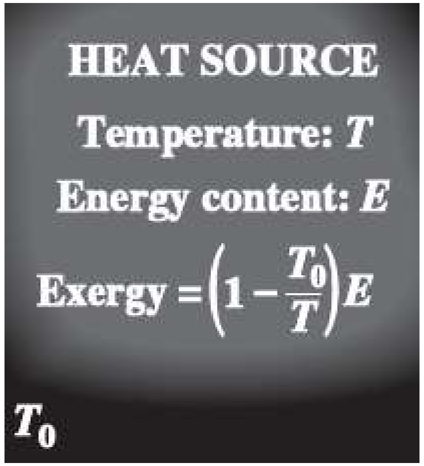
## Exergy by Heat Transfer, $Q$

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

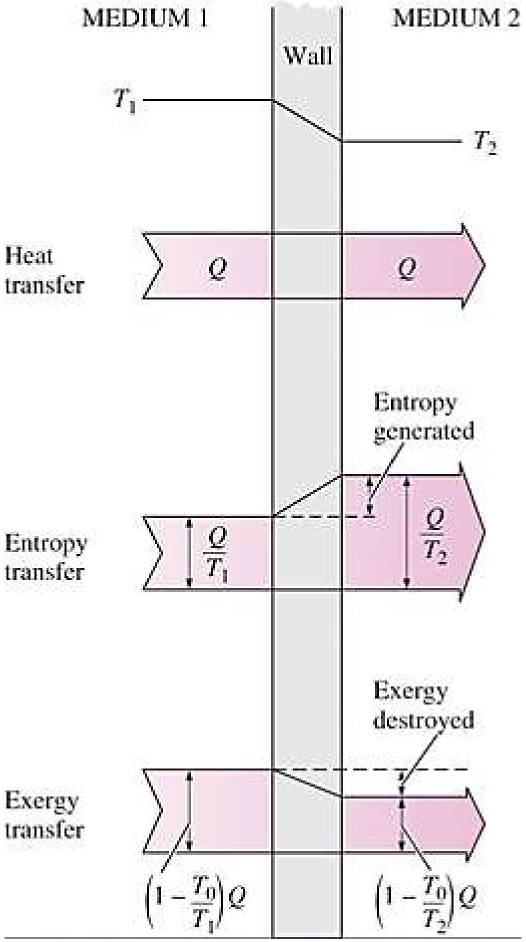
Exergy transfer by heat

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

When temperature is not constant




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 $T_0$.

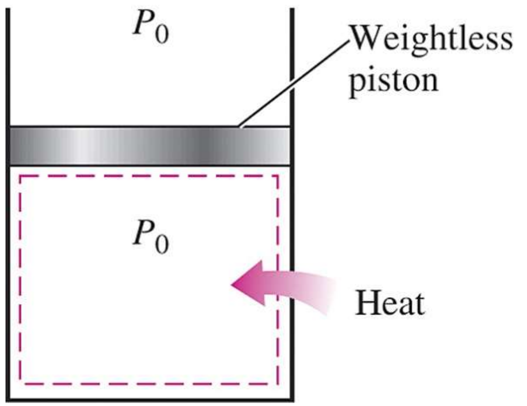



The transfer and destruction of exergy during a heat transfer process through a finite temperature difference.

# Exergy Transfer by Work, $W$

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

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



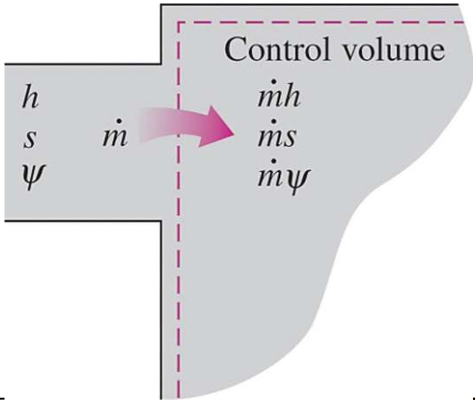

There is no useful work transfer associated with boundary work when the pressure of the system is maintained constant at atmospheric pressure.

# Exergy Transfer by Mass, *m*

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

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

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




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

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

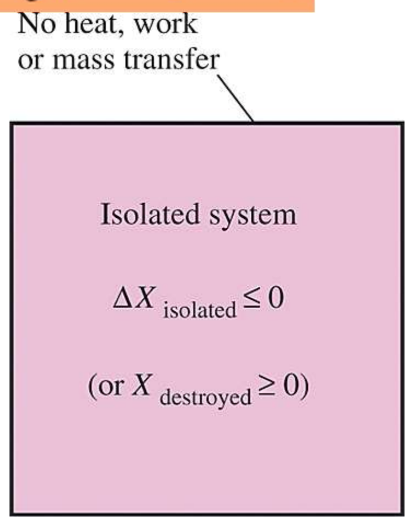
*Entropy balance:* $S_{in}^{\nearrow 0} - S_{out}^{\nearrow 0} + S_{gen} = \Delta S_{system} \rightarrow S_{gen} = S_2 - S_1$

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

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

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

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




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

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

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

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?

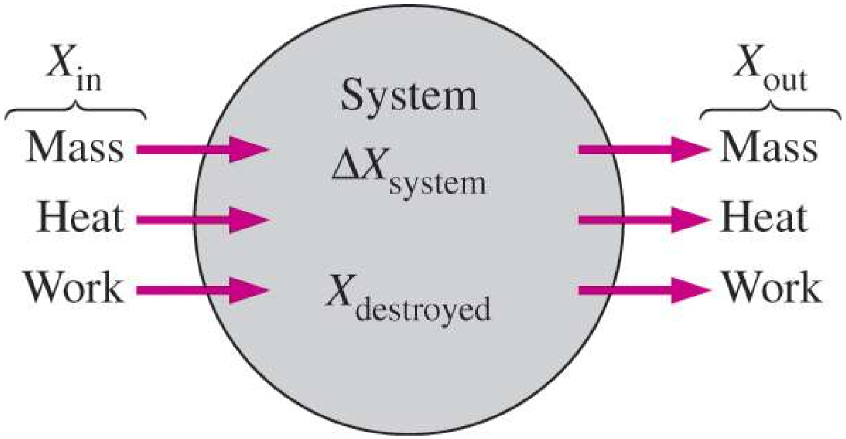

The exergy change of a system can be negative, but the exergy destruction cannot.

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

# EXERGY BALANCE: CLOSED SYSTEMS

The nature of exergy is opposite to that of entropy in that exergy can be *destroyed,* but it cannot be created.

Therefore, 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.




Mechanisms of exergy transfer.

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

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

in the **rate form**

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

$$\dot{X}_{heat} = (1 - T_0/T)\dot{Q},$$

$$\dot{X}_{work} = \dot{W}_{useful},$$

$$\dot{X}_{mass} = \dot{m}\psi$$

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

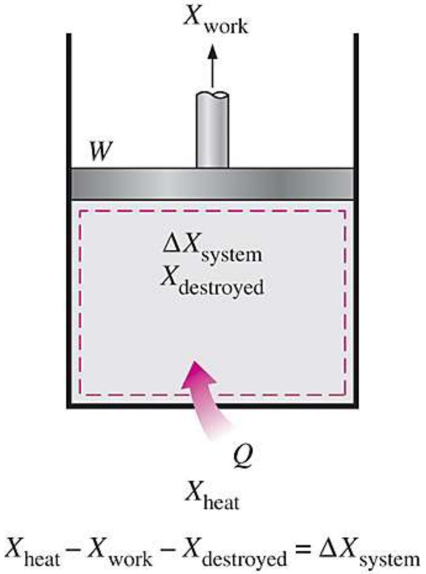
$$X_{destroyed} = T_0 S_{gen} \quad \text{or} \quad \dot{X}_{destroyed} = T_0 \dot{S}_{gen}$$

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

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

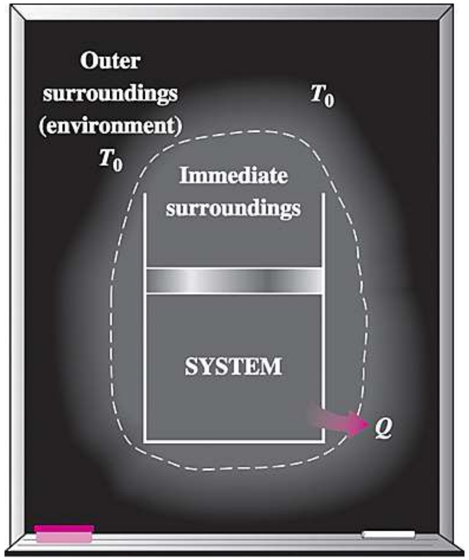
$$\textit{Rate form:} \quad \sum\left(1 - \frac{T_0}{T_k}\right)\dot{Q}_k - \left(\dot{W} - P_0 \frac{dV_{\text{system}}}{dt}\right) - T_0 \dot{S}_{\text{gen}} = \frac{dX_{\text{system}}}{dt}$$

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




Exergy balance for a closed system when heat transfer is to the system and the work is from the system.

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




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.

## EXAMPLE 8–9

Starting with energy and entropy balances, derive the general exergy balance relation for a closed system

$$\sum\left(1-\frac{T_0}{T_k}\right)Q_k-[W-P_0(V_2-V_1)]-T_0S_{\text{gen}}=X_2-X_1$$

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

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

$$Q-T_0\int_1^2\left(\frac{\delta Q}{T}\right)_{\text{boundary}}-W-T_0S_{\text{gen}}=E_2-E_1-T_0(S_2-S_1)$$

$$\int_1^2\delta Q-T_0\int_1^2\left(\frac{\delta Q}{T}\right)_{\text{boundary}}-W-T_0S_{\text{gen}}=X_2-X_1-P_0(V_2-V_1)$$

$$\int_1^2\left(1-\frac{T_0}{T_b}\right)\delta Q-[W-P_0(V_2-V_1)]-T_0S_{\text{gen}}=X_2-X_1$$

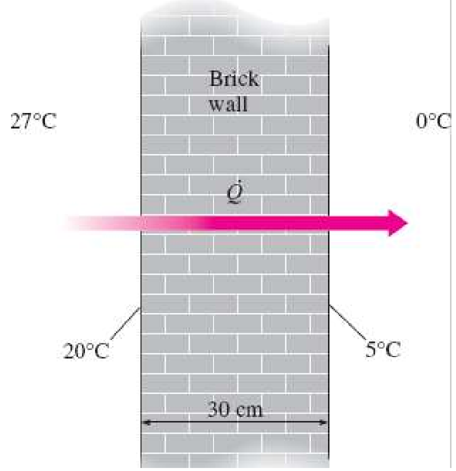
***Discussion*** The exergy balance relation above is obtained by adding the energy and entropy balance relations, and thus it is not an independent equation. However, it can be used in place of the entropy balance relation as an alternative second law expression in exergy analysis.

## EXAMPLE 8–10

Consider steady heat transfer through a 5-m x 6-m brick wall of a house of thickness 30 cm. On a day when the temperature of the outdoors is 0°C, the house is maintained at 27°C. The temperatures of the inner and outer surfaces of the brick wall are measured to be 20°C and 5°C, respectively, and the rate of heat transfer through the wall is 1035 W. Determine the rate of exergy destruction in the wall, and the rate of total exergy destruction associated with this heat transfer process.

**Solution** Steady heat transfer through a wall is considered. For specified heat transfer rate, wall surface temperatures, and environment conditions, the rate of exergy destruction within the wall and the rate of total exergy destruction are to be determined.

***Assumptions*** **1** The process is steady, and thus the rate of heat transfer through the wall is constant. **2** The exergy change of the wall is zero during this process since the state and thus the exergy of the wall do not change anywhere in the wall. **3** Heat transfer through the wall is 1-D.




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

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

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

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

the rate of total exergy destruction

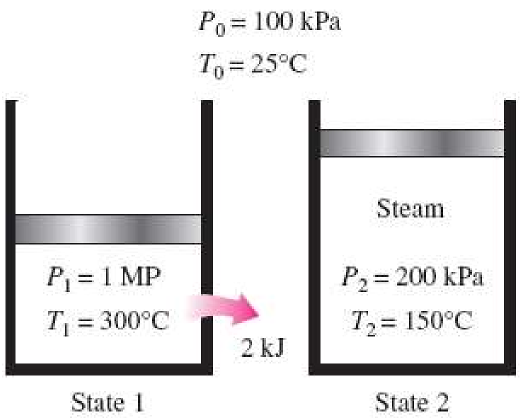
$$\dot{X}_{\text{destroyed, total}} = (1035\text{ W})\left(1 - \frac{273\text{ K}}{300\text{ K}}\right) - (1035\text{ W})\left(1 - \frac{273\text{ K}}{273\text{ K}}\right) = \mathbf{93.2\ W}$$

The difference between the two exergy destructions is 41.2 W and represents the exergy destroyed in the air layers on both sides of the wall. The exergy destruction in this case is entirely due to irreversible heat transfer through a finite temperature difference.

***Discussion*** We could have determined the exergy destroyed by simply multiplying the entropy generations by the environment temperature of $T_0$=273 K.

## EXAMPLE 8–11

A piston–cylinder device contains 0.05 kg of steam at 1 MPa and 300°C. Steam now expands to a final state of 200 kPa and 150°C, doing work. Heat losses from the system to the surroundings are estimated to be 2 kJ during this process. Assuming the surroundings to be at $T_0$=25°C and $P_0$=100 kPa, determine (*a*) the exergy of the steam at the initial and the final states, (*b*) the exergy change of the steam, (*c*) the exergy destroyed, and (*d*) the second-law efficiency for the process.




**Solution** Steam in a piston–cylinder device expands to a specified state. The exergies of steam at the initial and final states, the exergy change, the exergy destroyed, and the second-law efficiency for this process are to be determined.

***Assumptions*** The kinetic and potential energies are negligible.

(*a* the exergy of the steam at the initial and the final states, :

$$\text{State 1:} \quad \left.\begin{aligned} P_1 &= 1\text{ MPa} \\ T_1 &= 300°\text{C} \end{aligned}\right\} \quad \begin{aligned} u_1 &= 2793.7\text{ kJ/kg} \\ v_1 &= 0.25799\text{ m}^3/\text{kg} \\ s_1 &= 7.1246\text{ kJ/kg}\cdot\text{K} \end{aligned}$$

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

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

$$X_1 = m[(u_1 - u_0) - T_0(s_1 - s_0) + P_0(v_1 - v_0)]$$
$$= (0.05\text{ kg})\{(2793.7 - 104.83)\text{ kJ/kg}$$
$$- (298\text{ K})[(7.1246 - 0.3672)\text{ kJ/kg}\cdot\text{K}]$$
$$+ (100\text{ kPa})[(0.25799 - 0.00103)\text{ m}^3/\text{kg}]\}(\text{kJ/kPa}\cdot\text{m}^3)$$
$$= \mathbf{35.0\text{ kJ}}$$

$$X_2 = m[(u_2 - u_0) - T_0(s_2 - s_0) + P_0(v_2 - v_0)]$$
$$= (0.05\text{ kg})\{(2577.1 - 104.83)\text{ kJ/kg}$$
$$- (298\text{ K})[(7.2810 - 0.3672)\text{ kJ/kg}\cdot\text{K}]$$
$$+ (100\text{ kPa})[(0.95986 - 0.00103)\text{ m}^3/\text{kg}]\}(\text{kJ/kPa}\cdot\text{m}^3)$$
$$= \mathbf{25.4\text{ kJ}}$$

(*b*) The exergy change for a process is simply the difference between the exergy at the initial and final states of the process,

$$\Delta X = X_2 - X_1 = 25.4 - 35.0 = \mathbf{-9.6\text{ kJ}}$$

That is, if the process between states 1 and 2 were executed in a reversible manner, the system would deliver 9.6 kJ of useful work.

(*c*) The total exergy destroyed during this process can be determined from the exergy balance applied on 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),

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

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

By writing an energy balance on the system, the total boundary work done during the process is determined to be

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

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

$$\begin{aligned} W_{b,\text{ out}} &= -Q_{\text{out}} - \Delta U = -Q_{\text{out}} - m(u_2 - u_1) \\ &= -(2\text{ kJ}) - (0.05\text{ kg})(2577.1 - 2793.7)\text{ kJ/kg} \\ &= 8.8\text{ kJ} \end{aligned}$$

The useful work is the difference between the two:

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

$$= 8.8 \text{ kJ} - (100 \text{ kPa})(0.05 \text{ kg})[(0.9599 - 0.25799) \text{ m}^3/\text{kg}]\left(\frac{1 \text{ kJ}}{1 \text{ kPa} \cdot \text{m}^3}\right) = 5.3 \text{ kJ}$$

The exergy destroyed is determined to be

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

The exergy destroyed could also be determined from

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

$$= (298 \text{ K})\left\{(0.05 \text{ kg})[(7.2810 - 7.1246) \text{ kJ/kg} \cdot \text{K}] + \frac{2 \text{ kJ}}{298 \text{ K}}\right\} = 4.3 \text{ kJ}$$

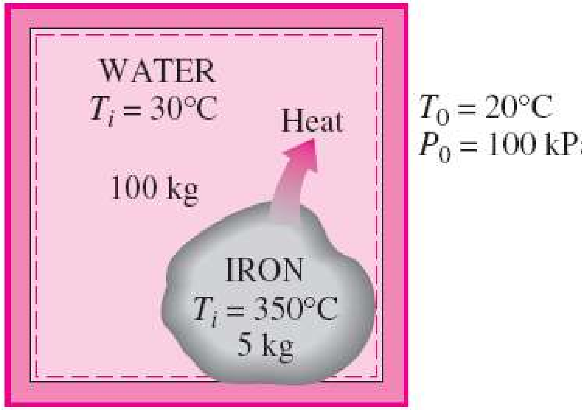
(*d*) The second-law efficiency for this process can be determined from

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

That is, 44.8 percent of the work potential of the steam is wasted during this process.

## EXAMPLE 8–13

A 5-kg block initially at 350°C is quenched in an insulated tank that contains 100 kg of water at 30°C. Assuming the water that vaporizes during the process condenses back in the tank and the surroundings are at 20°C and 100 kPa, determine
(*a*) the final equilibrium temperature,
(*b*) the exergy of the combined system at the initial and the final states, and
(*c*) the wasted work potential during this process.




**Solution** A hot iron block is quenched in an insulated tank by water. The final equilibrium temperature, the initial and final exergies, and the wasted work potential are to be determined.
***Assumptions*** **1** Both water and the iron block are incompressible substances. **2** Constant specific heats at room temperature can be used for both the water and the iron. **3** The system is stationary and thus the kinetic and potential energy changes are zero, ΔKE=ΔPE=0. **4** There are no electrical, shaft, or other forms of work involved. **5** The system is well-insulated and thus there is no heat transfer.

(*a*) Noting that no energy enters or leaves the system during the process, the application of the energy balance gives

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

$$0 = \Delta U$$

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

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

By using the specific-heat values for water and iron at room temperature (from Table A–3), the final equilibrium temperature $T_f$ becomes

$$0 = (5\text{ kg})(0.45\text{ kJ/kg}\cdot{}^\circ\text{C})(T_f - 350^\circ\text{C}) + (100\text{ kg})(4.18\text{ kJ/kg}\cdot{}^\circ\text{C})(T_f - 30^\circ\text{C})$$

$$T_f = \mathbf{31.7^\circ C}$$

(*b*) the exergy of the combined system at the initial and the final states,

$$X = (U - U_0) - T_0(S - S_0) + P_0(V - V_0)$$

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

$$X_{1,\text{ iron}} = (5\text{ kg})(0.45\text{ kJ/kg}\cdot\text{K})\left[(623 - 293)\text{ K} - (293\text{ K})\ln\frac{623\text{ K}}{293\text{ K}}\right]$$
$$= 245.2\text{ kJ}$$

$$X_{1,\text{ water}} = (100\text{ kg})(4.18\text{ kJ/kg}\cdot\text{K})\left[(303 - 293)\text{ K} - (293\text{ K})\ln\frac{303\text{ K}}{293\text{ K}}\right]$$
$$= 69.8\text{ kJ}$$

$$X_{1,\text{ total}} = X_{1,\text{ iron}} + X_{1,\text{ water}} = (245.2 + 69.8)\text{kJ} = \mathbf{315\text{ kJ}}$$

the exergy at the final state is

$$X_{2,\text{ iron}} = 0.5\text{ kJ}$$

$$X_{2,\text{ water}} = 95.2\text{ kJ}$$

$$X_{2,\text{ total}} = X_{2,\text{ iron}} + X_{2,\text{ water}} = 0.5 + 95.2 = \mathbf{95.7\text{ kJ}}$$

the exergy of the combined system (water + iron) decreased from 315 to 95.7 kJ as a result of this irreversible heat transfer process.

(*c*) the wasted work potential during this process.

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

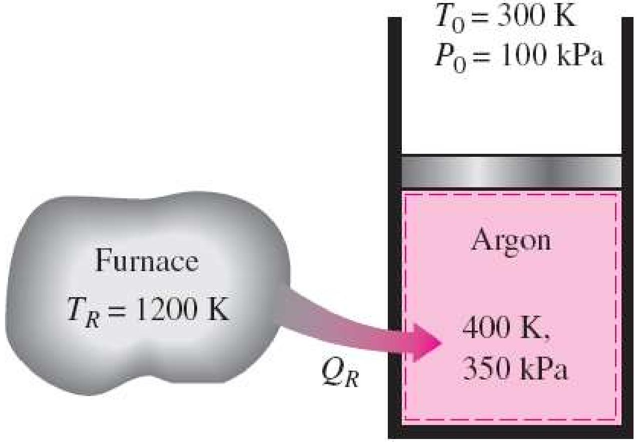
$$0 - X_{\text{destroyed}} = X_2 - X_1$$

$$X_{\text{destroyed}} = X_1 - X_2 = 315 - 9.7 = \mathbf{219.3\text{ kJ}}$$

***Discussion*** Note that 219.3 kJ of work could have been produced as the iron was cooled from 350 to 31.7°C and water was heated from 30 to 31.7°C, but was not.

## EXAMPLE 8–14

A frictionless piston–cylinder device, initially contains 0.01 $m^3$ of argon gas at 400 K and 350 kPa. Heat is now transferred to the argon from a furnace at 1200 K, and the argon expands isothermally until its volume is doubled. No heat transfer takes place between the argon and the surrounding atmospheric air, which is at $T_0$=300 K and $P_0$=100 kPa. Determine (*a*) the useful work output, (*b*) the exergy destroyed, and (*c*) the reversible work for this process.




**Solution** Argon gas in a piston–cylinder device expands isothermally as a result of heat transfer from a furnace. The useful work output, the exergy destroyed, and the reversible work are to be determined.

***Assumptions*** **1** Argon at specified conditions can be treated as an ideal gas since it is well above its critical temperature of 151 K. **2** The kinetic and potential energies are negligible.

(*a*) The only work interaction involved during this isothermal process is the quasi-equilibrium boundary work, which is determined from

$$W = W_b = \int_1^2 P\,dV = P_1V_1 \ln\frac{V_2}{V_1} = (350 \text{ kPa})(0.01 \text{ m}^3) \ln\frac{0.02 \text{ m}^3}{0.01 \text{ m}^3}$$

$$= 2.43 \text{ kPa}\cdot\text{m}^3 = 2.43 \text{ kJ}$$

$$W_{surr} = P_0(V_2 - V_1) = (100 \text{ kPa})[(0.02 - 0.01) \text{ m}^3]\left(\frac{1 \text{ kJ}}{1 \text{ kPa}\cdot\text{m}^3}\right) = 1 \text{ kJ}$$

The useful work is the difference between these two:

$$W_u = W - W_{surr} = 2.43 - 1 = \mathbf{1.43\ kJ}$$

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

$$Q_{in} - W_{b,\,out} = \Delta U = mc_V\,\Delta T^{\nearrow 0} = 0$$

$$Q_{in} = W_{b,\,out} = 2.43\ \text{kJ}$$

(*b*) the exergy destroyed

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

$$\frac{Q}{T_R} + S_{gen} = \Delta S_{system} = \frac{Q}{T_{sys}}$$

$$S_{gen} = \frac{Q}{T_{sys}} - \frac{Q}{T_R} = \frac{2.43\ \text{kJ}}{400\ \text{K}} - \frac{2.43\ \text{kJ}}{1200\ \text{K}} = 0.00405\ \text{kJ}$$

$$X_{destroyed} = T_0 S_{gen} = (300\ \text{K})(0.00405\ \text{kJ/K}) = \mathbf{1.22\ kJ/K}$$

(*c*) the reversible work for this process

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

$$\left(1 - \frac{T_0}{T_b}\right)Q - W_{\text{rev, out}} = X_2 - X_1$$
$$= (E_2 - E_1) + P_0(V_2 - V_1) - T_0(S_2 - S_1)$$
$$= 0 + W_{\text{surr}} - T_0 \frac{Q}{T_{\text{sys}}}$$

$$W_{\text{rev, out}} = T_0 \frac{Q}{T_{\text{sys}}} - W_{\text{surr}} + \left(1 - \frac{T_0}{T_R}\right)Q$$
$$= (300\text{ K})\frac{2.43\text{ kJ}}{400\text{ K}} - (1\text{ kJ}) + \left(1 - \frac{300\text{ K}}{1200\text{ K}}\right)(2.43\text{ kJ})$$
$$= \mathbf{2.65\ kJ}$$

Therefore, the useful work output would be 2.65 kJ instead of 1.43 kJ if the process were executed in a totally reversible manner.

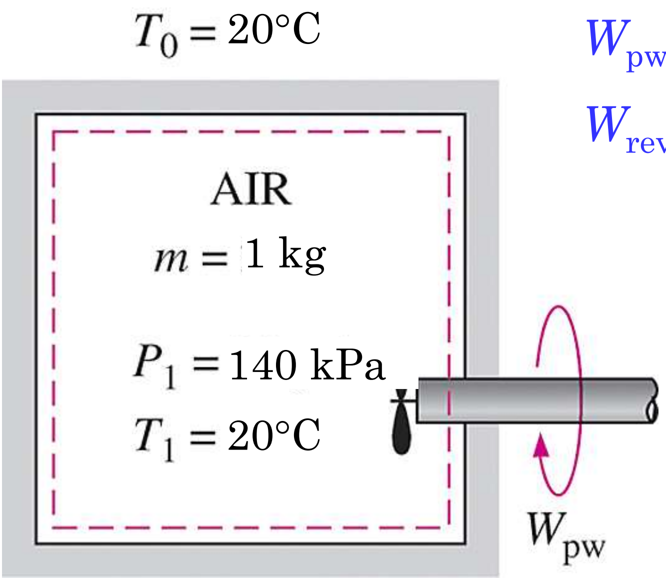
# Exergy balance for an air tank

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

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

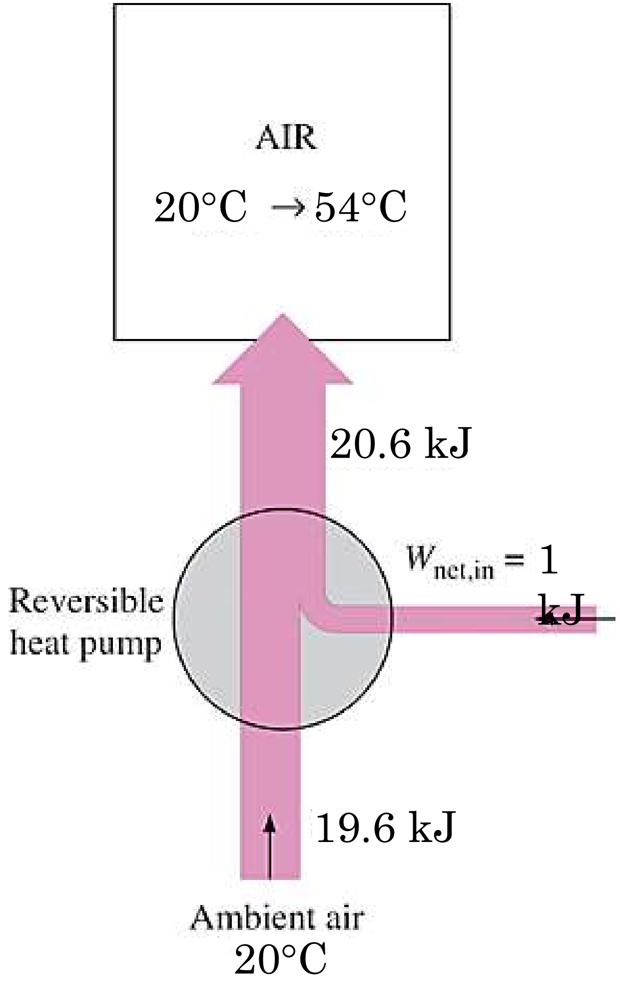
$$= (E_2 - E_1) + P_0(V_2 - V_1)^{\nearrow 0} - T_0(S_2 - S_1)$$

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




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

$W_{rev,in} = 1$ kJ




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

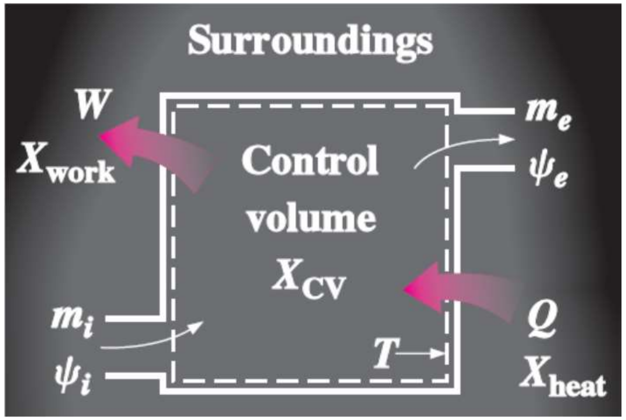
# EXERGY BALANCE: CONTROL VOLUMES

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

$$\sum \left(1 - \frac{T_0}{T_k}\right) Q_k - [W - P_0(V_2 - V_1)] + \sum m_i \psi_i - \sum m_e \psi_e - X_{\text{destroyed}} = (X_2 - X_1)_{\text{CV}}$$

$$\sum \left(1 - \frac{T_0}{T_k}\right) \dot{Q}_k - \left(\dot{W} - P_0 \frac{dV_{\text{CV}}}{dt}\right) + \sum \dot{m}_i \psi_i - \sum \dot{m}_e \psi_e - \dot{X}_{\text{destroyed}} = \frac{dX_{\text{CV}}}{dt}$$

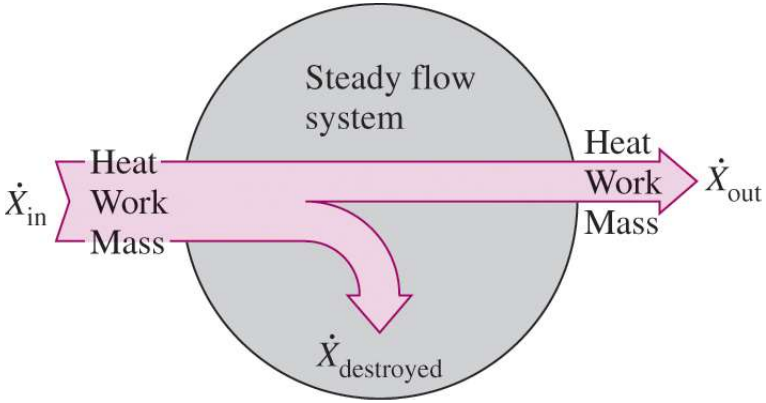
The rate of exergy change within the control volume during a process is equal to the rate of net exergy transfer through the control volume boundary by heat, work, and mass flow minus the rate of exergy destruction within the boundaries of the control volume.




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.




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

*Steady-flow:* $$\sum\left(1-\frac{T_0}{T_k}\right)\dot{Q}_k - \dot{W} + \sum \dot{m}_i\psi_i - \sum \dot{m}_e\psi_e - \dot{X}_{destroyed} = 0$$

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

# Reversible Work, $W_{rev}$

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

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

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

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

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, $\eta_{II}$

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

Turbine

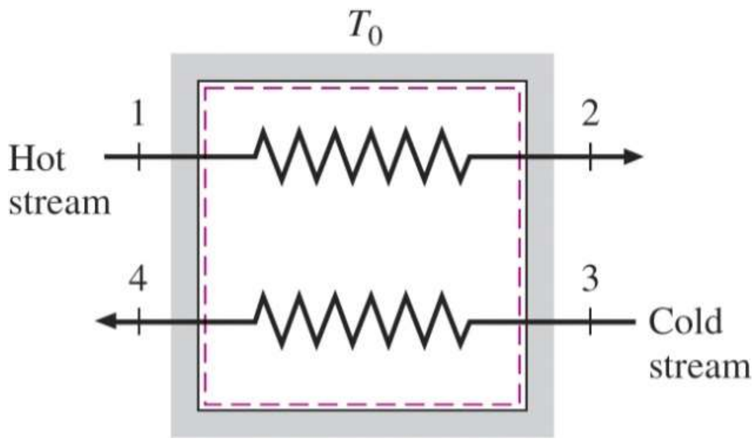
$$\eta_{\text{II, turb}} = \frac{w}{w_{\text{rev}}} = \frac{h_1 - h_2}{\psi_1 - \psi_2} \quad \text{or} \quad \eta_{\text{II, turb}} = 1 - \frac{T_0 s_{\text{gen}}}{\psi_1 - \psi_2}$$

Compressor

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

Heat exchanger

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




A heat exchanger with two unmixed fluid streams.

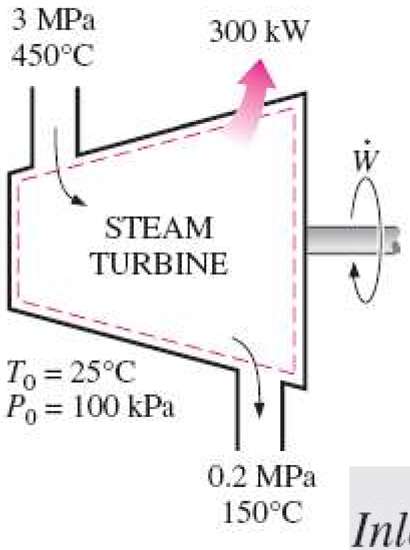
Mixing chamber

$$\eta_{\text{II, mix}} = \frac{\dot{m}_3\psi_3}{\dot{m}_1\psi_1 + \dot{m}_2\psi_2} \quad \text{or} \quad \eta_{\text{II, mix}} = 1 - \frac{T_0\dot{S}_{\text{gen}}}{\dot{m}_1\psi_1 + \dot{m}_2\psi_2}$$

where $\dot{m}_3 = \dot{m}_1 + \dot{m}_2$ and $\dot{S}_{\text{gen}} = \dot{m}_3 s_3 - \dot{m}_2 s_2 - \dot{m}_1 s_1$.

## EXAMPLE 8–15

Steam enters a turbine steadily at 3 MPa and 450°C at a rate of 8 kg/s and exits at 0.2 MPa and 150°C. The steam is losing heat to the surrounding air at 100 kPa and 25°C at a rate of 300 kW, and the kinetic and potential energy changes are negligible. Determine (*a*) the actual power output, (*b*) the maximum possible power output, (*c*) the second-law efficiency, (*d*) the exergy destroyed, and (*e*) the exergy of the steam at the inlet conditions.




**Solution** A steam turbine operating steadily between specified inlet and exit states is considered. The actual and maximum power outputs, the second-law efficiency, the exergy destroyed, and the inlet exergy are to be determined.

***Assumptions*** **1** This is a steady-flow process since there is no change with time at any point and thus $\Delta m_{CV}=0$, $\Delta E_{CV}=0$, and $\Delta X_{CV}=0$. **2** The kinetic and potential energies are negligible.

$$\text{Inlet state: } \left.\begin{array}{l} P_1 = 3\text{ MPa} \\ T_1 = 450°\text{C} \end{array}\right\} \quad \begin{array}{l} h_1 = 3344.9\text{ kJ/kg} \\ s_1 = 7.0856\text{ kJ/kg}\cdot\text{K} \end{array}$$

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

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

(*a*) The actual power output of the turbine;

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

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

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

$$= (8 \text{ kg/s})[(3344.9 - 2769.1) \text{ kJ/kg}] - 300 \text{ kW}$$

$$= \mathbf{4306\ kW}$$

(*b*) the maximum possible power output

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

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

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

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

$$\dot{W}_{rev,\,out} = (8 \text{ kg/s})[(3344.9 - 2769.1) \text{ kJ/kg} - (298 \text{ K})(7.0856 - 7.2810) \text{kJ/kg} \cdot \text{K}] = \mathbf{5072\ kW}$$

(*c*) The second-law efficiency of a turbine is the ratio of the actual work delivered to the reversible work,

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

That is, 15.1 percent of the work potential is wasted during this process.

(*d*) The difference between the reversible work and the actual useful work is the exergy destroyed, which is determined to be

$$\dot{X}_{\text{destroyed}} = \dot{W}_{\text{rev, out}} - \dot{W}_{\text{out}} = 5072 - 4306 = \mathbf{766\ kW}$$

(*e*) The exergy (maximum work potential) of the steam at the inlet conditions is simply the stream exergy, and is determined from

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

That is, not counting the kinetic and potential energies, every kilogram of the steam entering the turbine has a work potential of 1238 kJ. This corresponds to a power potential of (8 kg/s)(1238 kJ/kg)= 9904 kW. Obviously, the turbine is converting 4306/9904=43.5 % of the available work potential of the steam to work.

## 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