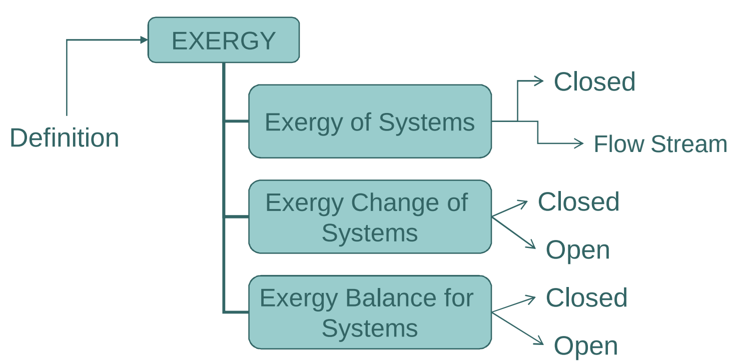
CHAPTER 8

EXERGY

Prolog

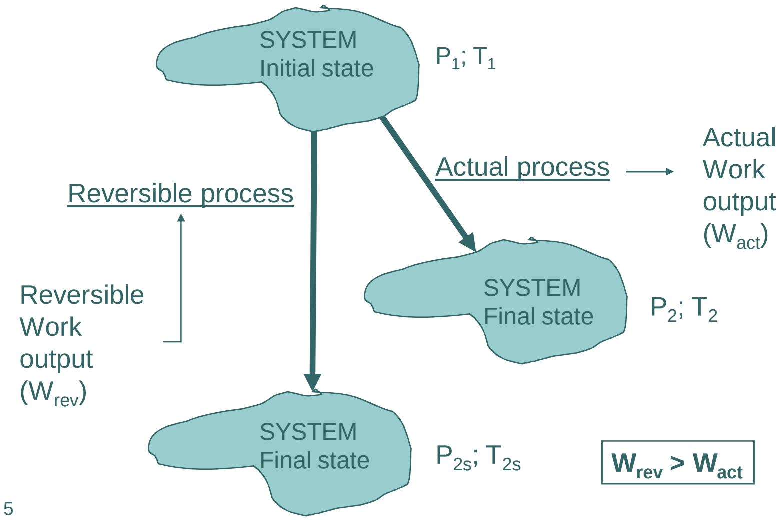


8.1 Introduction

- Definition of exergy – is a **property** that enable us to determine useful work potential of a given amount of energy at some specified state.
- Also called as **availability** or **available energy**.
- Another definition – maximum useful work that can be obtained from the system.

Recall, in energy analysis, we know that work,

$$work = f\left(initial\ state,\ process\ path,\ final\ state\right)$$



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In exergy analysis, initial state is specified.

$$\text{Work output} = f\left(\textit{process path},\ \textit{final state}\right)$$

$$\text{Process path} \rightarrow \text{reversible process}$$

$$\text{Final state} \rightarrow \text{Dead state}, \left(P_o ; T_o\right)$$

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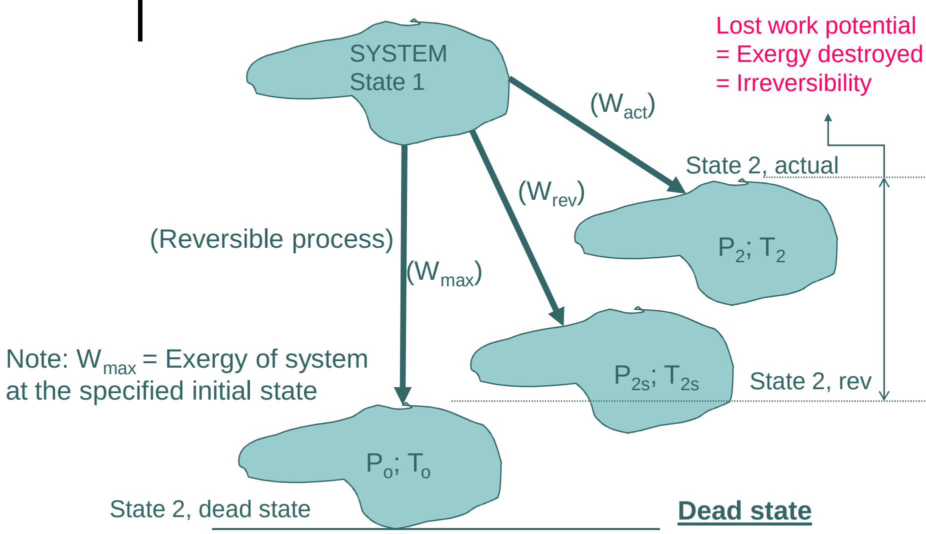

What is Dead State?

System is at thermodynamic equilibrium with the environment;

$P = P_o$ (mechanical equilibrium)
$T = T_o$ (thermal equilibrium)
$\Delta KE = \Delta PE = 0$
Exergy = Availability = 0

Note:
Dead state are denoted by subscript zero.

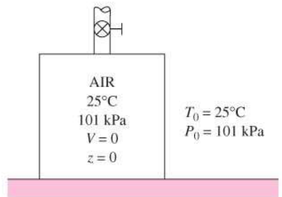

FIGURE 8–1
A system that is in equilibrium with its environment is said to be at the dead state.

FIGURE 8–2
At the dead state, the useful work potential (exergy) of a system is zero.

Conclusion

- A system will deliver the maximum possible work as it undergoes a reversible process from the specified initial state to the final dead state.
- This work represents useful work potential of the system at the specified state.
- This useful work potential is called **EXERGY**.

8.1.1 Exergy of Kinetic Energy (KE)

Kinetic energy ≡ Form of mechanical energy

Exergy of KE = The KE itself

$$x_{ke} = ke = \frac{1}{2}\bar{V}^2 \quad (kJ/kg)$$

where : $\bar{V}$ = velocity of system

8.1.2 Exergy of Potential Energy (PE)

Potential energy ≡ Form of mechanical energy

Exergy of PE = The PE itself

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

where : g = gravitational acceleration

z = elevation of the system

Example 8-2 (page 427)

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 ^{o}C.

Example 8-2

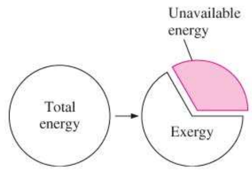

FIGURE 8–7
Unavailable energy is the portion of energy that cannot be converted to work by even a reversible heat engine.

8.2 Reversible Work & Irreversibility – Reversible Work

- Reversible work 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 fully reversible process between the specified initial and final states.
- When the final state is the dead state, W_{rev} = Exergy of system.

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8.2 Reversible Work & Irreversibility - Irreversibility

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

$$I = W_{rev,out} - W_{u,out} \quad \text{(work producing devices)} \quad \text{or}$$
$$I = W_{u,in} - W_{rev.in} \quad \text{(work consuming devices)}$$

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- *I* is equivalent to “exergy destroyed”.
- For totally reversible process,

$$\left.\begin{aligned} W_{sys} &= W_{rev,out} = W_{u,out} \\ &= W_{rev,in} = W_{u,in} \end{aligned}\right\} \quad S_{gen} = 0$$

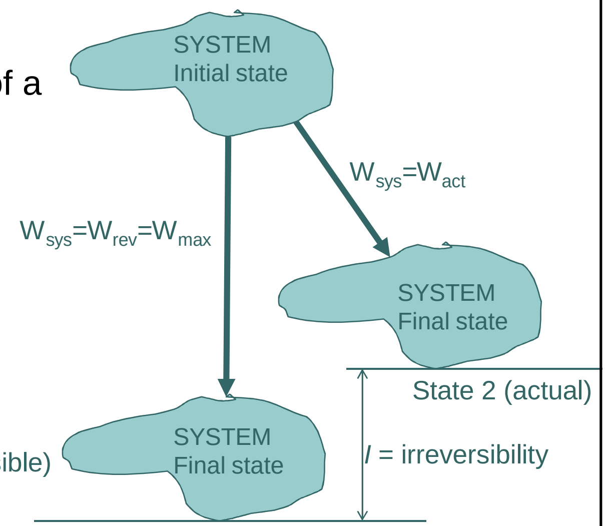
so that, *I* = 0.

- *I* is a positive quantity for all actual processes.

$$\begin{aligned} &W_{rev,out} \geq W_{u,out} \quad \text{(work producing devices)} \\ &W_{rev,in} \leq W_{u,in} \quad \text{(work consuming devices)} \end{aligned}$$

- *I* can be viewed as:
  - wasted work potential
  - lost opportunity to do work.

- Performance of a system can be improved by minimizing I.



8.2 Reversible Work & Irreversibility

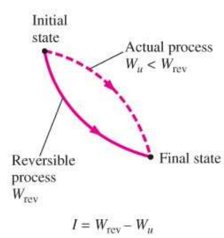


FIGURE 8–10
The difference between reversible work and actual useful work is the irreversibility.

8.2 Reversible Work & Irreversibility - Useful Work & Surrounding Work

Closed System

- **Useful work**, W_u is expressed as

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

- This equation has significance only for systems whose volume changes during the process (such as piston-cylinder device).
- **Surrounding Work**, W_{surr} : The work needed to push the atmospheric air during an expansion process in a closed system.

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

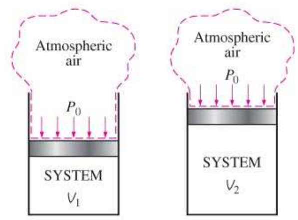


FIGURE 8–8
As a closed system expands, some work needs to be done to push the atmospheric air out of the way (W_{surr}).

Work done by **SYSTEM**, W_{sys} (boundary work)

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Open System (CV)

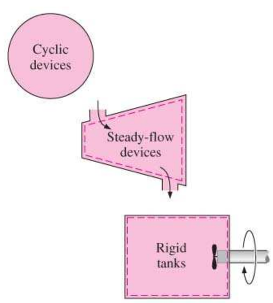

FIGURE 8–9
For constant-volume systems, the total actual and useful works are identical ($W_u = W$).

For cyclic devices and system whose boundaries remain fixed during a process such as rigid tanks and steady-flow devices, the useful work equals the work done by them, i.e.

$$W_u = W_{sys}$$

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Example 8-3 (page 429)

A heat engine receives heat from a source at 1200 K at a rate of 500 kJ/s and rejects the waste 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 8-3

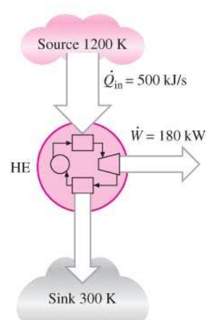

FIGURE 8–11
Schematic for Example 8–3.

8.3 Second-Law Efficiency, η_{II}

- The first-law efficiency alone is not a realistic measure of performance of engineering devices.
- To overcome this deficiency, a second-law efficiency η_{II} is defined.
- η_{II} is the ratio of the actual thermal efficiency to the maximum possible (reversible) thermal efficiency under the same conditions.

Various definitions of η_{II} are as follows:

i. **<u>Heat engines</u>**

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

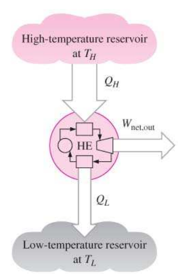

FIGURE 6–13
Schematic of a heat engine.

ii. **Work-producing devices**

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

Note: η_{II} < 100% and W_u = actual work

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iii **Work-consuming devices**

For a compressor,

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

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iv. **Refrigerators and Heat pumps**

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

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The η_{II} of a system during a process can be generally expressed as:

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

or

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

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- In reversible processes, exergy recovered = exergy supplied, thus exergy destroyed = 0.
- η_{II} = 0, when the exergy destroyed = exergy supplied.
- Exergy can be recovered or supplied in the form of work, heat, ke, pe, internal energy and enthalpy.
- For a heat engine,

  Exergy supplied = (X of Q_H – X of Q_L)

  Exergy recovered = W_{out}
- For a refrigerator or heat pump,

  Exergy supplied = W_{in}

  Exergy recovered = (X of Q_L) refrigerator

  = (X of Q_H) heat pump

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Example 8-6 (page 434)

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 ^oC and outdoor temperature of 10 ^oC, determine the second-law efficiency of these heaters.

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Example 8-6 (page 434)

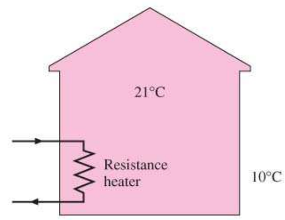

FIGURE 8–19

Schematic for Example 8–6.

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8.4 Exergy Change of A System – Closed System

- The exergy of a closed system of mass, *m* at any given state is:

$$X = (U - U_o) + P_o(V - V_o) - T_o(S - S_o) + m\frac{\overline{V}^2}{2} + mgz \quad \text{(kJ)}$$

- Where *U*, *V* and *S* are internal energy, volume and entropy respectively. $\overline{V}$ is velocity of the system and *z* is the elevation relative to the surroundings.

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- U_o, V_o, and S_o are the properties of the system evaluated at the dead state.
- P_o and T_o are pressure and temperature of the surroundings (dead state), respectively.
- On a unit mass basis, the closed system exergy, ϕ is expressed as:

$$\phi = (u - u_o) + P_o(v - v_o) - T_o(s - s_o) + \frac{\overline{V}^2}{2} + gz \quad (\text{kJ/kg})$$

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- ϕ can also be written as:

$$\phi = (e - e_o) + P_o(v - v_o) - T_o(s - s_o) \quad (\text{kJ/kg})$$

Note:
At the dead state, $\phi = 0$, since $u = u_o$, $v = v_o$ and $s = s_o$, when ke = pe = 0.

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Exergy Change

Exergy change for a closed system,

$$\Delta X = X_2 - X_1$$
$$= (U_2 - U_1) + P_o(V_2 - V_1) - T_o(S_2 - S_1) + m\frac{\vec{V}_2^{\,2} - \vec{V}_1^{\,2}}{2} + mg(z_2 - z_1)\ (\text{kJ})$$

i.e.

$$\Delta X = (E_2 - E_1) + P_o(V_2 - V_1) - T_o(S_2 - S_1)\ (\text{kJ})$$

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On a unit mass basis,

$$\Delta \phi = \phi_2 - \phi_1$$
$$= (u_2 - u_1) + P_o(v_2 - v_1) - T_o(s_2 - s_1) + \frac{\vec{V}_2^{\,2} - \vec{V}_1^{\,2}}{2} + g(z_2 - z_1)\ (\text{kJ/kg})$$

i.e.

$$\Delta \phi = (e_2 - e_1) + P_o(v_2 - v_1) - T_o(s_2 - s_1)\ (\text{kJ/kg})$$

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Note

- Exergy (X,ϕ) is a property. So $\Delta X = 0$ and $\Delta\phi = 0$ if the state of system does not change during a process.
- Exergy of closed systems (X or ϕ) is either positive or zero. It is **NEVER** negative.

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8.4 Exergy Change of A System

Exergy change of a closed 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}.

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Question 8-35 (page 472)

An insulated piston-cylinder device contains 2 L of saturated liquid at a constant pressure of 150 kPa. An electric resistance heater inside the cylinder is turned on, and electrical work is done on the water in the amount of 2200 kJ. Assuming the surroundings to be at T_o = 25^{o}C and P_o = 100 kPa, determine,

a) The reversible work input during this process [kJ];
b) The exergy destroyed during this process [kJ].

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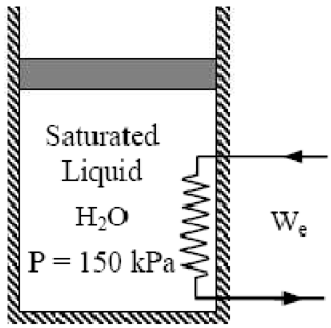
Question 8-35 (page 472)



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Question 8-29 (page 472)

A piston-cylinder device contains 5 kg of refrigerant-134a at 0.7 MPa and 60ºC. The refrigerant is now cooled at constant pressure until it exists as a liquid at 24ºC. If the surroundings are at 100 kPa and 24ºC, determine,

a) The exergy of the refrigerant at the initial and the final states;
b) The exergy destroyed during this process.

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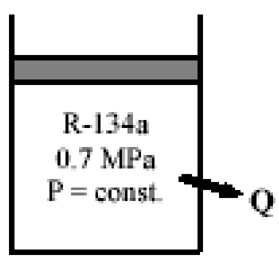
Question 8-29 (page 472)



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Question 8-28 (page 472)

A piston–cylinder device initially contains 2 L of air at 100 kPa and 25°C. Air is now compressed to a final state of 600 kPa and 150°C. The useful work input is 1.2 kJ. Assuming the surroundings are at 100 kPa and 25°C, determine

(a) the exergy of the air at the initial and the final states,

(b) the minimum work that must be supplied to accomplish this compression process, and

(c) the second-law efficiency of this process.

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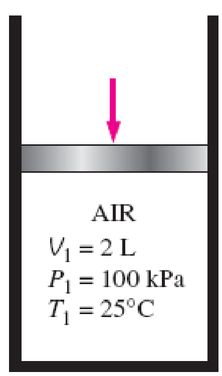
Question 8-28 (page 472)



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Question 8-33 (page 472)

A rigid tank is divided into two equal parts by a partition. One part of the tank contains 1.5 kg of compressed liquid water at 300 kPa and 60°C and the other side is evacuated. Now the partition is removed, and the water expands to fill the entire tank. If the final pressure in the tank is 15 kPa, determine, the exergy destroyed during this process. Assume the surroundings to be at 25°C and 100 kPa.

Question 8-41 (page 473)

An insulated rigid tank is divided into two equal parts by a partition. Initially, one part contains 3 kg of argon gas at 300 kPa and 70°C, and the other side is evacuated. The partition is now removed, and the gas fills the entire tank. Assuming the surroundings to be at 25°C, determine the exergy destroyed during this process.

Example 8-11 (page 449)

A piston-cylinder device contains 0.05 kg of steam at 1 MPa and 300ºC. Steam now expands to a final state of 200 kPa and 150ºC, 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_o = 25ºC and P_o = 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;
d) The second-law efficiency for the process.

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Example 8-11 (page 449)

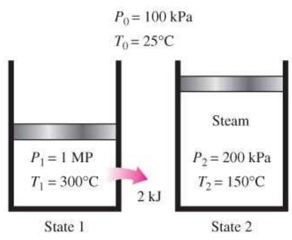

FIGURE 8–37
Schematic for Example 8–11.

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Question 8-32 (page 472)

A well-insulated rigid tank contains 3 kg of saturated liquid-vapour mixture of water at 250 kPa. Initially, three quarters of the mass is in the liquid phase. An electric resistance heater placed in the tank is turned on and kept on until all the liquid in the tank is vaporized. Assuming the surroundings to be at 25°C and 100 kPa, determine,

a) the exergy destruction and
b) the second-law efficiency for this process.

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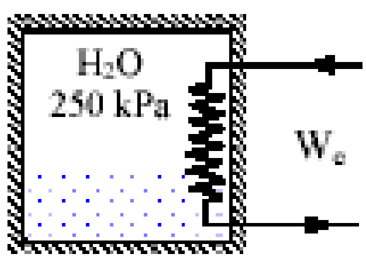
Question 8-32 (page 472)



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8.4 Exergy Change of A System – Open System

- Flow (or stream) exergy at any given state, ψ is given by

$$\psi = (h - h_o) - T_o(s - s_o) + \frac{\bar{V}^2}{2} + gz \quad \text{(kJ/kg)}$$

where *h*, *s* and $\bar{V}$ are specific enthalpy, specific entropy and velocity of the system respectively.

- h_o and s_o are enthalpy and entropy of the stream measured at the dead state.

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Exergy Change

When a fluid stream undergoes a process from state 1 to state 2, the exergy change

$$\Delta\psi = \psi_2 - \psi_1$$
$$= (h_2 - h_1) - T_o(s_2 - s_1) + \frac{\bar{V}_2^2 - \bar{V}_1^2}{2} + g(z_2 - z_1)\,\text{(kJ/kg)}$$

If Δke = Δpe = 0

$$\Delta\psi = (h_2 - h_1) - T_o(s_2 - s_1)\,\text{(kJ/kg)}$$

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Note:

Exergy of a fluid stream can be negative at pressures $P < P_o$

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Question 8-53 (page 475)

Air is compressed steadily by an 8 kW compressor from 100 kPa and 17 ^oC to 600 kPa to 167 ^oC at a rate of 2.1 kg/min. Neglecting the changes in kinetic and potential energies, determine,

a) the increase in the exergy of the air
b) The rate of exergy destroyed during this process. Assuming surroundings to be at 17 ^oC

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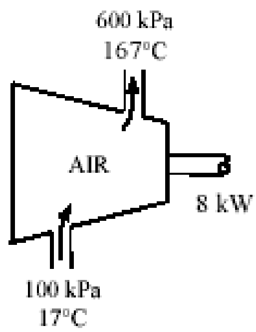
Question 8-53 (page 475)



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Question 8-61 (page 475)

Steam enters an adiabatic turbine at 6 MPa, 600°C,and 80 m/s and leaves at 50 kPa, 100°C, and 140 m/s. If the power output of the turbine is 5 MW, determine

(a) the reversible power output and

(b) the second-law efficiency of the turbine.

Assume the surroundings to be at 25°C.

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Question 8-60 (page 475)

Air is compressed steadily by a compressor from 100 kPa and 17°C to 700 kPa and 247°C at a rate of 10 kg/min. Assuming the surroundings to be at 17°C, determine the minimum power input to the compressor. Assume air to be an ideal gas with constant specific heats, and neglect the changes in kinetic and potential energies.

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Question 8-62 (page 476)

Steam is throttled from 9 MPa and 500°C to a pressure of 7 MPa. Determine the decrease in exergy of the steam during this process. Assume the surroundings to be at 25°C.

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Question 8-69 (page 476)

Air enters a compressor at ambient conditions at 100 kPa and 17 ^oC with a low velocity and exits at to 1 MPa, 327 ^oC and 105 m/s. The compressor is cooled by the ambient air at 17 ^oC at a rate of 1500 kJ/min. The power input to the compressor is 300 kW. Determine,

a) the mass flow rate of air;
b) the portion of power input that is used just to overcome the irreversibilities.

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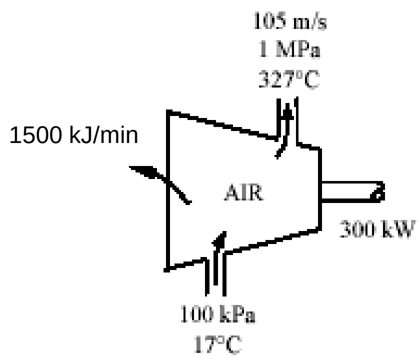
Question 8-69 (page 476)



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Question 8-73 (page 476)

A hot-water stream at 70°C enters an adiabatic mixing chamber with a mass flow rate of 2 kg/s, where it is mixed with a stream of cold water at 20°C. If the mixture leaves the chamber at 45°C, determine

(a) the mass flow rate of the cold water and

(b) the exergy destroyed during this adiabatic mixing process.

Assume all the streams are at a pressure of 350 kPa and the surroundings are at 25°C.

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8.4 Summary of Exergy Change of A System

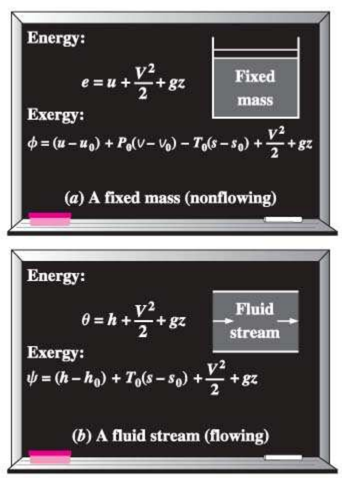

FIGURE 8–23

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

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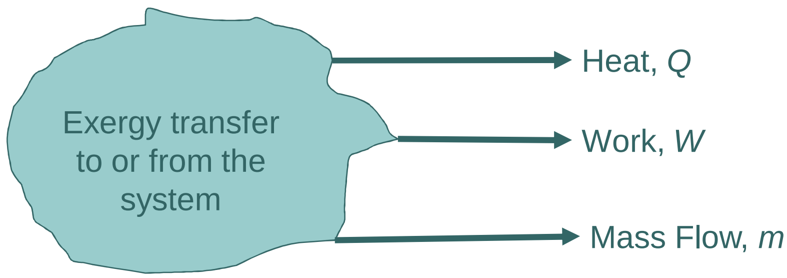
8.5 Exergy Transfer



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By heat transfer, Q

Heat transfer, *Q*, at a location at absolute temperature *T* is always accompanied by exergy transfer X_{heat}, in the amount of, Carnot efficiency – represents the fraction of *Q* that can be converted into work, during a reversible process.

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

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8.5 Exergy Transfer

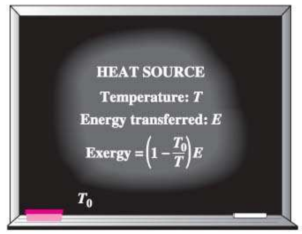

FIGURE 8–26

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.

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- When $T > T_o$, Q into the system increases exergy of the system, and Q from the system decreasing it.
- When $T < T_o$, the opposite happens.
- When $T = T_o$, the $X_{heat} = 0$.

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8.5 Exergy Transfer

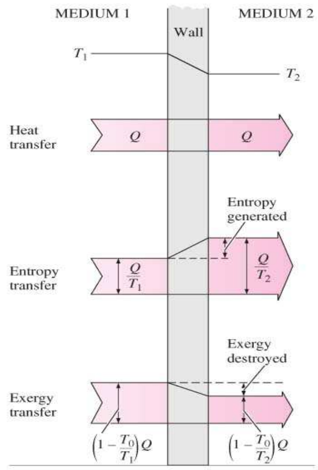

FIGURE 8–27

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

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By work, W

- Exergy transfer by work can be expressed as:

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

- where,

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

- In which P_o is atmospheric pressure, V_1 and V_2 are initial and final volumes of the system.

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By mass, m

- When mass in the amount of *m* enters or leaves a system, exergy in the amount of $m\Psi$ accompanies it, i.e. exergy transfer by mass,

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

where,

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

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Note:

- X_{heat} = 0, for adiabatic system.
- X_{mass} = 0, for closed system.
- X_{total} = 0 for isolated systems, since they do not involve *Q*, *W* and *m* transfer.

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8.6 The Decrease of Exergy Principle and Exergy Destruction

Exergy Destruction

- Anything that generates entropy will destroy exergy.
- Irreversibilities – friction, chemical reactions etc. – always generates entropy.
- So, exergy destroyed,

$$X_{destroyed} = T_o S_{gen} \geq 0$$

- $X_{destroyed}$ is positive for actual processes, and zero for a reversible process.

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8.7 Exergy Balance – Closed System

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

$$\underbrace{X_{in} - X_{out}}_{\substack{\text{net exergy transfer} \\ \text{by heat, work, and} \\ \text{mass}}} - \underbrace{X_{destroyed}}_{\text{Exergy distruction}} = \underbrace{\Delta X_{system}}_{\substack{\text{change of} \\ \text{exergy of the} \\ \text{system}}} \quad (\text{kJ})$$

Exergy destruction,
$X_{destroyed} = T_o S_{gen}$

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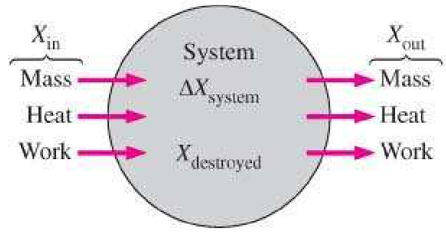

FIGURE 8–32
Mechanisms of exergy transfer.

It can also be expressed as,

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

That is,

$$\sum \left(1 - \frac{T_o}{T}\right) Q_k - \left[W - P_o\left(V_2 - V_1\right)\right] - T_o S_{gen} = X_2 - X_1 \quad (\text{kJ})$$

Where,

- Q_k = heat transfer through the system boundary at temperature T_k, at location *k*.
- *W* = work done by or on the system
- $P_o\ (V_2 – V_1)$ = surroundings work
- S_{gen} = entropy generation during the process, within the system

The exergy balance equation can be expressed in a rate form as,

$$\sum\left(1-\frac{T_o}{T}\right)\dot{Q}_k-\left[\dot{W}-P_o\left(V_2-V_1\right)\right]-T_o\,\dot{S}_{gen}=\frac{dX_{sys}}{dt}\qquad(\text{kJ})$$

Note:

- $W = W_{rev}$ when $X_{destroyed} = T_o S_{gen} = 0$.
- $X_{destroyed}$ represents exergy destruction within system boundary only.
- For a reversible process, $S_{gen} = 0$, thus, $X_{destroyed} = 0$. Therefore ΔX_{system} = exergy transfer.