

Thermodynamics: An Engineering Approach

8th Edition

Yunus A. Çengel, Michael A. Boles

McGraw-Hill, 2015

Topic 13 **ENTROPY**

Objectives

- Apply the second law of thermodynamics to processes.
- Define a new property called *entropy* to quantify the second-law effects.
- Establish the *increase of entropy principle*.
- Calculate the entropy changes that take place during processes for pure substances.

ENTROPY

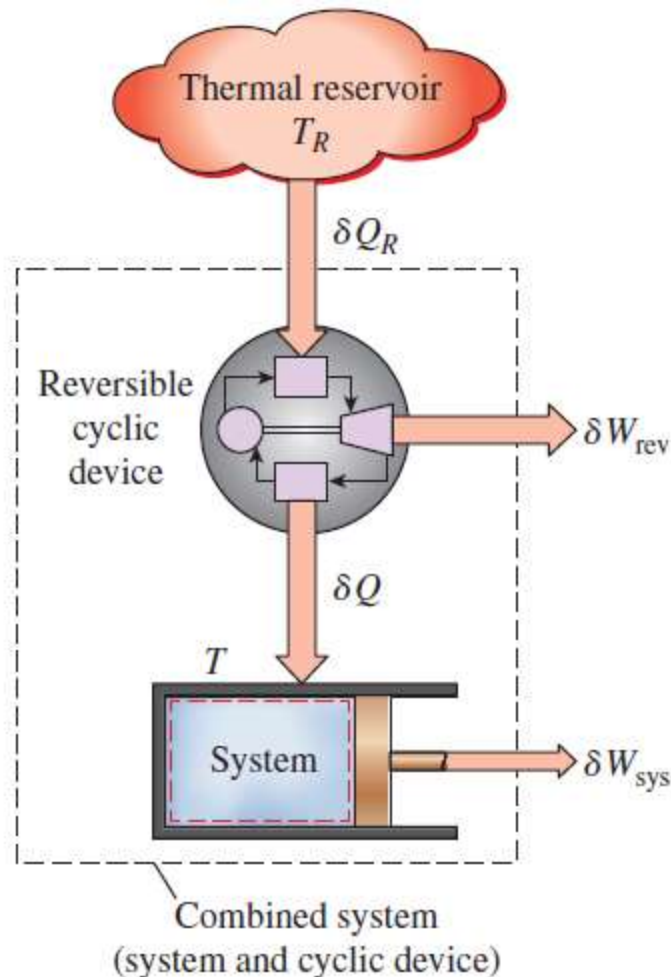


FIGURE 7-1

The system considered in the development of the Clausius inequality.

$$\oint \frac{\delta Q}{T} \leq 0 \quad \text{Clausius inequality}$$

$$\oint \left(\frac{\delta Q}{T} \right)_{\text{int rev}} = 0$$

$$dS = \left(\frac{\delta Q}{T} \right)_{\text{int rev}} \quad (\text{kJ/K}) \quad \text{Formal definition of entropy}$$

$$\Delta S = S_2 - S_1 = \int_1^2 \left(\frac{\delta Q}{T} \right)_{\text{int rev}}$$

The equality in the Clausius inequality holds for totally or just internally reversible cycles and the inequality for the irreversible ones.

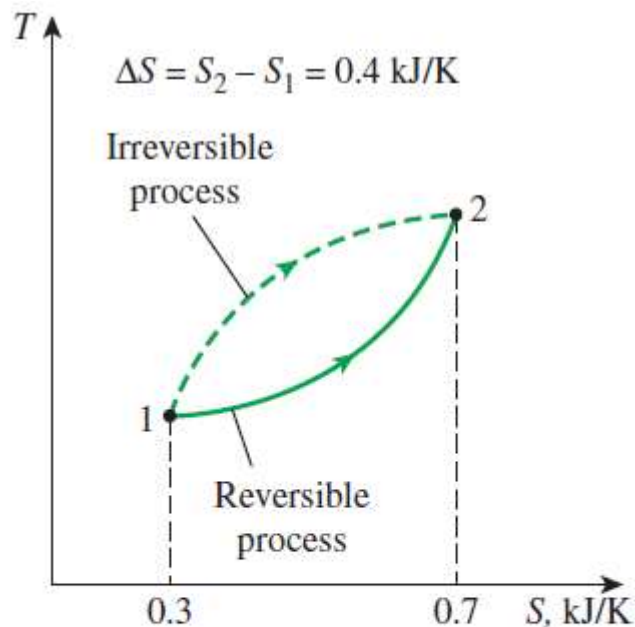


FIGURE 7-3

The entropy change between two specified states is the same whether the process is reversible or irreversible.

A Special Case: Internally Reversible Isothermal Heat Transfer Processes

$$\Delta S = \int_1^2 \left(\frac{\delta Q}{T} \right)_{\text{int rev}} = \int_1^2 \left(\frac{\delta Q}{T_0} \right)_{\text{int rev}} = \frac{1}{T_0} \int_1^2 (\delta Q)_{\text{int rev}}$$

$\Delta S = \frac{Q}{T_0}$ This equation is particularly useful for determining the entropy changes of thermal energy reservoirs.

$$\oint \left(\frac{\delta Q}{T} \right)_{\text{int rev}} = 0$$

A quantity whose cyclic integral is zero (i.e., a property like volume)

Entropy is an extensive property of a system.

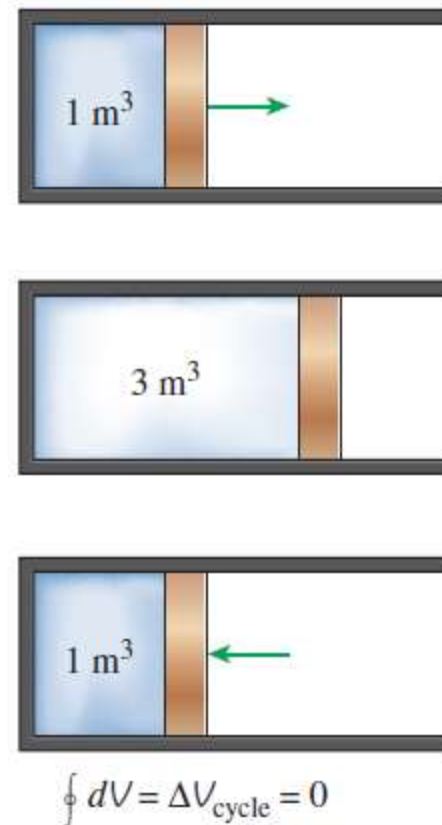


FIGURE 7-2

The net change in volume (a property) during a cycle is always zero.

Entropy Change Example

A piston cylinder device contains a liquid-vapor mixture of water at 27°C. During a constant pressure process, 750 kJ of heat is transferred to the water. As a result, part of the liquid in the cylinder vaporizes. Determine the entropy change of the water during this process.

Solution

THE INCREASE OF ENTROPY PRINCIPLE

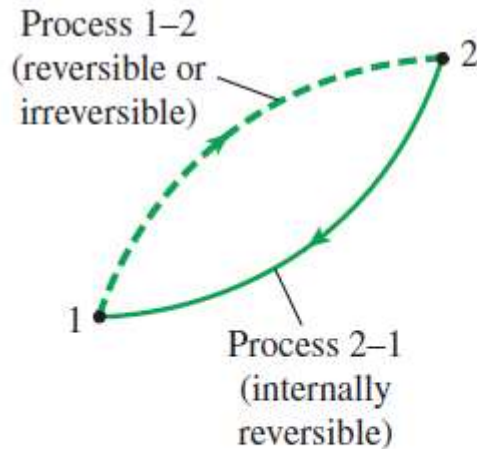


FIGURE 7-5

A cycle composed of a reversible and an irreversible process.

$$\oint \frac{\delta Q}{T} \leq 0 \quad \int_1^2 \frac{\delta Q}{T} + \int_2^1 \left(\frac{\delta Q}{T} \right)_{\text{int rev}} \leq 0$$

$$\int_1^2 \frac{\delta Q}{T} + s_1 - s_2 \leq 0 \quad s_2 - s_1 \geq \int_1^2 \frac{\delta Q}{T}$$

$$dS \geq \frac{\delta Q}{T}$$

The equality holds for an internally reversible process and the inequality for an irreversible process.

$$\Delta S_{\text{sys}} = s_2 - s_1 = \int_1^2 \frac{\delta Q}{T} + S_{\text{gen}}$$

$$S_{\text{gen}} = \Delta S_{\text{total}} = \Delta S_{\text{sys}} + \Delta S_{\text{surr}} \geq 0$$

Some entropy is *generated* or *created* during an irreversible process, and this generation is due entirely to the presence of irreversibilities.

The entropy generation S_{gen} is always a positive quantity or zero.
Can the entropy of a system during a process decrease?

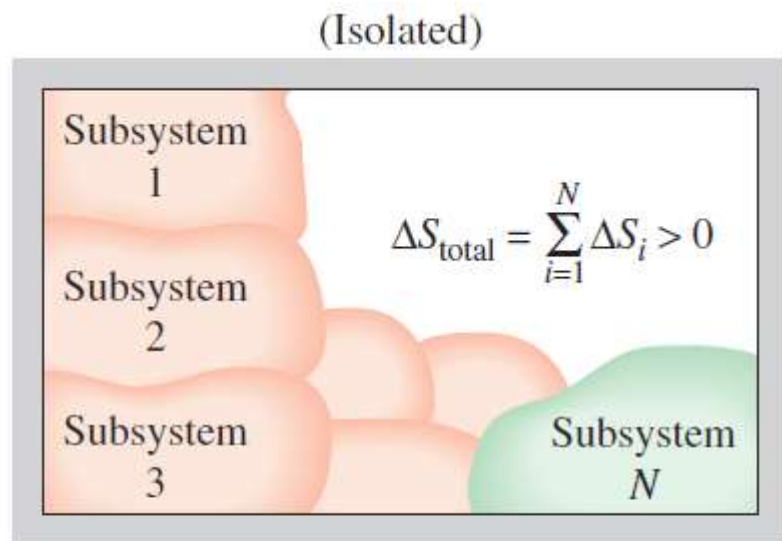


FIGURE 7–6

The entropy change of an isolated system is the sum of the entropy changes of its components, and is never less than zero.

$$\Delta S_{\text{isolated}} \geq 0$$

$$S_{\text{gen}} = \Delta S_{\text{total}} = \Delta S_{\text{sys}} + \Delta S_{\text{surr}} \geq 0$$

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

The increase of entropy principle

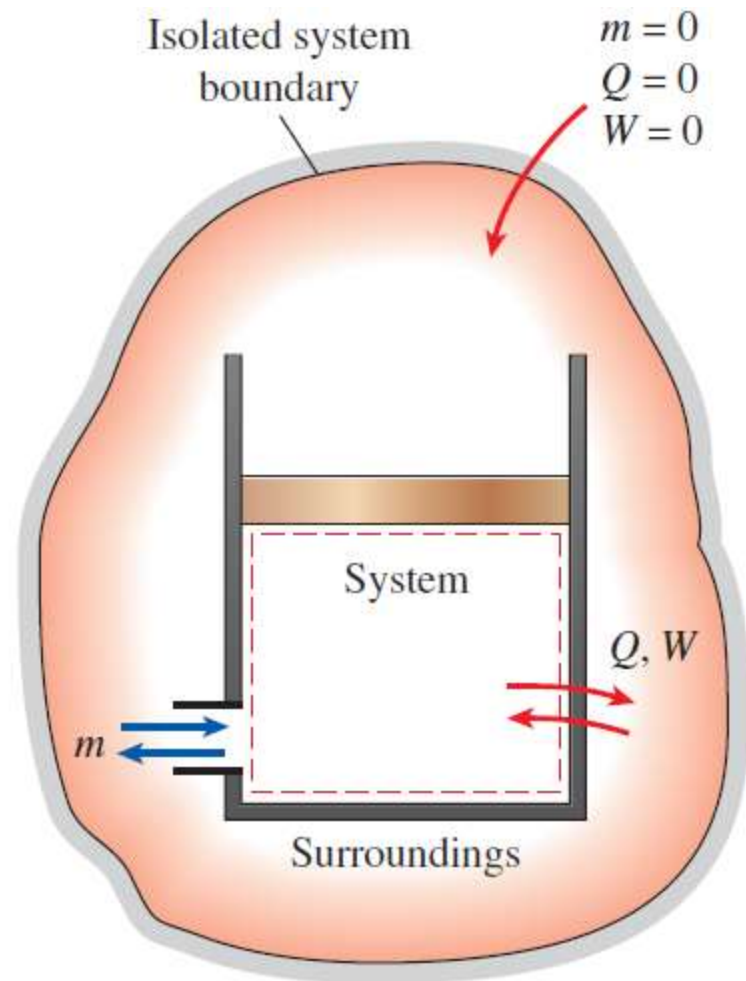
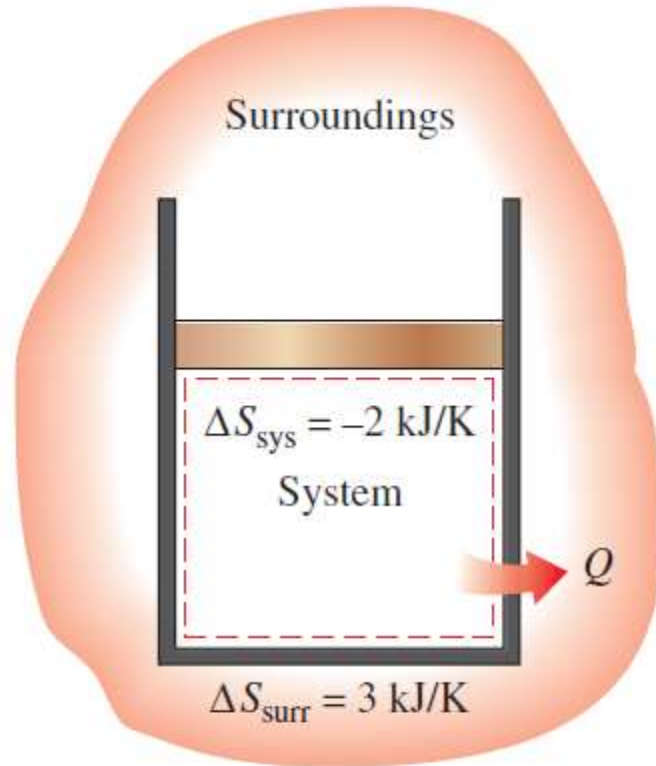


FIGURE 7–7

A system and its surroundings form an isolated system.

Some Remarks about Entropy



$$S_{\text{gen}} = \Delta S_{\text{total}} = \Delta S_{\text{sys}} + \Delta S_{\text{surr}} = 1 \text{ kJ/K}$$

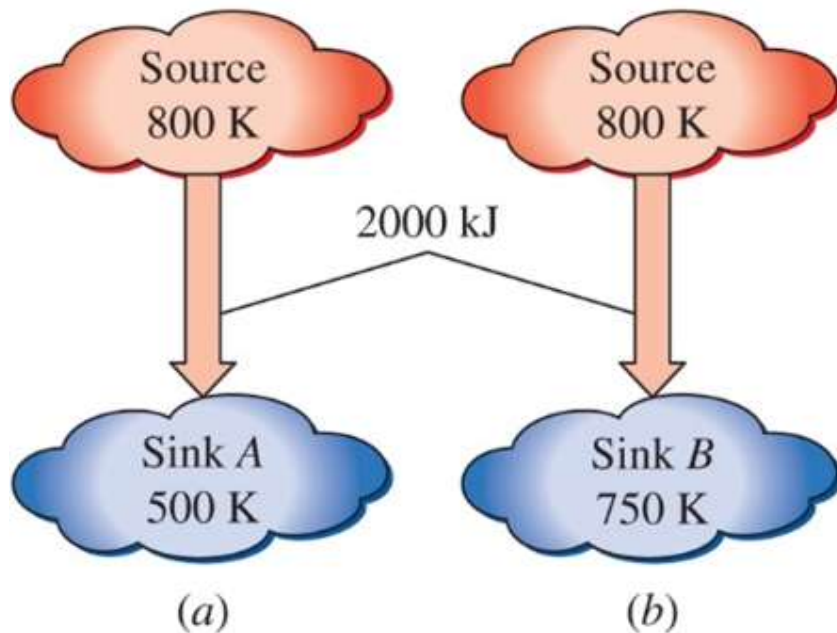
FIGURE 7–8

The entropy change of a system can be negative, but the entropy generation cannot.

1. Processes can occur in a certain direction only, not in any direction. A process must proceed in the direction that complies with the increase of entropy principle, that is, $S_{\text{gen}} \geq 0$. A process that violates this principle is impossible.
2. Entropy is a nonconserved property, and there is *no* such thing as the conservation of entropy principle. Entropy is conserved during the idealized reversible processes only and increases during *all* actual processes.
3. The performance of engineering systems is degraded by the presence of irreversibilities, and entropy generation is a measure of the magnitudes of the irreversibilities during that process. It is also used to establish criteria for the performance of engineering devices.

Entropy Generation during Heat Transfer

A heat source at 800 K loses 2000 kJ of heat to a sink at 500 K and at 750 K. Determine which heat transfer process is more irreversible.



Solution

ENTROPY CHANGE OF PURE SUBSTANCES

Entropy is a property, and thus the value of entropy of a system is fixed once the state of the system is fixed.

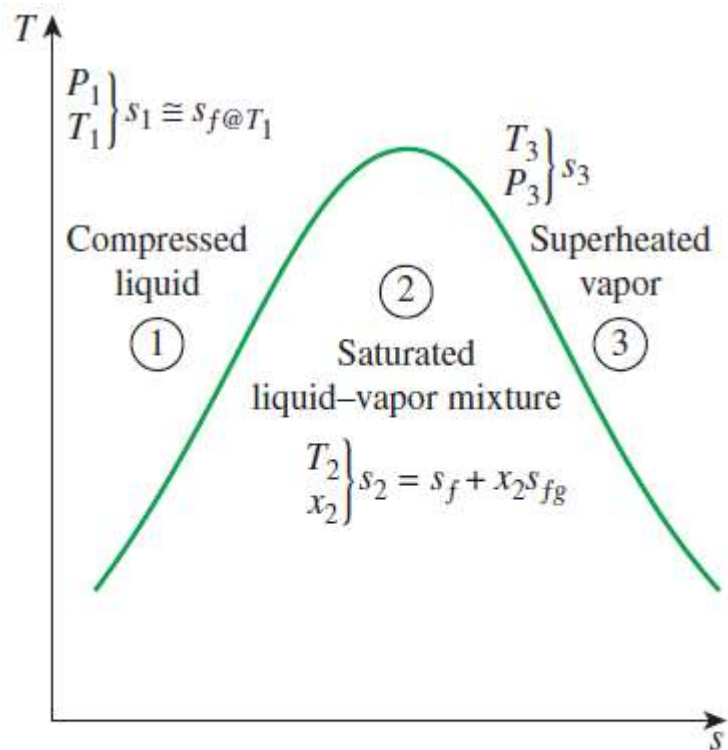


FIGURE 7-10

The entropy of a pure substance is determined from the tables (like other properties).

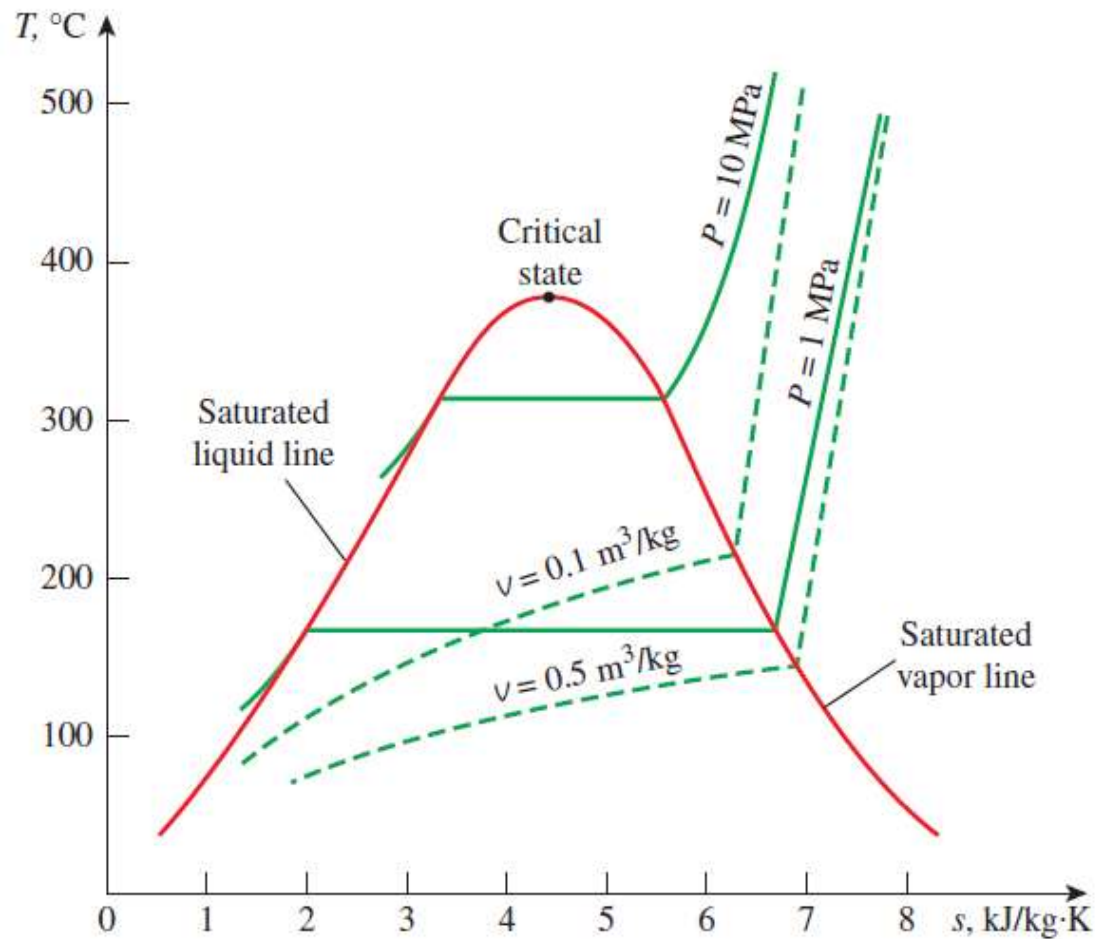


FIGURE 7-11

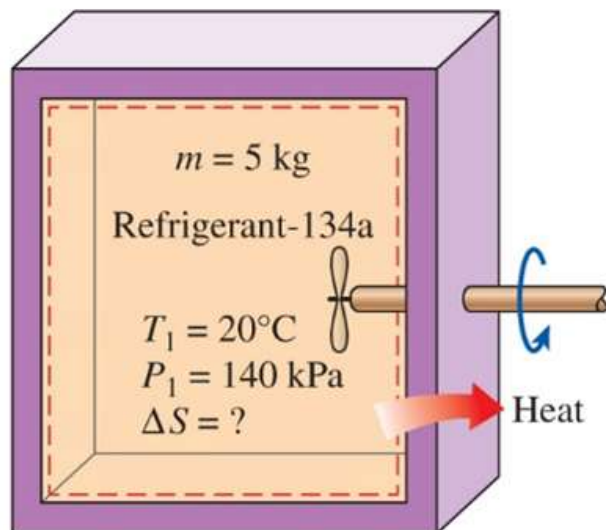
Schematic of the T - s diagram for water.

Entropy change

$$\Delta S = m \Delta s = m(s_2 - s_1) \quad (\text{kJ/K})$$

Entropy Change of a Substance in a Tank

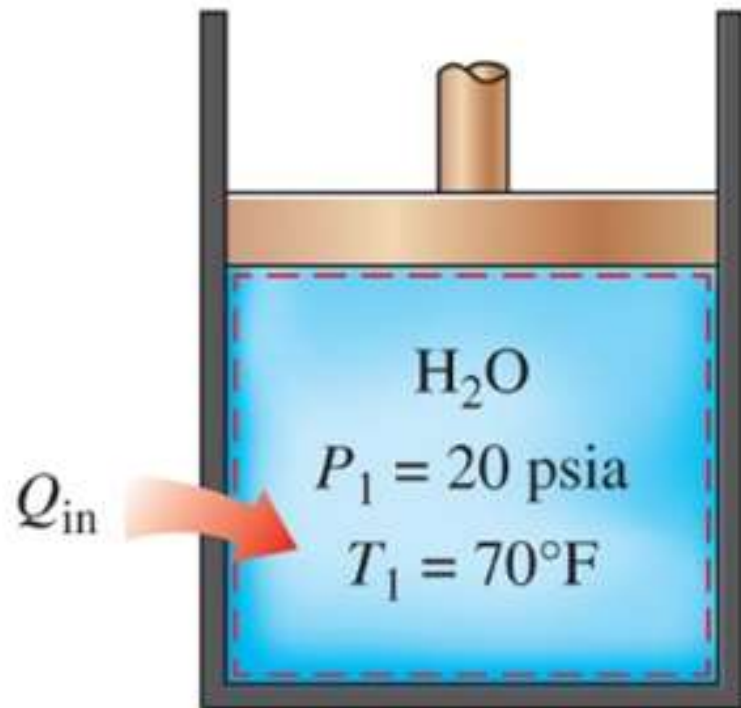
A rigid tank contains 5 kg of R-134a initially at 20°C and 140 kPa. The R-134a is now cooled while being stirred until its pressure drops to 100 kPa. Determine the entropy change of the R-134a during this process.



Solution

Entropy Change during a Constant Pressure Process

A piston cylinder device initially contains 3 lbm of liquid water at 20 psia and 70°F. The water is now heated at constant pressure by the addition of 3450 Btu of heat. Determine the entropy change of the water during this process.



Solution

ISENTROPIC PROCESSES

A process during which the entropy remains constant is called an **isentropic process**.

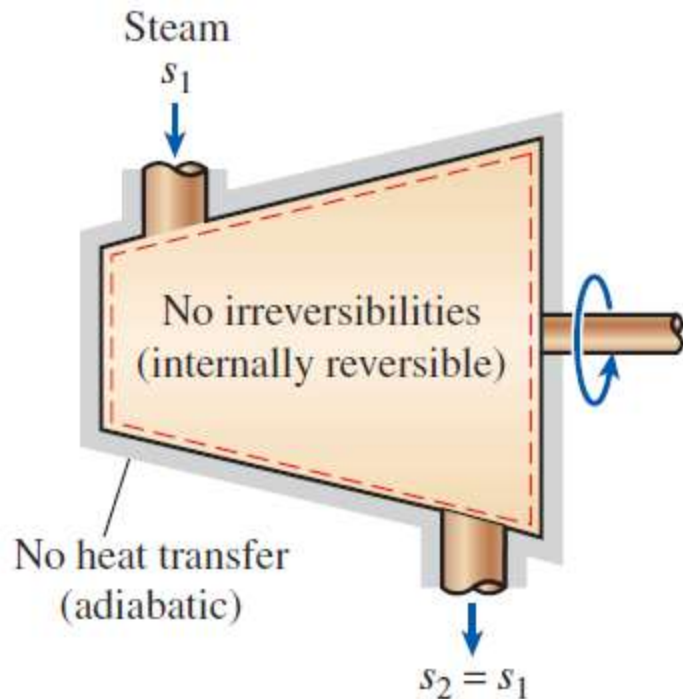


FIGURE 7-14

During an internally reversible, adiabatic (isentropic) process, the entropy remains constant.

$$\Delta s = 0 \quad \text{or} \quad s_2 = s_1 \text{ (kJ/kg} \cdot \text{K)}$$

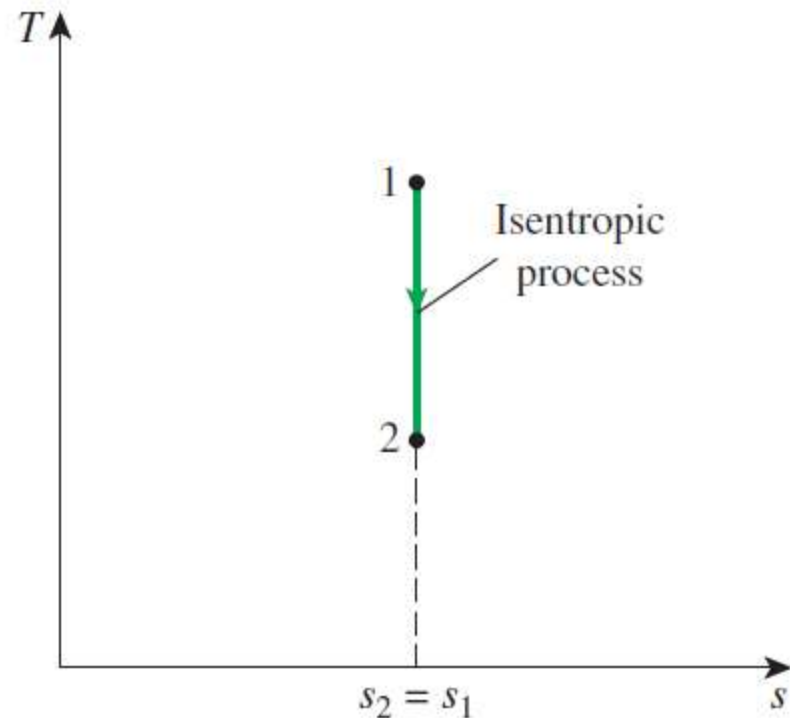


FIGURE 7-17

The isentropic process appears as a vertical line segment on a $T-s$ diagram.

Expansion of Steam in a Turbine

Steam enters an adiabatic turbine at 5 MPa and 450°C and leaves at a pressure of 1.2 MPa. Determine the work output of the turbine per unit mass of steam if the process is reversible.

Solution

PROPERTY DIAGRAMS INVOLVING ENTROPY

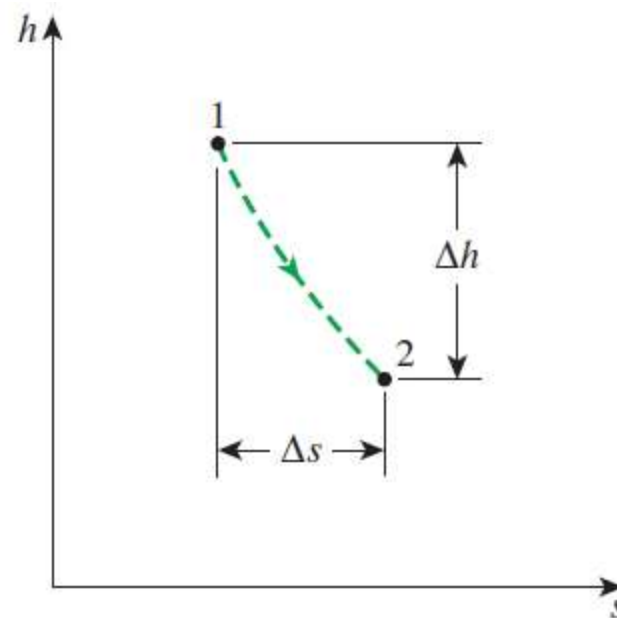
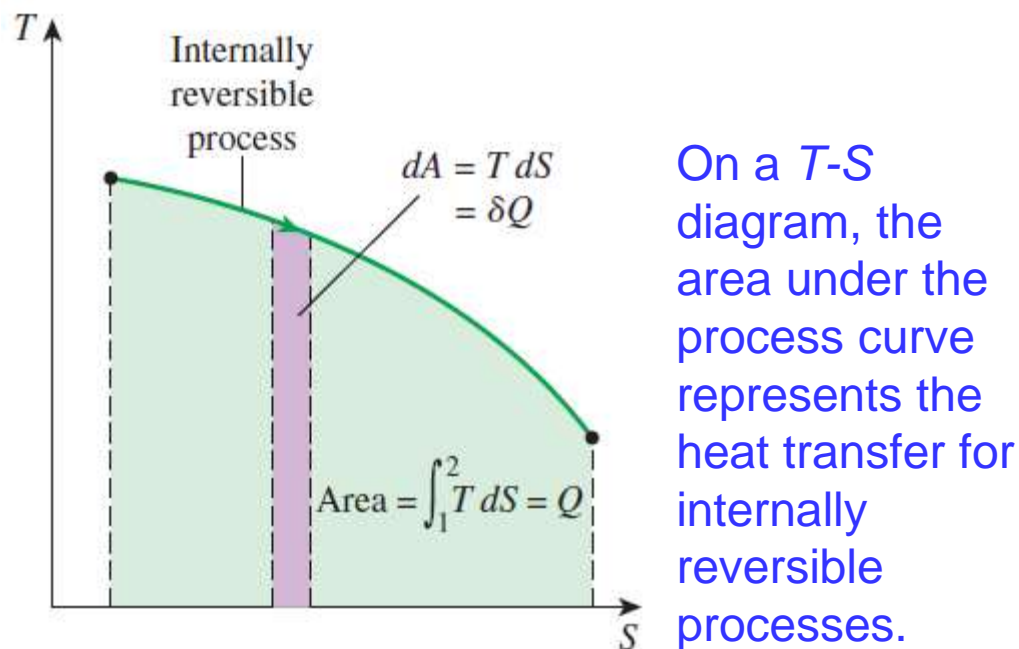


FIGURE 7-18

For adiabatic steady-flow devices, the vertical distance Δh on an h - s diagram is a measure of work, and the horizontal distance Δs is a measure of irreversibilities.

$$\delta Q_{\text{int rev}} = T dS \quad Q_{\text{int rev}} = \int_1^2 T dS$$

$$\delta q_{\text{int rev}} = T ds \quad q_{\text{int rev}} = \int_1^2 T ds$$

$$Q_{\text{int rev}} = T_0 \Delta S \quad q_{\text{int rev}} = T_0 \Delta s$$

Mollier diagram: The h - s diagram

$$W_{\text{net,out}} = Q_H - Q_L$$

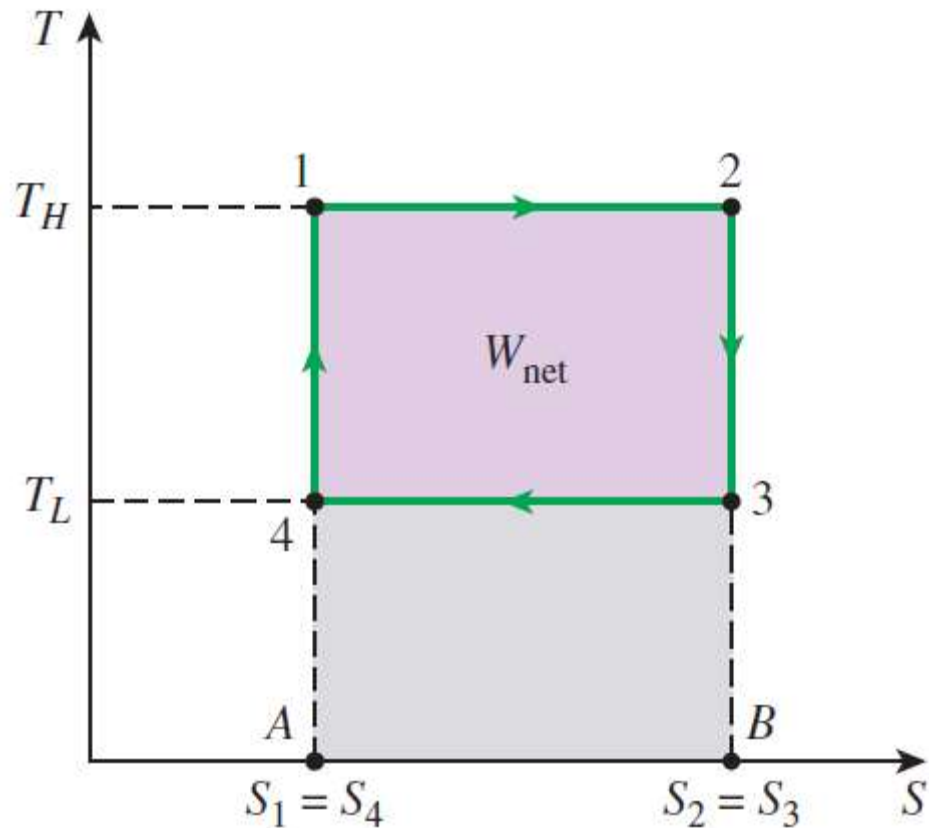


FIGURE 7–19

The T - S diagram of a Carnot cycle

WHAT IS ENTROPY?

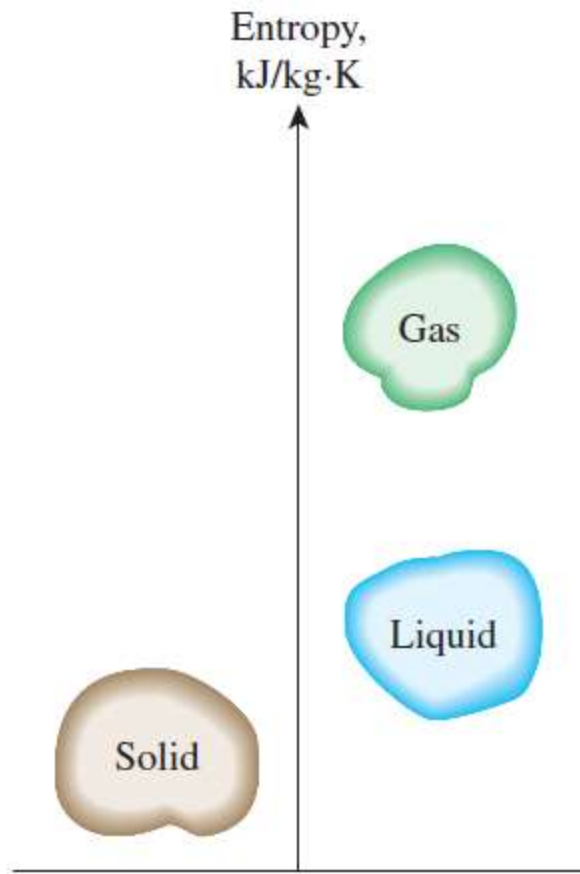


FIGURE 7–20

The level of molecular disorder (entropy) of a substance increases as it melts or evaporates.

Boltzmann relation

$$S = k \ln W$$

W the total number of possible relevant microstates of the system

Gibbs' formulation

$$S = -k \sum p_i \log p_i$$

p_i sum of all microstates' uncertainties, i.e., probabilities

$$k = 1.3806 \times 10^{-23} \text{ J/K}$$

Boltzmann constant

A pure crystalline substance at absolute zero temperature is in perfect order, and its entropy is zero (**the third law of thermodynamics**).

Pure crystal
 $T = 0 \text{ K}$
Entropy = 0



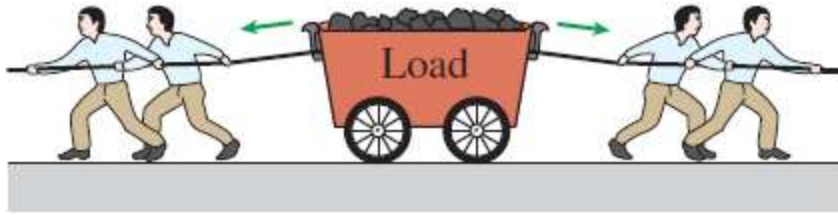


FIGURE 7-22

Disorganized energy does not create much useful effect, no matter how large it is.

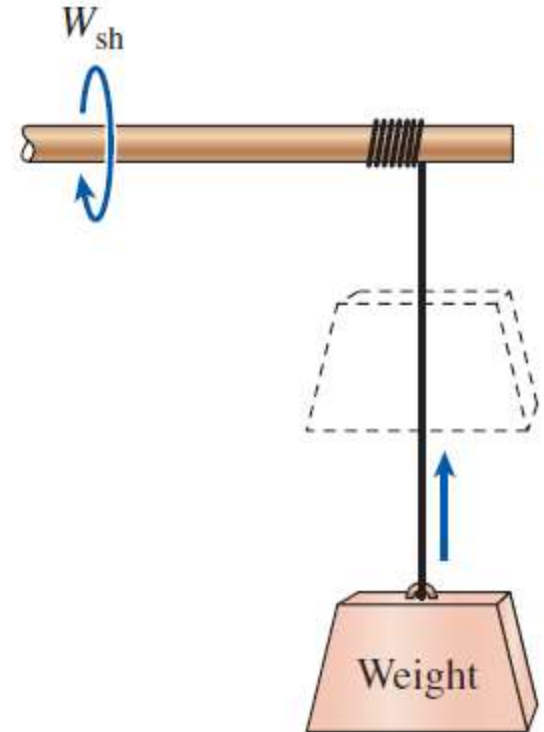


FIGURE 7-23

In the absence of friction, raising a weight by a rotating shaft does not create any disorder (entropy), and thus energy is not degraded during this process.

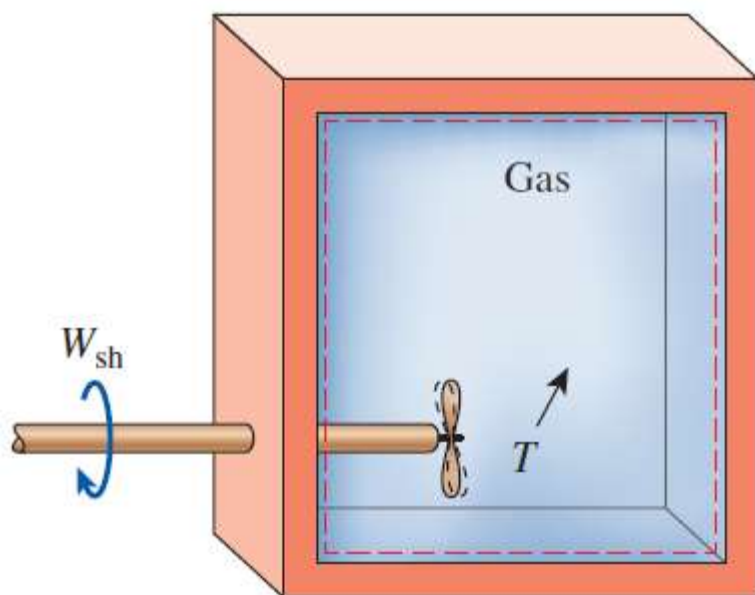


FIGURE 7–24

The paddle-wheel work done on a gas increases the level of disorder (entropy) of the gas, and thus energy is degraded during this process.

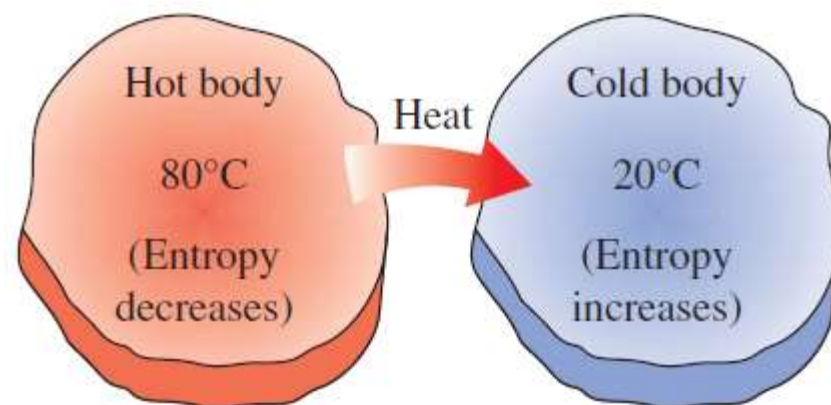


FIGURE 7–25

During a heat transfer process, the net entropy increases. (The increase in the entropy of the cold body more than offsets the decrease in the entropy of the hot body.)

THE T ds RELATIONS

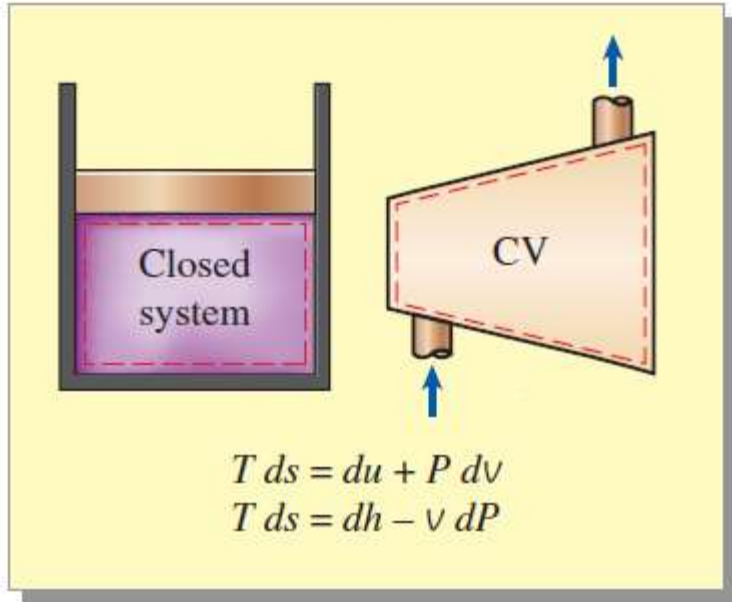


FIGURE 7-27

The $T ds$ relations are valid for both reversible and irreversible processes and for both closed and open systems.

$$\delta Q_{\text{int rev}} - \delta W_{\text{int rev,out}} = dU$$

$$\delta Q_{\text{int rev}} = T dS$$

$$\delta W_{\text{int rev,out}} = P dV$$

$$T dS = dU + P dV \quad (\text{kJ})$$

$$T ds = du + P dv \quad (\text{kJ/kg})$$

the first $T ds$, or Gibbs equation

$$h = u + Pv$$

$$\left. \begin{array}{l} dh = du + P dv + v dP \\ T ds = du + P dv \end{array} \right\} T ds = dh - v dP$$

the second $T ds$ equation

$$ds = \frac{du}{T} + \frac{P dv}{T}$$

$$ds = \frac{dh}{T} - \frac{v dP}{T}$$

Differential changes
in entropy in terms
of other properties

Summary

- Entropy
- The Increase of entropy principle
- Entropy change of pure substances
- Isentropic processes
- Property diagrams involving entropy
- What is entropy?
- The Tds relations