Chapter 7 SUMMARY

- The energy content of the universe is constant, just as its mass content is. Yet at times of crisis we are bombarded with speeches and articles on how to "conserve" energy. As engineers, we know that energy is already conserved. What is not concerned is *exergy,* which is the useful work potential of the energy. Once the exergy is wasted, it can never be recovered. When we use energy (to heat our homes for example), we are not destroying any energy; we are merely converting it to a less useful form, a form of less exergy.

- The useful work potential of a system at the specified state is called *exergy.* Exergy is a property and is associated with the state of the system and the environment. A system that is in equilibrium with its surroundings has zero exergy and is said to be at the *dead state.* The exergy of the thermal energy of thermal reservoirs is equivalent to the work output of a Carnot heat engine operating between the reservoir and the environment.

- *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 when the process between the initial and final states is executed in a totally reversible manner.

- The difference between the reversible work W_{rev} and the useful work W_u is due to the irreversibilities present during the process and is called the *irreversibility I.* It is equivalent to the *exergy destroyed* and is expressed as

$$I = X_{destroyed} = T_o S_{gen} = W_{rev,out} - W_{u,out} = W_{u,in} - W_{rev,in}$$

  where S_{gen} is the entropy generated during the process. For a totally reversible process, the useful and reversible work terms are identical and thus irreversibility is zero.

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

- The *second-law efficiency* is a measure of the performance of a device relative to the performance under reversible conditions for the same end states and is given by

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

  for heat engines and other work-producing devices and

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

for refrigerators, heat pumps, and other work-consuming devices.

- In general, the second-law efficiency is expressed as

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

- The exergies of a fixed mass (nonflow exergy) and of a flow stream are expressed as

Nonflow exergy:

$$\phi = (u - u_o) + P_o(v - v_o) - T_o(s - s_o) + \frac{\vec{V}^2}{2} + gz$$
$$= (e - e_o) + P_o(v - v_o) - T_o(s - s_o)$$

Flow exergy:

$$\psi = (h - h_o) - T_o(s - s_o) + \frac{\vec{V}^2}{2} + gz$$

- The *exergy change* of a fixed mass or fluid stream as it undergoes a process from state 1 to state 2 is given by

$$
\begin{aligned}
\Delta X &= X_2 - X_1 = m(\phi_2 - \phi_1) \\
&= (E_2 - E_1) + P_o(V_2 - V_1) - T_o(S_2 - S_1) \\
&= (U_2 - U_1) + P_o(V_2 - V_1) - T_o(S_2 - S_1) + m\frac{\vec{V}_2^2 - \vec{V}_1^2}{2} + mg(z_2 - z_1)
\end{aligned}
$$

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

- Exergy can be transferred by heat, work, and mass flow, and exergy transfer accompanied by heat, work, and mass transfer are given by

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

Exergy transfer by work: $$X_{\text{heat}} = \begin{cases} W - W_{\text{surr}} & \text{(for bounary work)} \\ W & \text{(for other forms of work)} \end{cases}$$

Exergy transfer by mass: $$X_{\text{mass}} = m\psi$$

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

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

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

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:

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

General, unit-mass basis:

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

where

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

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

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

$$\Delta\dot{X}_{\text{system}} = dX_{\text{system}} / dt$$

For a *reversible process*, the exergy destruction term $X_{\text{destroyed}}$ drops out.

- 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 general exergy balance relations can be expressed more explicitly as

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

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

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