Thermodynamics: An Engineering Approach
8th Edition
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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

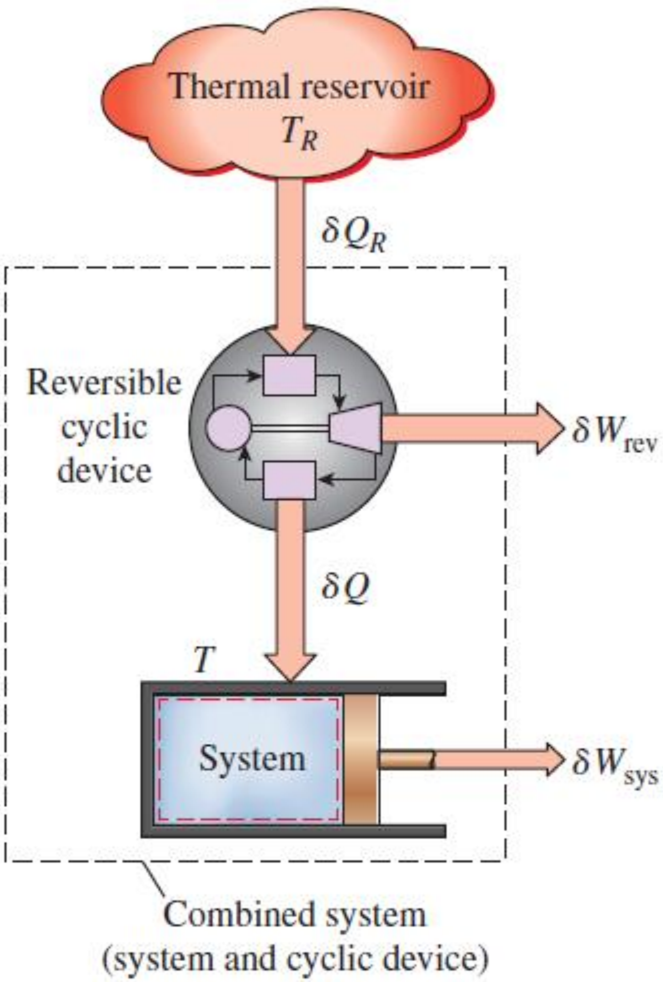


FIGURE 7–1
The system considered in the development of the Clausius inequality.

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

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

$$dS = \left(\frac{\delta Q}{T}\right)_{\text{int rev}} \qquad (\text{kJ/K})$$ 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.

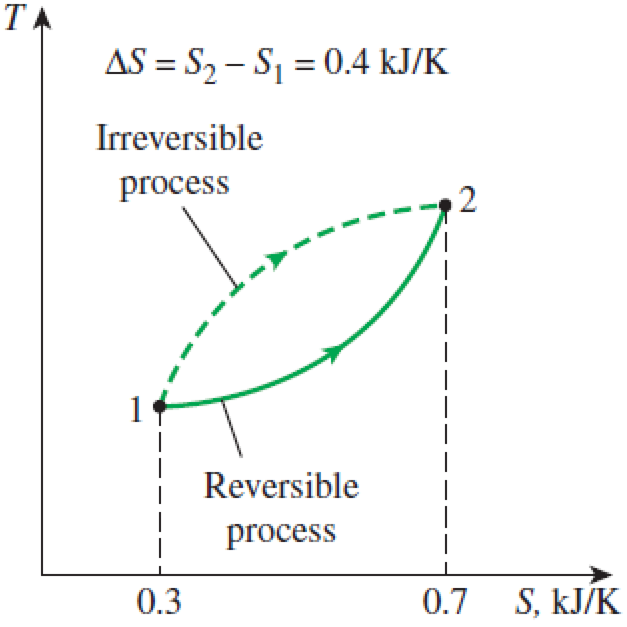


FIGURE 7–3
The entropy change between two specified states is the same whether the process is reversible or irreversible.

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

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

Entropy is an extensive property of a system.

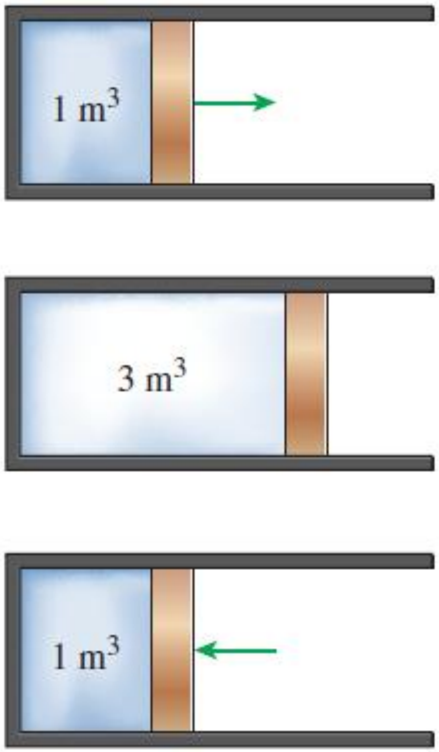


FIGURE 7–2
The net change in volume (a property) during a cycle is always zero.

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.

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

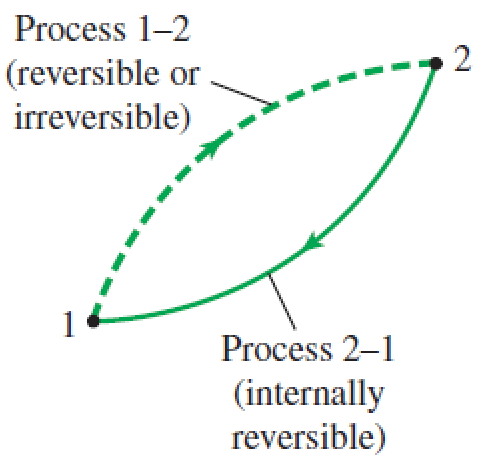


FIGURE 7–5
A cycle composed of a reversible and an irreversible process.

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

$$\int_1^2 \frac{\delta Q}{T} + S_1 - S_2 \le 0 \qquad S_2 - S_1 \ge \int_1^2 \frac{\delta Q}{T}$$

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

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

$$\Delta S_{\text{sys}} = S_2 - S_1 = \int_1^2 \frac{\delta Q}{T} + S_{\text{gen}}$$

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

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?

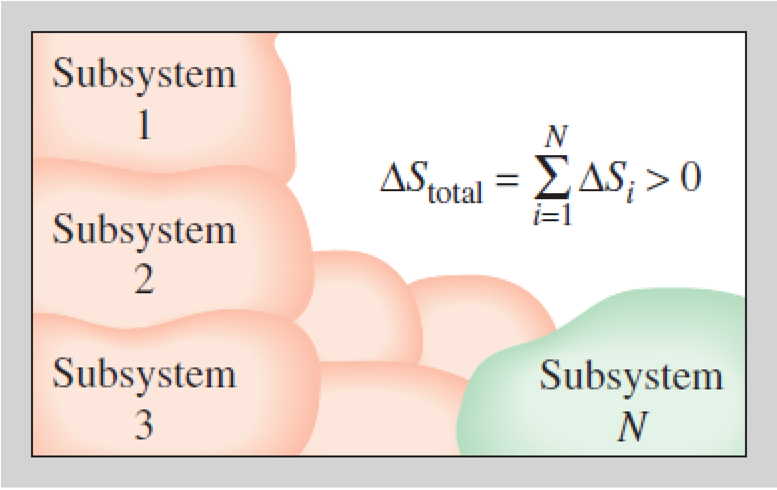


FIGURE 7–6

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

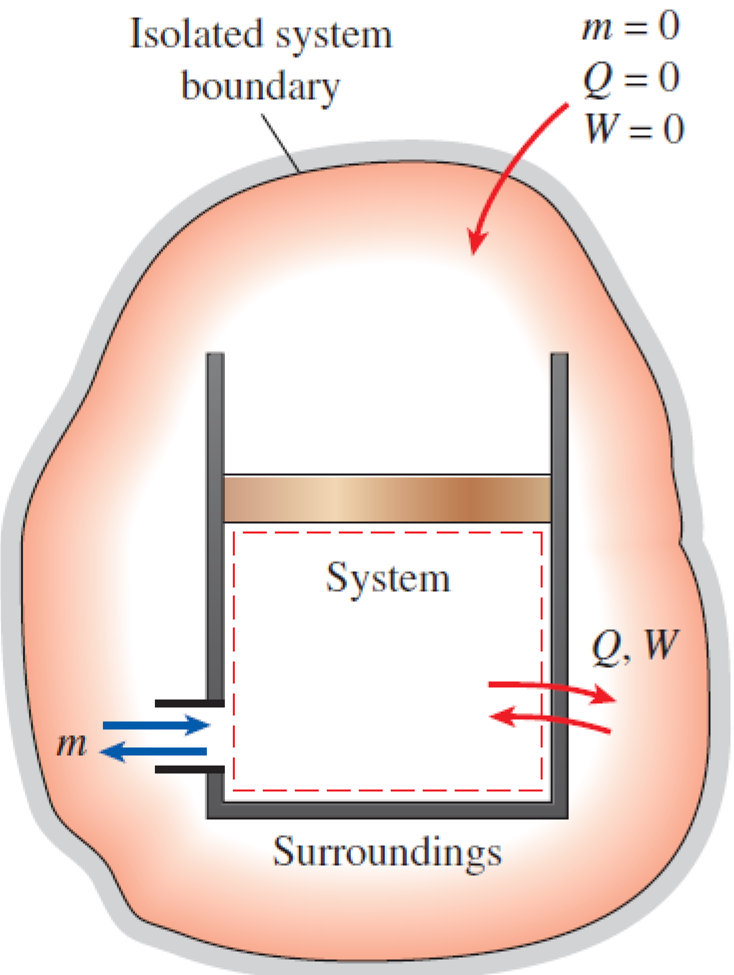


FIGURE 7–7

A system and its surroundings form an isolated system.

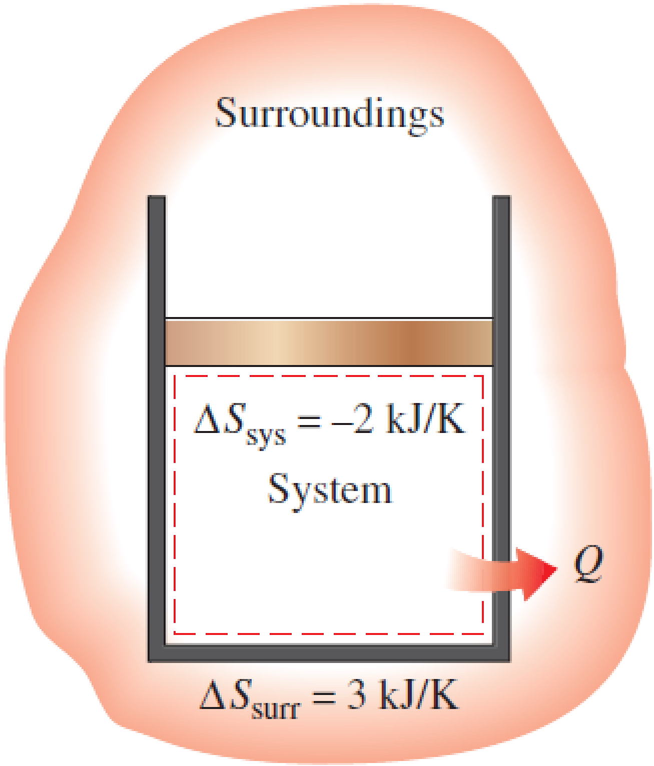
$$\Delta S_{\text{isolated}} \geq 0$$

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

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

The increase of entropy principle

Some Remarks about Entropy



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

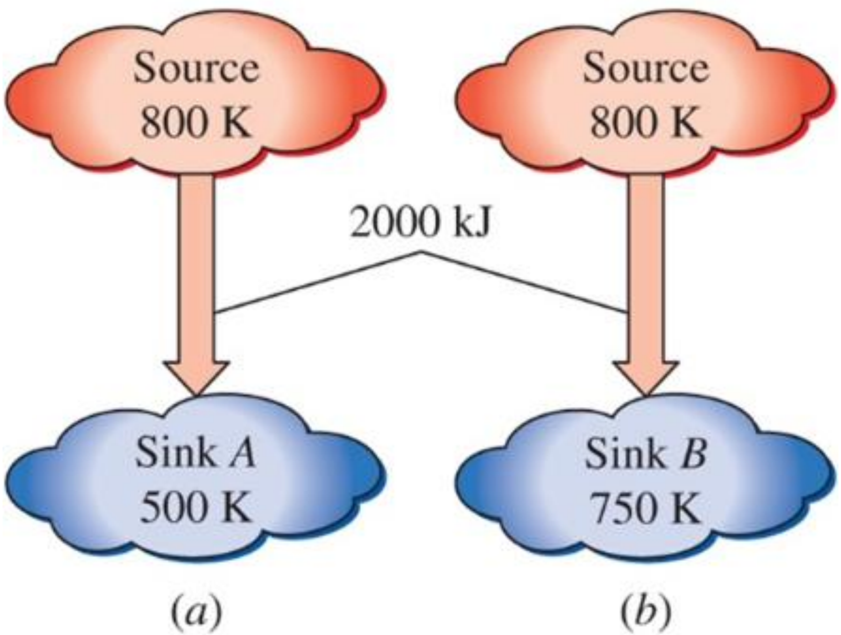
FIGURE 7–8

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, $S_{gen} \geq 0$. 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.

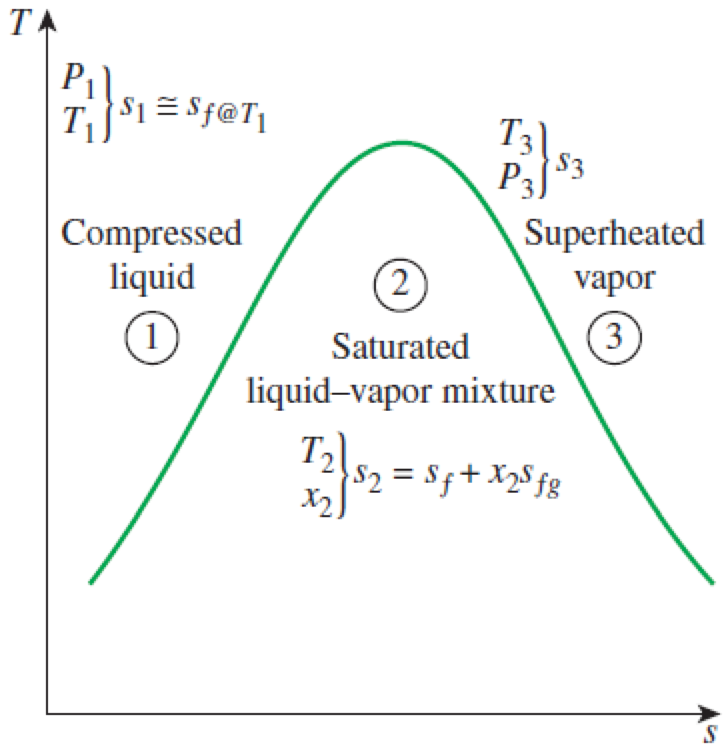


FIGURE 7–10
The entropy of a pure substance is determined from the tables (like other properties).

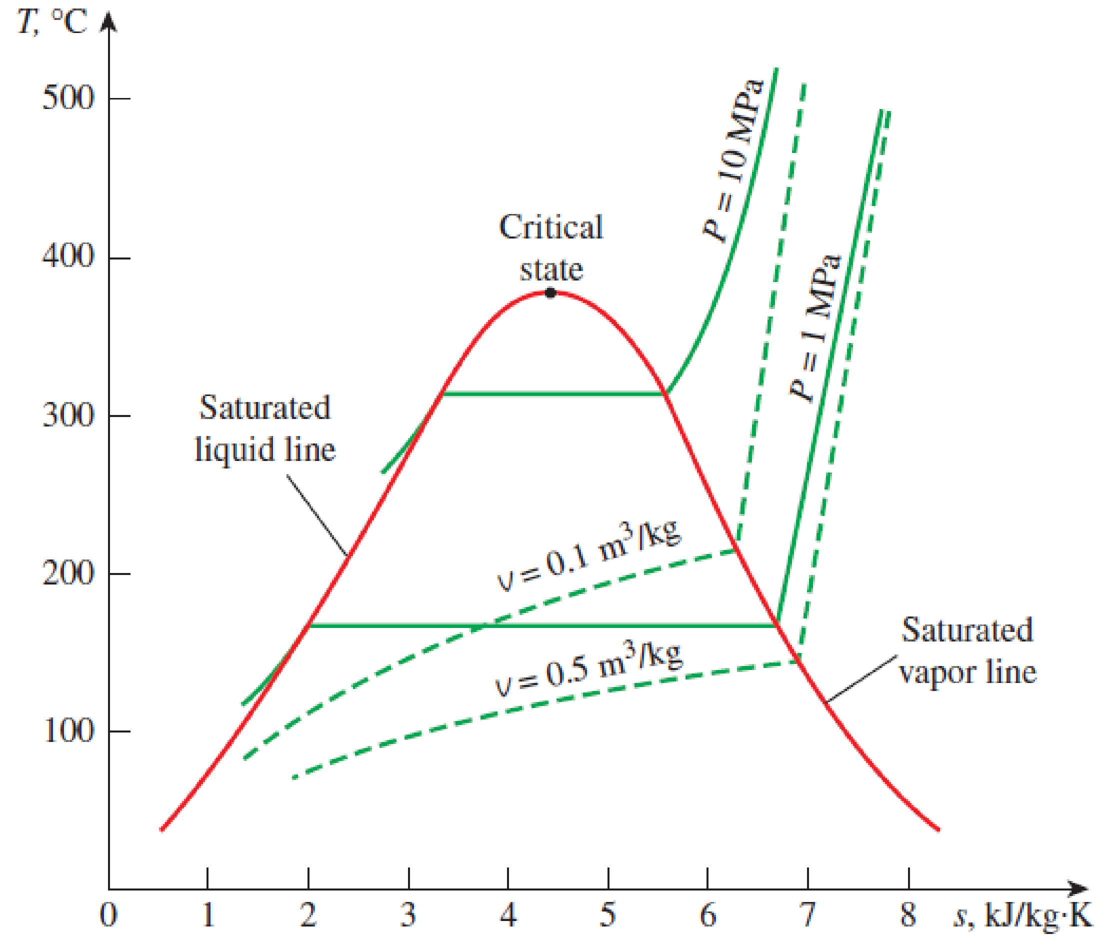


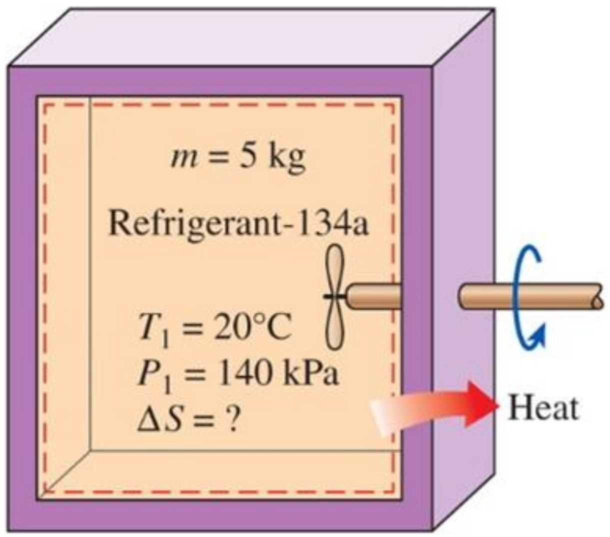
FIGURE 7–11
Schematic of the *T-s* diagram for water.

Entropy change

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

Entropy Change of a Substance in a Tank

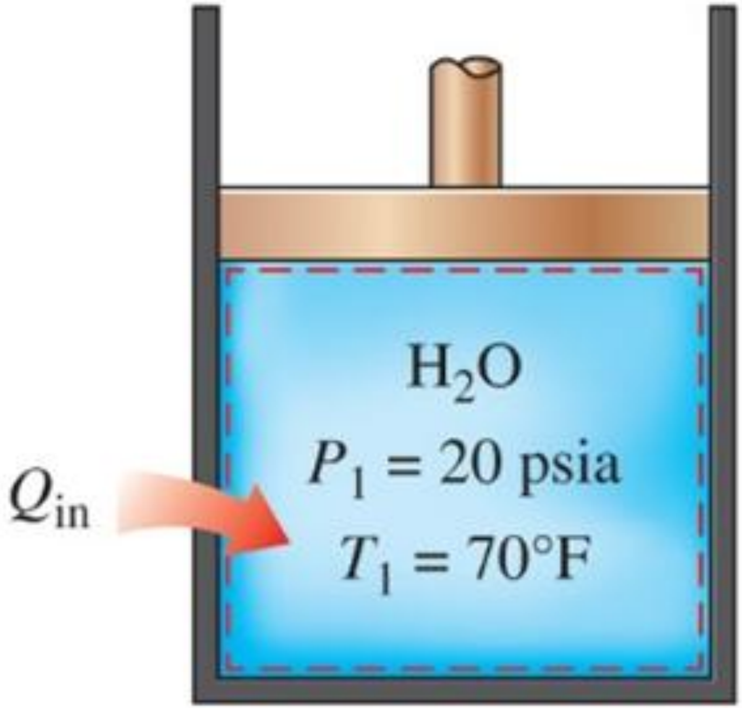
A rigid tank contains 5 kg of R-134a initially at 20°C and 140 kPa. The R-134a is now cooled while being stirred until its pressure drops to 100 kPa. Determine the entropy change of the R-134a during this process.



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**.

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

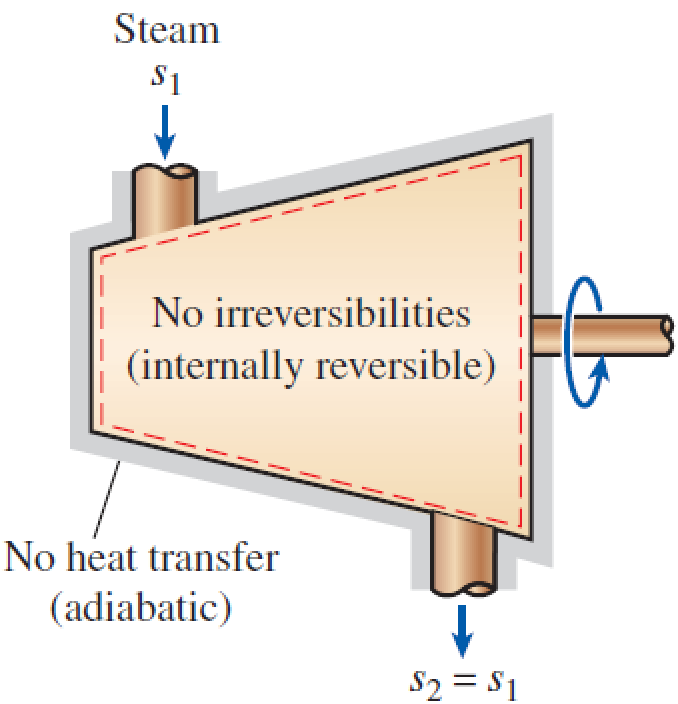


FIGURE 7–14
During an internally reversible, adiabatic (isentropic) process, the entropy remains constant.

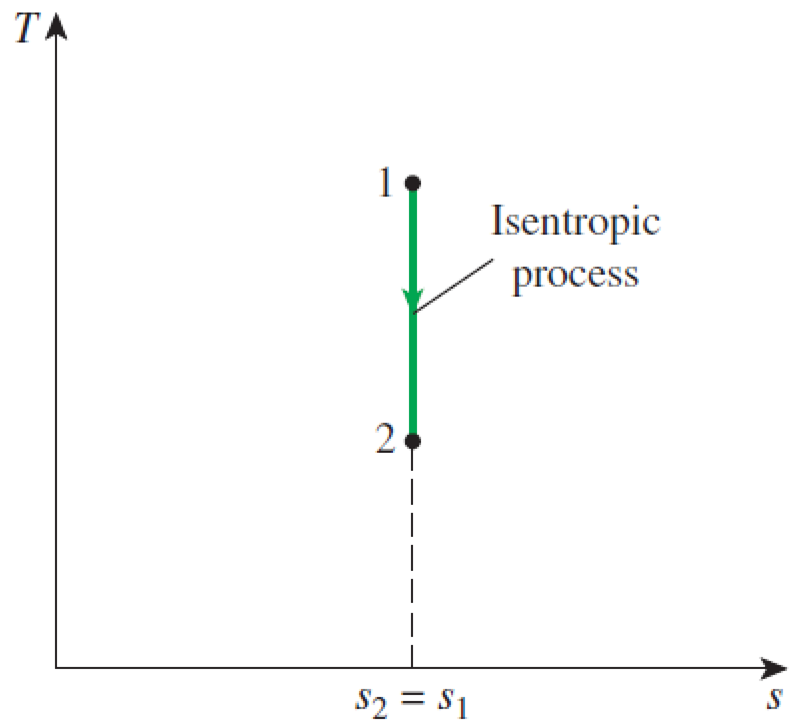


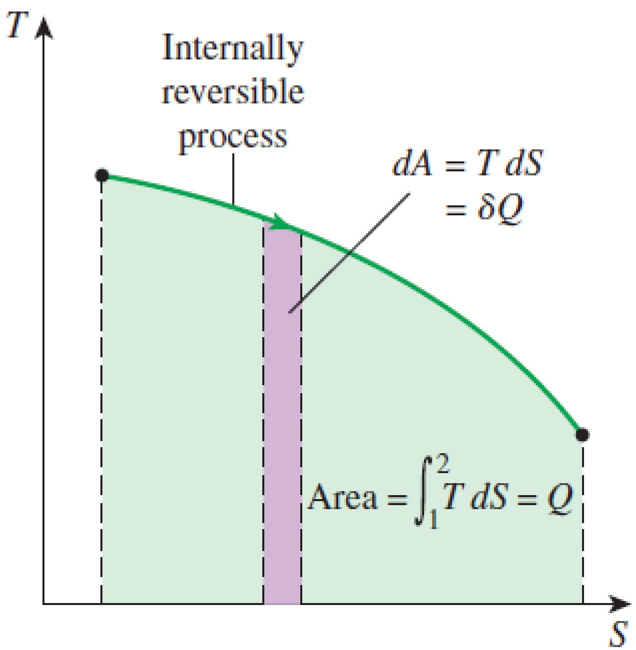
FIGURE 7–17
The isentropic process appears as a vertical line segment on a *T-s* diagram.

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



On a *T-S* diagram, the area under the process curve represents the heat transfer for internally reversible processes.

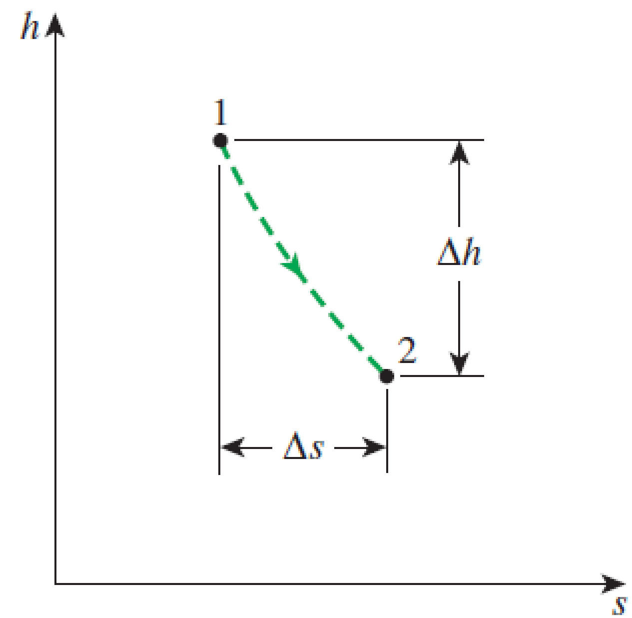


FIGURE 7–18

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.

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

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

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

Mollier diagram: The *h-s* diagram

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

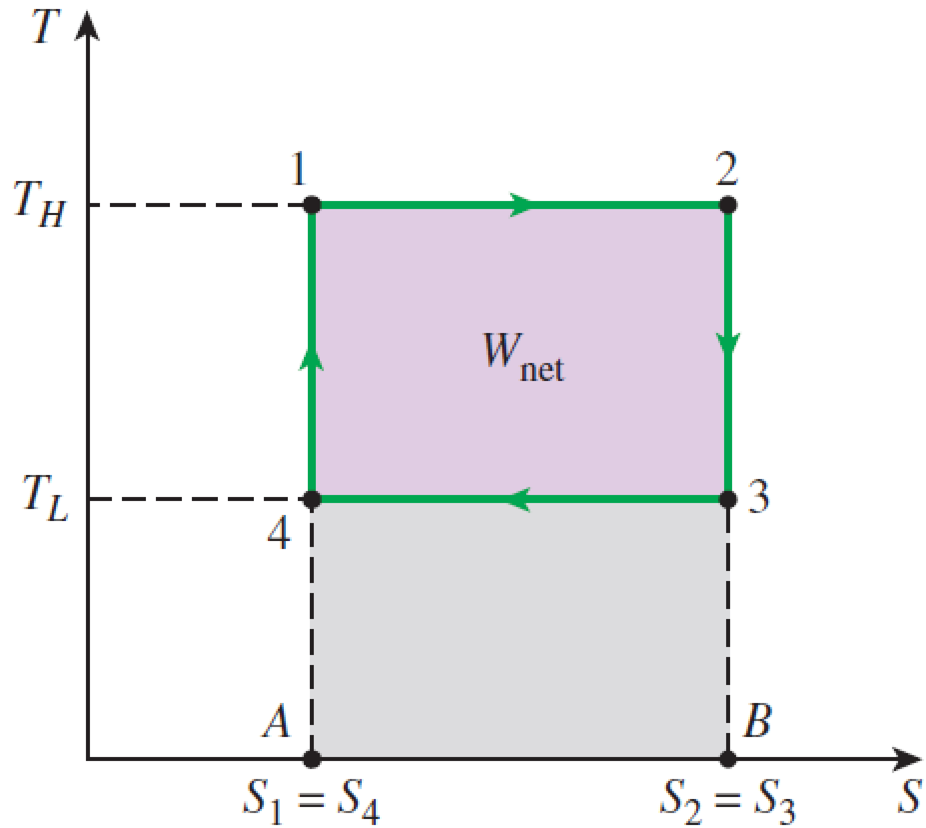


FIGURE 7–19

The *T-S* diagram of a Carnot cycle

WHAT IS ENTROPY?

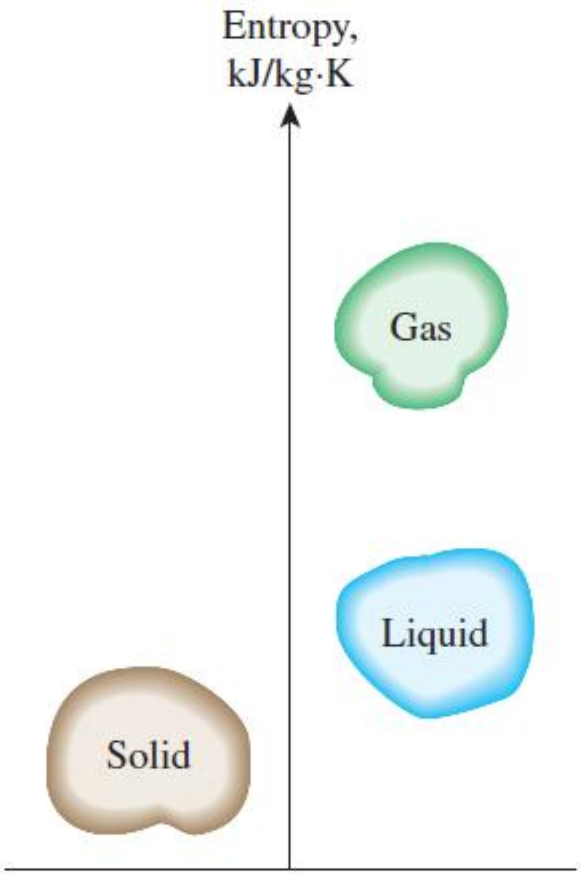


FIGURE 7–20
The level of molecular disorder (entropy) of a substance increases as it melts or evaporates.

Boltzmann relation

$$S = k \ln W$$

W the total number of possible relevant microstates of the system

Gibbs' formulation

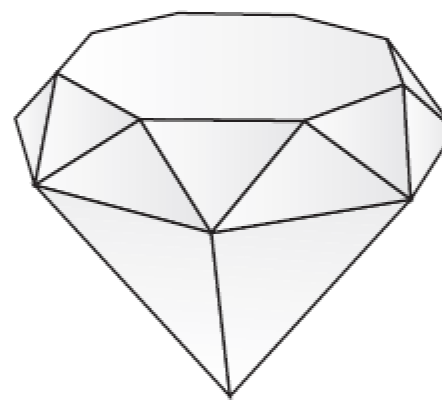
$$S = -k \sum p_i \log p_i$$

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

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

Boltzmann constant

Pure crystal
$T = 0$ K
Entropy = 0



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

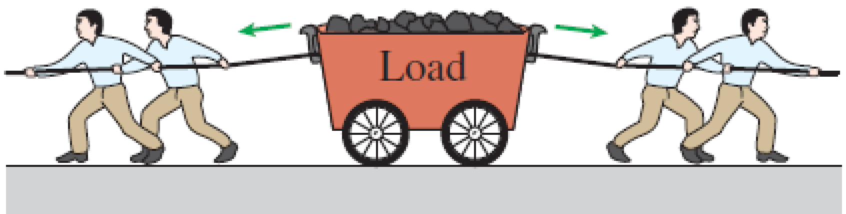


FIGURE 7–22
Disorganized energy does not create much useful effect, no matter how large it is.

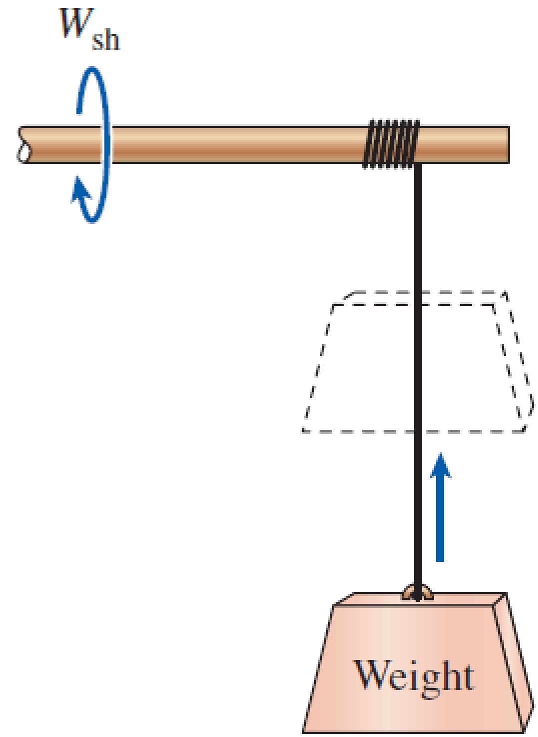


FIGURE 7–23
In the absence of friction, raising a weight by a rotating shaft does not create any disorder (entropy), and thus energy is not degraded during this process.

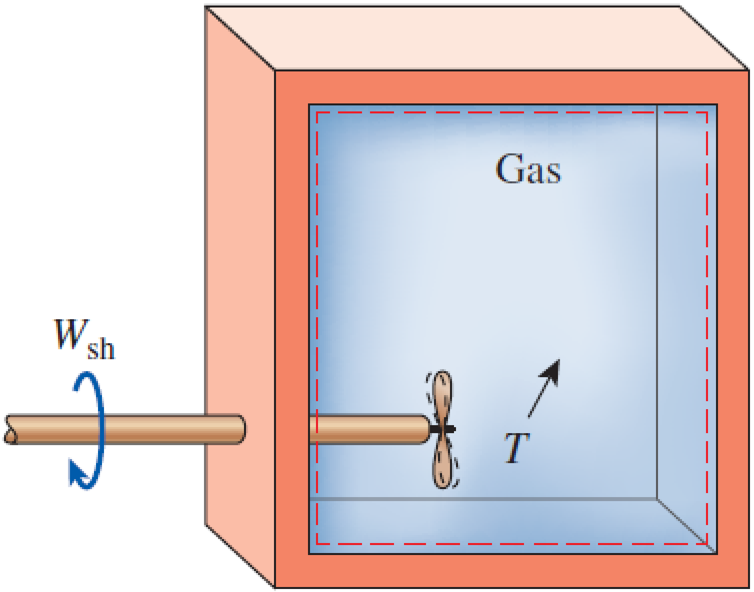


FIGURE 7–24
The paddle-wheel work done on a gas increases the level of disorder (entropy) of the gas, and thus energy is degraded during this process.

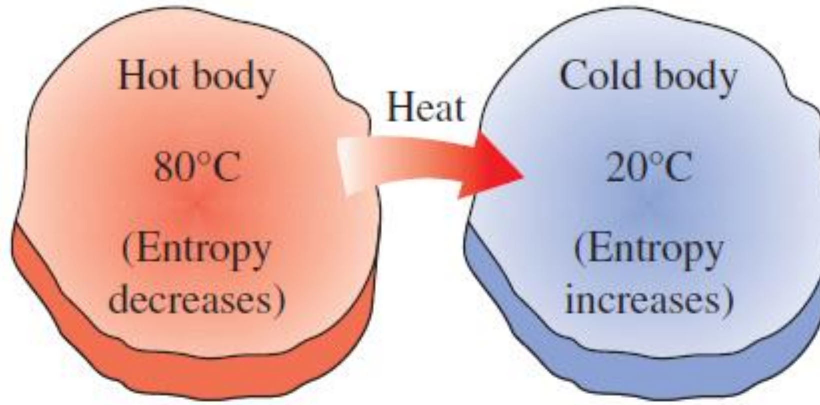


FIGURE 7–25
During a heat transfer process, the net entropy increases. (The increase in the entropy of the cold body more than offsets the decrease in the entropy of the hot body.)

THE *T ds* RELATIONS

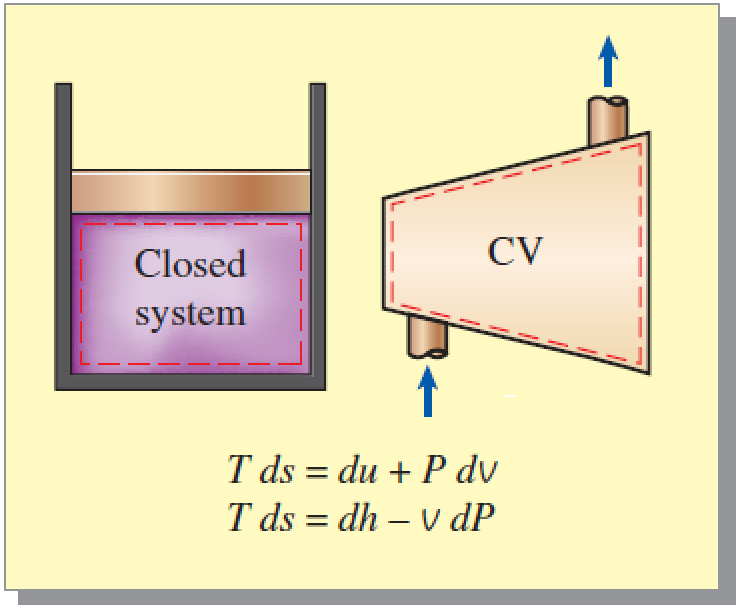


FIGURE 7–27
The *T ds* relations are valid for both reversible and irreversible processes and for both closed and open systems.

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

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

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

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

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

the first *T ds*, or *Gibbs equation*

$$h = u + Pv$$

$$\left.\begin{aligned} dh &= du + P\,dv + v\,dP \\ T\,ds &= du + P\,dv \end{aligned}\right\} \; T\,ds = dh - v\,dP$$

the second *Tds 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