EXERGY:

A MEASURE OF WORK POTENTIAL

EXERGY: WORK POTENTIAL OF ENERGY

- When a new energy source, such as a geothermal well, is discovered, the first thing the explorers do is estimate the amount of energy contained in the source.

- This information alone, however, is of little value in deciding whether to build a power plant on that site.

- What we really need to know is the *work potential* of the source-that is, the amount of energy we can extract as useful work.

- The rest of the energy is eventually discarded as waste energy and is not worthy of our consideration.

- Thus, it would be very desirable to have a property to enable us to determine the useful work potential of a given amount of energy at some specified state.

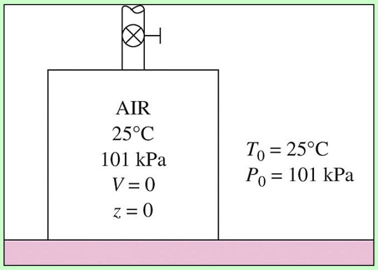
- This property is *exergy*, which is also called the *availability* or *available energy*.

EXERGY: WORK POTENTIAL OF ENERGY

- The work potential of the energy contained in a system at a specified state is simply the maximum useful work that can be obtained from the system.
- You will recall that the work done during a process depends on the initial state, the final state, and the process path.
  - That is, Work = *f* (initial state, process path, final state)
- In an exergy analysis, the *initial state* is specified, and thus it is not a variable.
- The work output is maximized when the process between two specified states is executed in a *reversible manner*.
- Therefore, all the irreversibilities are disregarded in determining the work potential.
- Finally, the system must be in the *dead state* at the end of the process to maximize the work output.

Dead State

- A system is said to be in the **dead state** when it is in thermodynamic equilibrium with the environment.
- 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).
- The properties of a system at the dead state are denoted by subscript zero, for example, P_0, T_0, v_0, h_0, u_0, and s_0.



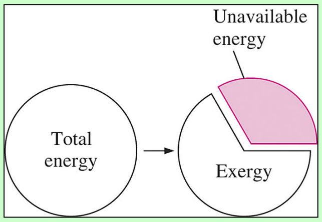
- A system has zero availability at the dead state.

Exergy

- Therefore, we conclude that 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.**
- It is important to realize that exergy does not represent the amount of work that a work-producing device will actually deliver upon installation.
- Rather, it represents the *upper limit on the amount of work a device can deliver without violating any thermodynamic laws*.
- There will always be a difference, large or small, between exergy and the actual work delivered by a device.
- This difference represents the room engineers have for improvement.

Exergy (Availability) and Unavailable energy

- The term *availability* was made popular in the United States by the M.I.T. School of Engineering in the 1940s.
- Today, an equivalent term, *exergy*, introduced in Europe in the 1950s, has found global acceptance partly because:
  - it is shorter,
  - it rhymes with energy and entropy, and
  - it can be adapted without requiring translation.
- In this text the preferred term is *exergy.*



- 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.

Exergy (Work Potential) Associated with Kinetic and Potential Energy

- Kinetic or potential energy is form of *mechanical energy*, and thus it can be converted to work entirely.

- Therefore, the *work potential* or *exergy* of the kinetic or potential energy of a system is equal to the kinetic or potential energy itself regardless of the temperature and pressure of the environment.

- That is,

$$x_{ke} = ke = \frac{V^2}{2}$$

$$x_{pe} = pe = gz$$

- where V is the velocity of the system relative to the environment,
- g is the gravitational acceleration, and
- z is the elevation of the system relative to a reference level in the environment.

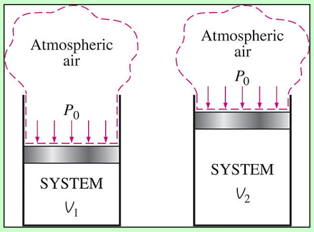
Useful and Surrounding Work

- The **surroundings work** is the work done by or against the surroundings during a process.

- The work done by work-producing devices is not always entirely in a usable form.

- For example, when a gas in a piston–cylinder device expands, part of the work done by the gas is used to push the atmospheric air out of the way of the piston.

- This work is equal to the atmospheric pressure times the volume change of the system.



From 1st Law:

$$W_a = W_u + W_{surr}$$

$$W_{surr} = \int P_0 \, dV = P_0 (V_2 - V_1)$$

Useful and Surrounding Work

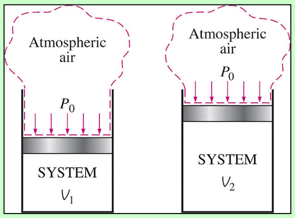
- The difference between the actual work W and the surroundings work is called the **useful work**.

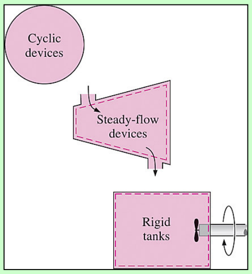
$$W_u = W - W_{surr}$$

- Note that the work done by or against the atmospheric pressure 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.) as shown.

$$W_u = W$$





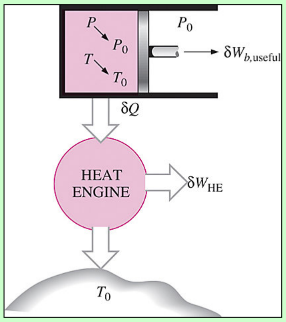
Exergy of a Fixed Mass:
Non-flow (or Closed System) Exergy

- Consider a stationary closed system at a specified state that undergoes a reversible process to the state of the environment.

- The useful work delivered during this process is the exergy of the system at its initial state.

- Taking the direction of heat and work transfers to be *from* the system (heat and work outputs).

- The energy balance for the system during this differential process can be expressed as:



$$\delta E_{in} - \delta E_{out} = dE_{system}$$
$$0 - \delta Q - \delta W = dU$$

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

- The work is the boundary work and can be written as:

$$\begin{aligned}\delta W &= \delta W_{\text{b, useful}} + \delta W_{\text{surr}} \\ &= \delta W_{\text{b, useful}} + P_0\,dV\end{aligned}$$

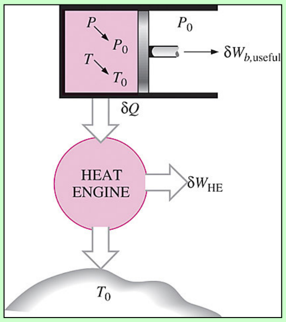
- The fraction of energy of a heat source at temperature T that can be converted to work by transferring it to a heat engine.

$$\delta W_{\text{HE}} = \eta_{\text{th}}\delta Q = (1-\frac{T_0}{T})\delta Q = \delta Q - T_0\frac{\delta Q}{T}$$

$$dS = \frac{\delta Q_{\text{net}}}{T} = \frac{-\delta Q}{T}$$

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

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



$$\delta E_{\text{in}} - \delta E_{\text{out}} = dE_{\text{system}}$$

$$0 - \delta Q - \delta W = dU$$

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

$$-\left(\delta W_{\text{HE}} - T_0\,dS\right) - \left(\delta W_{\text{b, useful}} + P_0\,dV\right) = dU$$

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

Integrating from the given state (no subscript) to the dead state (0 subscript), we get:

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

This is the total useful work due to a system undergoing a reversible process from a given state to the dead state, which is the definition of exergy.

Including the kinetic energy and potential energy, the exergy of a closed system is

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

On a unit mass basis, the closed system (or nonflow) exergy is

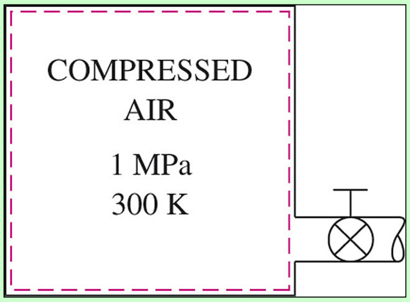
$$\boxed{\begin{aligned}\phi &= (u - u_0) + P_0(v - v_0) - T_0(s - s_0) + \frac{\vec{V}^2}{2} + gz \\ &= (e - e_0) + P_0(v - v_0) - T_0(s - s_0)\end{aligned}}$$

EXAMPLE 7–7

Work Potential of Compressed Air in a Tank

- 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.

- Note that we can consider this as a closed system with piston cylinder device.

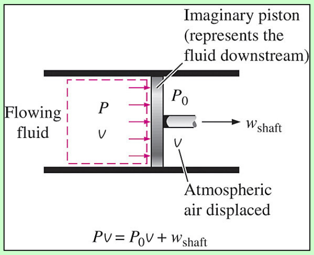


Exergy of a Flow Stream: Flow (or Stream) Exergy

The exergy associated with the flow energy is $x_{\text{flow energy}} = Pv - P_0 v = (P - P_0)v$

Since flow energy is the sum of nonflow energy and the flow energy, the exergy of flow is the sum of the exergies of nonflow exergy and flow exergy.

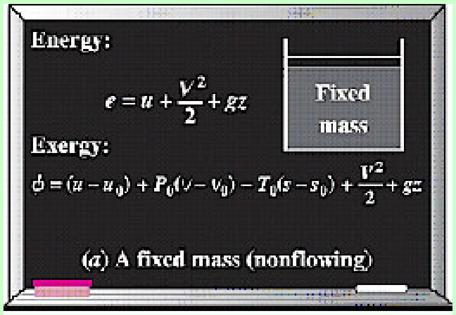
$$
\begin{aligned}
x_{\text{flowing fluid}} &= x_{\text{nonflowing fluid}} + x_{\text{flow exergy}} \\
&= (u-u_0) + P_0(v-v_0) - T_0(s-s_0) + \frac{\vec{V}^2}{2} + gz + (P-P_0)v \\
&= (u+Pv) - (u_0+P_0v_0) - T_0(s-s_0) + \frac{\vec{V}^2}{2} + gz \\
&= (h-h_0) - T_0(s-s_0) + \frac{\vec{V}^2}{2} + gz
\end{aligned}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



The flow (or stream) exergy is given by

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

The Energy and Exergy Contents



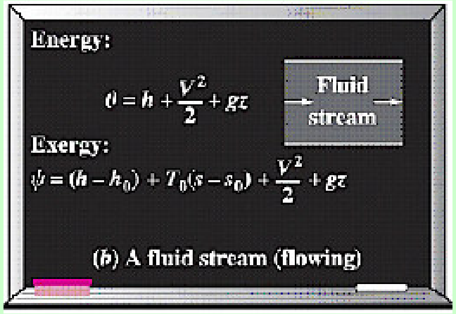
Energy:

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

Exergy:

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

(*a*) A fixed mass (nonflowing)



Energy:

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

Exergy:

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

(*b*) A fluid stream (flowing)

REVERSIBLE WORK AND IRREVERSIBILITY

- The property exergy serves as a valuable tool in determining the quality of energy and comparing the work potentials of different energy sources or systems.
- The evaluation of exergy alone, however, is not sufficient for studying engineering devices operating between two fixed states.
- This is because when evaluating exergy, the final state is always assumed to be the *dead state*, which is hardly ever the case for actual engineering systems.
- The isentropic efficiencies discussed previously are also of limited use because the exit state of the model (isentropic) process is not the same as the actual exit state and it is limited to adiabatic processes.
- In this section, we describe two quantities that are related to the actual initial and final states of processes and serve as valuable tools in the thermodynamic analysis of components or systems.
- These two quantities are the *reversible work* and *irreversibility* (or *exergy destruction*).

REVERSIBLE WORK AND IRREVERSIBILITY

- **Reversible work** W_{rev} is defined as *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.*
- This 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.
- Any difference between the reversible work W_{rev} and the useful work W_u is due to the irreversibilities present during the process.
- This difference is called **irreversibility** *I*.

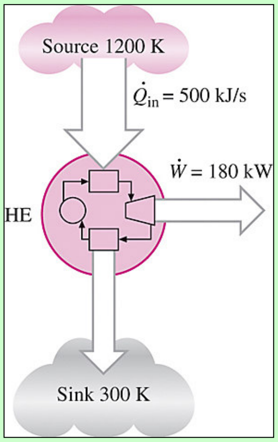
$$I = W_{\text{rev, out}} - W_{\text{u, out}}$$
$$= W_{\text{u, in}} - W_{\text{rev, in}}$$

- It represent the amount of energy that could have been converted to work but was not.

EXAMPLE 7–3

The Rate of Irreversibility of a Heat Engine

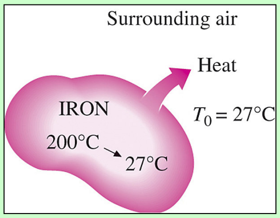
- A heat engine receives heat from a source at 1200 K at a rate of 500 kJ/s and rejects the waste heat to a medium at 300 K. The power output of the heat engine is 180 kW. Determine the reversible power and the irreversibility rate for this process.

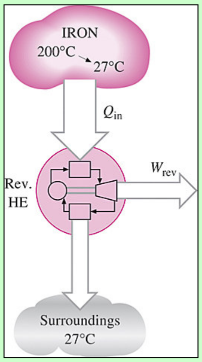


EXAMPLE 7–4

Irreversibility during the Cooling of an Iron Block

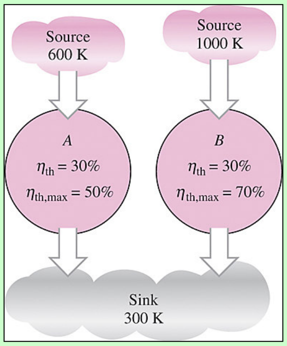
- A 500-kg iron block shown is initially at 200°C and is allowed to cool to 27°C by transferring heat to the surrounding air at 27°C. Determine the reversible work and the irreversibility for this process.





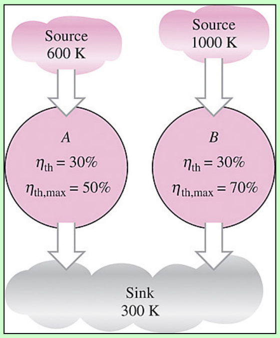
SECOND-LAW EFFICIENCY η_{II}

- Previously, we defined the *thermal efficiency* and the *coefficient of performance* for devices as a measure of their performance.
- They are defined on the basis of the first law only, and they are sometimes referred to as the *first-law efficiencies.*
- The first law efficiency, however, makes no reference to the best possible performance, and thus it may be misleading.
- Consider two heat engines, both having a thermal efficiency of 30 percent, as shown.



SECOND-LAW EFFICIENCY η_{II}

- One of the engines (engine *A*) is supplied with heat from a source at 600 K, and the other one (engine *B*) from a source at 1000 K.
- Both engines reject heat to a medium at 300 K.
- At first glance, both engines seem to convert to work the same fraction of heat that they receive; thus they are performing equally well.
- When we take a second look at these engines in light of the second law of thermodynamics, however, we see a totally different picture.
- These engines, at best, can perform as reversible engines, in which case their efficiencies would be

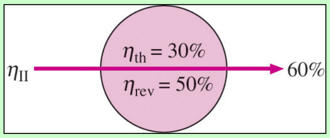


$$\eta_{rev,A} = \left(1 - \frac{T_L}{T_H}\right)_A = 1 - \frac{300}{600} = 50\%$$

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

SECOND-LAW EFFICIENCY η_{II}

- Now it is becoming apparent that engine *B* has a greater work potential available to it, and thus it should do a lot better than engine *A*.
- Therefore, we can say that engine *B* is performing poorly relative to engine *A* even though both have the same thermal efficiency.
- It is obvious from this example that the first-law efficiency alone is not a realistic measure of performance of engineering devices.
- To overcome this deficiency, we define a **second-law efficiency** η_{II} as the ratio of the actual thermal efficiency to the maximum possible (reversible) thermal efficiency under the same conditions.



$$\eta_{II} = \frac{\eta_{th}}{\eta_{th,rev}}$$

SECOND-LAW EFFICIENCY η_{II}

- Based on this definition, the second-law efficiencies of the two heat engines discussed above are:

$$\eta_{II,A} = \frac{0.30}{0.50} = 0.60 \qquad and \qquad \eta_{II,B} = \frac{0.30}{0.70} = 0.43$$

- That is, engine *A* is converting 60 percent of the available work potential to useful work. This ratio is only 43 percent for engine *B.*
- For cyclic devices such as refrigerators and heat pumps, it can also be expressed in terms of the coefficients of performance as:

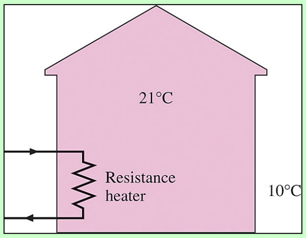
$$\eta_{II} = \frac{COP}{COP_{rev}}$$

- Because of the way we defined the second-law efficiency, its value cannot exceed 100 percent.

EXAMPLE 7–6

Second-Law Efficiency of Resistance Heaters

- A dealer advertises that he has just received a shipment of electric resistance heaters for residential buildings that have an efficiency of 100 percent (COP = 1). Assuming an indoor temperature of 21°C and outdoor temperature of 10°C, determine the second-law efficiency of these heaters.



- It means that for each unit of electric energy (work) consumed, the heater will supply the house with 1 unit of energy (heat).
- The 2nd law efficiency will give 3.7%
- which does not look so impressive.
- The dealer will not be happy to see this value.

SECOND-LAW EFFICIENCY η_{II}

- This definition is more general since it can be applied to processes (in turbines, compressor, and piston–cylinder devices, etc.) as well as to cycles.

- The second-law efficiency can be expressed as the ratio of the useful work output and the maximum possible (reversible) work output. On the other hand, the second-law efficiency can also be expressed as the ratio of the minimum work (reversible) input to the useful work input.

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

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

- The second-law efficiency in a very general definition

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

EXERGY CHANGE OF A SYSTEM

- The property *exergy* is the work potential of a system in a specified environment and represents the maximum amount of useful work that can be obtained as the system is brought to equilibrium with the environment.

- Unlike energy, the value of exergy depends on the state of the environment as well as the state of the system.

- Therefore, exergy is a system - environment combination property.

- The exergy of a system that is in equilibrium with its environment is zero.

- The state of the environment is referred to as the “dead state” since the system is practically “dead” (cannot do any work) from a thermodynamic point of view.

EXERGY CHANGE OF A SYSTEM

- The evaluation of exergy alone, however, is not sufficient for studying engineering devices operating between two fixed states.

- This is because when evaluating exergy, the final state is always assumed to be the *dead state*, which is hardly ever the case for actual engineering systems.

- The exergy change during a process is simply the difference between the final and initial exergies of the system.

$$\Delta\phi = (\phi_2 - \phi_1) = (u - u_0) + P_0(v - v_0) - T_0(s - s_0) + \frac{\vec{V}_2^{\,2} - \vec{V}_1^{\,2}}{2} + g(z_2 - z_1)$$

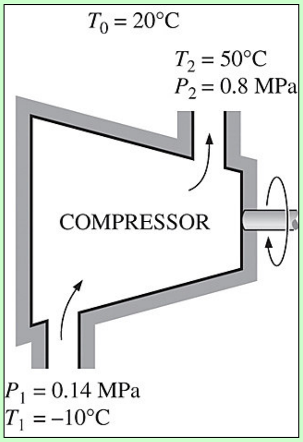
$$\Delta\psi = \psi_2 - \psi_1 = (h_2 - h_1) - T_0(s_2 - s_1) + \frac{\vec{V}_2^{\,2} - \vec{V}_1^{\,2}}{2} + g(z_2 - z_1)$$

- Note that 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 changes from state 1 to state 2 in a specified environment, and represents the *reversible work* W_{rev}.

EXAMPLE 7–8

Exergy Change during a Compression Process

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



EXERGY TRANSFER BY HEAT, WORK, AND MASS

Exergy Transfer by Heat Transfer

- By the second law we know that only a portion of heat transfer at a temperature above the environment temperature can be converted into work.
- The maximum useful work is produced from it by passing this heat transfer through a reversible heat engine.
- The exergy transfer by heat is $$X_{\text{heat}} = \left(1 - \frac{T_0}{T}\right)Q$$
- Note that exergy transfer by heat is zero for adiabatic systems.

EXERGY TRANSFER BY HEAT, WORK, AND MASS

Exergy Transfer by Work

- The exergy transfer by work can simply be expressed as $$X_{\text{work}} = \begin{cases} W - W_{\text{surr}} & \text{(for boundary work)} \\ W & \text{(for other forms of work)} \end{cases}$$
- where $W_{\text{surr}} = P_0(V_2 - V_1)$, P_0 is atmospheric pressure, and V_1 and V_2 are the initial and final volumes of the system.
- The exergy transfer for shaft work and electrical work is equal to the work W itself.

Exergy Transfer by Mass

- When mass in the amount of m enters or leaves a system, exergy in the amount of $m\psi$ accompanies it. That is, $$X_{mass} = m\psi$$

EXERGY DESTRUCTION

- Irreversibilities such as friction, mixing, chemical reactions, heat transfer through finite temperature difference, unrestrained expansion, non-quasi-equilibrium compression, or expansion always generate entropy, and anything that generates entropy always destroys exergy.
- The exergy destroyed is proportional to the entropy generated and can be expressed as:

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

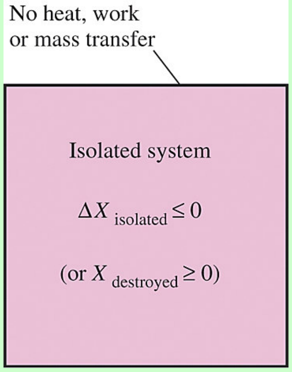
- Note that exergy destroyed is a *positive quantity* for any actual process and becomes *zero* for a reversible process.
- Exergy destroyed represents the lost work potential and is also called the *irreversibility* or *lost work.*

THE DECREASE OF EXERGY PRINCIPLE

- Previously, we presented the *conservation of energy principle* and indicated that energy cannot be created or destroyed during a process.
- Also, we established the *increase of entropy principle,* which can be regarded as one of the statements of the second law, and indicated that entropy can be created but cannot be destroyed.
- That is, entropy generation S_{gen} must be positive (actual processes) or zero (reversible processes), but it cannot be negative.
- Now we are about to establish an alternative statement of the second law of thermodynamics, called the *decrease of exergy principle,* which is the counterpart of the increase of entropy principle.

THE DECREASE OF EXERGY PRINCIPLE

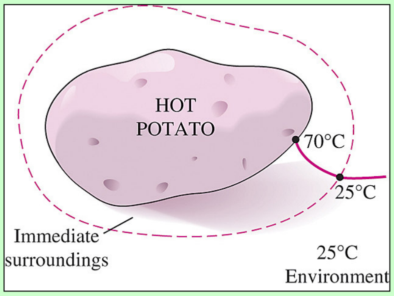
- The exergy of an isolated system during a process always decreases or remains constant, in the limiting case of a reversible process.
- This is known as the *decrease of exergy principle* and is expressed as



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

Immediate Surroundings

- Distinction should be made between the *surroundings, immediate surroundings,* and the *environment*.
- By definition, **surroundings** are everything outside the system boundaries.
- The **immediate surroundings** refer to the portion of the surroundings that is affected by the process.
- The **environment** refers to the region beyond the immediate surroundings whose properties are not affected by the process at any point.



- Therefore, any irreversibilities during a process occur within the system and its immediate surroundings, and the environment is free of any irreversibilities.

EXERGY BALANCE: CLOSED SYSTEM

Exergy balance for *any system* undergoing *any process* can be expressed as:

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

General:

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

General, rate form:

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

General, unit-mass basis:

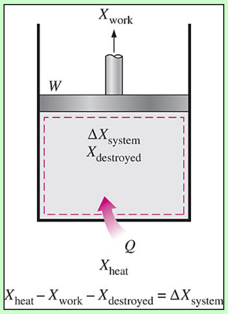
$$(x_{\text{in}} - x_{\text{out}}) - x_{\text{destroyed}} = \Delta x_{\text{system}}$$

EXERGY BALANCE: CLOSED SYSTEM

- Taking the positive direction of heat transfer to be to the system and the positive direction of work transfer to be from the system, the exergy balance for a closed system can be expressed more explicitly as:

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

- The *total* exergy destroyed during a process can be determined by applying the exergy balance to an extended system (Q = 0) that includes the system itself and its immediate surroundings where external irreversibilities might be occurring.



EXERGY BALANCE: CLOSED SYSTEM (Notes)

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

- It is usually more convenient to find the entropy generation first, and then evaluate the exergy destroyed directly from $X_{des} = T_0 S_{gen}$.
- No exergy is destroyed during a revisable process ($X_{des,rev} = 0$).
- The exergy balance relations presented above can be used to determine the *reversible work* W_{rev} by setting the exergy destruction term equal to zero.
- That is, $W = W_{\text{rev}} = X_2 - X_1$ when $X_{des} = T_0 S_{gen} = 0$.

EXAMPLE 7–11

Exergy Destruction during Expansion of Steam

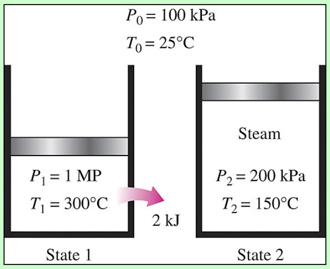
- A piston–cylinder device contains 0.05 kg of steam at 1 MPa and 300°C. Steam now expands to a final state of 200 kPa and 150°C, doing work. Heat losses from the system to the surroundings are estimated to be 2 kJ during this process. Assuming the surroundings to be at T_0 25°C and P_0 100 kPa, determine:

(*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

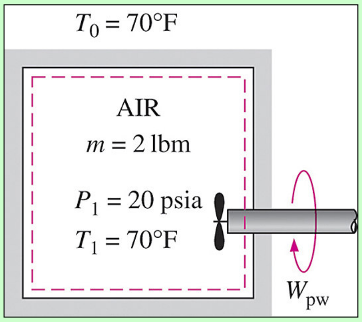
(*d*) the second-law efficiency for the process.



EXAMPLE 7–12

Exergy Destroyed during Stirring of a Gas

- An insulated rigid tank contains 2 lbm of air at 20 psia and 70°F. A paddle wheel inside the tank is now rotated by an external power source until the temperature in the tank rises to 130°F. If the surrounding air is at *T*0 70°F, determine:
- (*a*) the exergy destroyed and
- (*b*) the reversible work for this process.



EXERGY BALANCE: CONTROL VOLUME

- The exergy balance for a control volume can be expressed more explicitly as:

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

- It can also be expressed in the **rate form** as:

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

- For a **steady-flow process,** the rate form of the general exergy balance reduces

$$\sum\left(1-\frac{T_0}{T_{\text{k}}}\right)\dot{Q}_k-\left[\dot{W}\right]+\sum\dot{m}_i\psi_i-\sum\dot{m}_e\psi_e-\dot{X}_{\text{destroyed}}=0$$

- where the subscripts are *i* = inlet, *e* = exit, 1 = initial state, and 2 = final state of the system

EXERGY BALANCE: CONTROL VOLUME (Notes)

- The exergy balance relations presented above can be used to determine the *reversible work* W_{rev} by setting the exergy destruction term equal to zero of the extended system.
- That is, $W = W_{\text{rev}} = \psi_2 - \psi_1$ when $X_{des} = T_0 S_{gen} = 0$.
- The second-law efficiency of steady-flow devices,
  η_{II} = (exergy recovered / exergy supplied)

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

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

EXERGY BALANCE: CONTROL VOLUME (Notes)

- The second-law efficiency for heat exchanger is

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

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

- The second-law efficiency for mixing chamber is

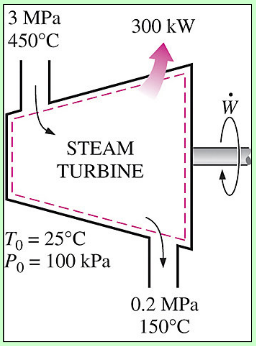
$$\eta_{II,mix} = \frac{\dot{m}_3 \psi_3}{\dot{m}_1 \psi_1 + \dot{m}_2 \psi_2} \quad or \quad \eta_{II,mix} = 1 - \frac{T_0 S_{gen}}{\dot{m}_1 \psi_1 + \dot{m}_2 \psi_2}$$

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

EXAMPLE 7–15

Second-Law Analysis of a Steam Turbine

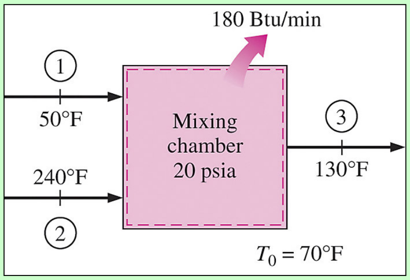
- Steam enters a turbine steadily at 3 MPa and 450°C at a rate of 8 kg/s and exits at 0.2 MPa and 150°C, (Fig. 8–45). The steam is losing heat to the surrounding air at 100 kPa and 25°C at a rate of 300 kW, and the kinetic and potential energy changes are negligible. Determine:
- (*a*) the actual power 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.



EXAMPLE 7–16

Exergy Destroyed during Mixing of Fluid Streams

- Water at 20 psia and 50°F enters a mixing chamber at a rate of 300 lbm/min, where it is mixed steadily with steam entering at 20 psia and 240°F. The mixture leaves the chamber at 20 psia and 130°F, and heat is being lost to the surrounding air at T_0 70°F at a rate of 180 Btu/min. Neglecting the changes in kinetic and potential energies, determine the reversible power and the rate of exergy destruction for this process.



EXAMPLE 7–17

Charging a Compressed Air Storage System

- A 200-m3 rigid tank initially contains atmospheric air at 100 kPa and 300 K and is to be used as a storage vessel for compressed air at 1 MPa and 300 K. Compressed air is to be supplied by a compressor that takes in atmospheric air at P_0 100 kPa and T_0 300 K. Determine the minimum work requirement for this process.