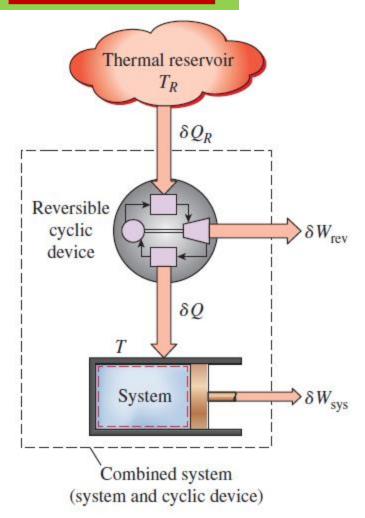
# Thermodynamics: An Engineering Approach 8th Edition Yunus A. Çengel, Michael A. Boles McGraw-Hill, 2015

Topic 13 **ENTROPY** 

### **Objectives**

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

### **ENTROPY**



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

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

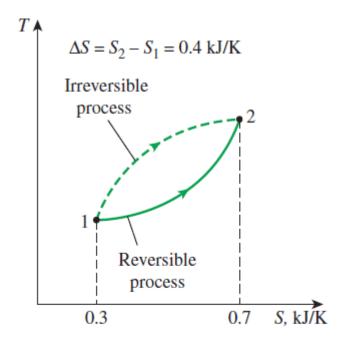
$$dS = \left(\frac{\delta Q}{T}\right)_{\text{int rev}}$$
 Formal (kJ/K) definition of entropy

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

### FIGURE 7-1

The system considered in the development of the Clausius inequality.

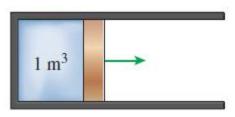
The <u>equality</u> in the Clausius inequality holds for totally or just internally <u>reversible</u> cycles and the <u>inequality</u> for the <u>irreversible</u> ones.

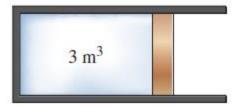


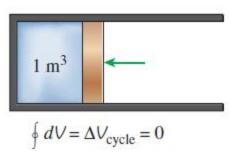
$$\oint \left(\frac{\delta Q}{T}\right)_{\text{int rev}} = 0$$

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.

#### 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 <a href="Isothermal">Isothermal</a> Heat Transfer Processes

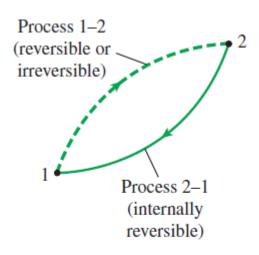
$$\Delta S = \int_{1}^{2} \left(\frac{\delta Q}{T}\right)_{\text{int rev}} = \int_{1}^{2} \left(\frac{\delta Q}{T_{0}}\right)_{\text{int rev}} = \frac{1}{T_{0}} \int_{1}^{2} (\delta Q)_{\text{int rev}}$$

$$\Delta S = \frac{Q}{T_0}$$
 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.

### THE INCREASE OF ENTROPY PRINCIPLE



#### FIGURE 7-5

A cycle composed of a reversible and an irreversible process.

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

$$\int_{1}^{2} \frac{\delta Q}{T} + S_{1} - S_{2} \le 0 \quad S_{2} - S_{1} \ge \int_{1}^{2} \frac{\delta Q}{T}$$

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

 $\frac{dS}{T} \geq \frac{\delta Q}{T}$  The equality holds for an internally reversible process and the inequality for an irreversible process.

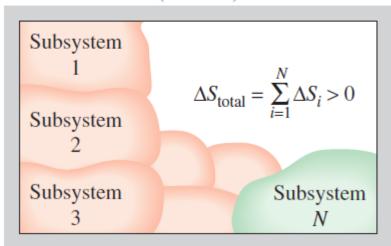
$$\Delta S_{\text{sys}} = S_2 - S_1 = \int_1^2 \frac{\delta Q}{T} + S_{\text{gen}}$$
$$S_{\text{gen}} = \Delta S_{\text{total}} = \Delta S_{\text{sys}} + \Delta S_{\text{surr}} \ge 0$$

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

The entropy generation  $S_{qen}$  is always a <u>positive</u> quantity or zero.

Can the entropy of a system during a process decrease?

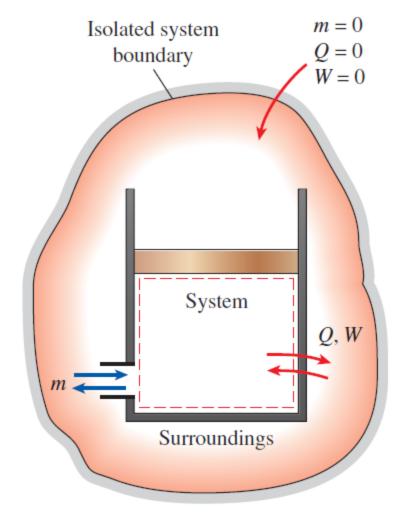
(Isolated)



### 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.

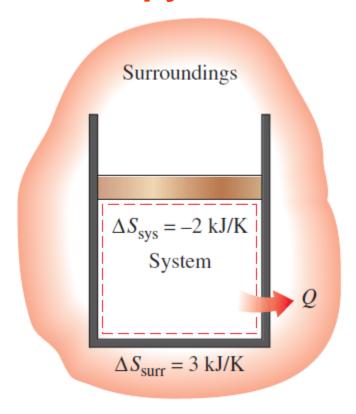
$$\begin{split} &\Delta S_{\rm isolated} \geq 0 \\ &S_{\rm gen} = \Delta S_{\rm total} = \Delta S_{\rm sys} + \Delta S_{\rm surr} \geq 0 \\ &S_{\rm gen} \left\{ \begin{array}{l} > \ 0 \ \ {\rm Irreversible\ process} \ \ {\rm The\ increase} \\ = \ 0 \ \ {\rm Reversible\ process} \ \ {\rm of\ entropy} \\ < \ 0 \ \ {\rm Impossible\ process} \ \ {\rm principle} \end{array} \right. \end{split}$$



### 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

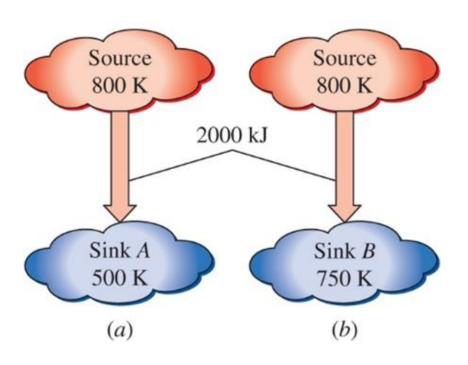
The entropy change of a system can be negative, but the entropy generation cannot.

- 1. Processes can occur in a <u>certain</u> direction only, not in <u>any</u> direction. A process must proceed in the direction that complies with the increase of entropy principle, that is,  $S_{gen} \ge 0$ . A process that violates this principle is impossible.
- Entropy is a <u>nonconserved</u> 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.

8

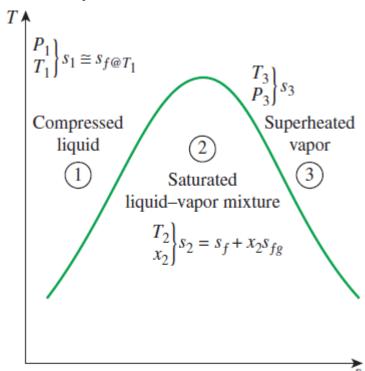
### **Entropy Generation during Heat Transfer**

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.



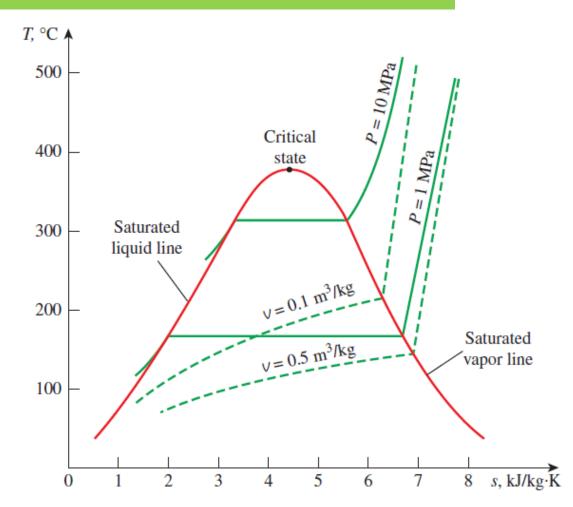
### **ENTROPY CHANGE OF PURE SUBSTANCES**

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

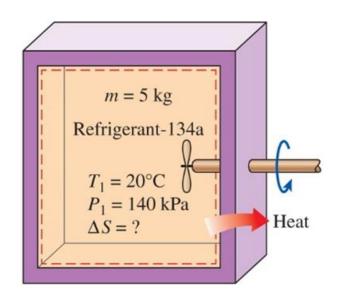
Schematic of the *T-s* diagram for water.

Entropy change

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

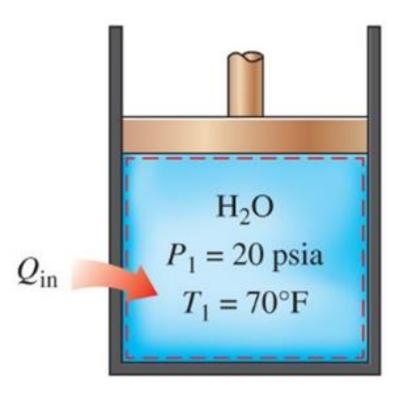
### **Entropy Change of a Substance in a Tank**

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.



### **Entropy Change during a Constant Pressure Process**

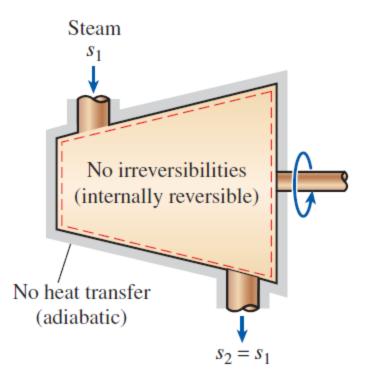
A piston cylinder device initially contains 3 lbm of liquid water at 20 psia and 70°F. The water is now heated at constant pressure by the addition of 3450 Btu of heat. Determine the entropy change of the water during this process.



### **ISENTROPIC PROCESSES**

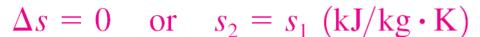
A process during which the entropy remains constant is called

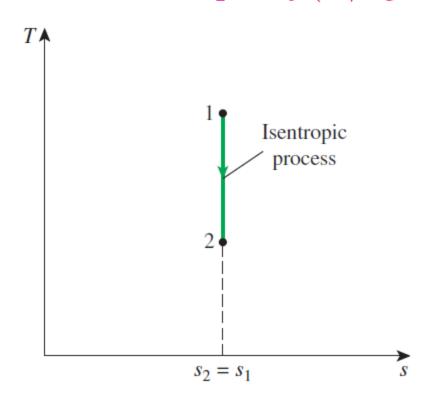
an isentropic process.



#### FIGURE 7-14

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





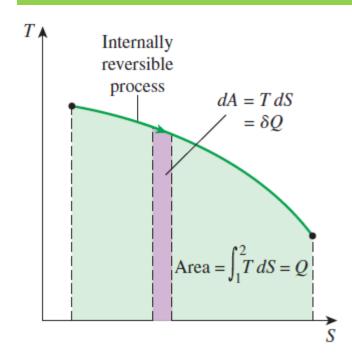
### FIGURE 7–17

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.

### PROPERTY DIAGRAMS INVOLVING ENTROPY

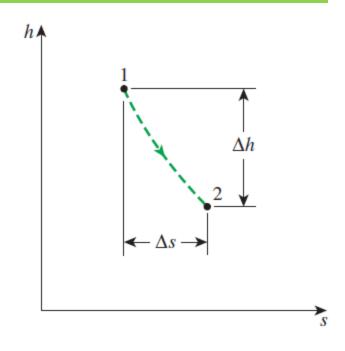


On a *T-S* diagram, the area under the process curve represents the heat transfer for internally reversible processes.



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

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

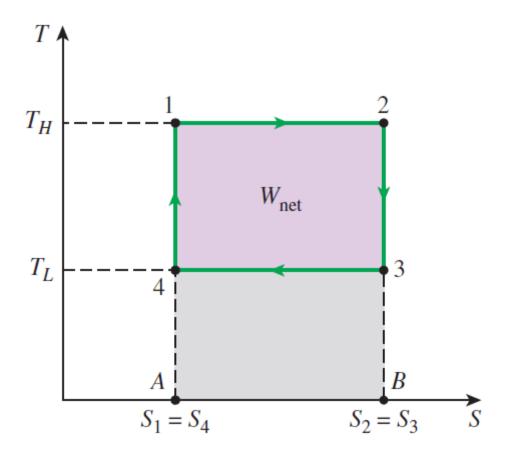


#### FIGURE 7–18

For adiabatic steady-flow devices, the vertical distance  $\Delta h$  on an h-sdiagram is a measure of work, and the horizontal distance  $\Delta s$  is a measure of irreversibilities.

Mollier diagram: The h-s diagram

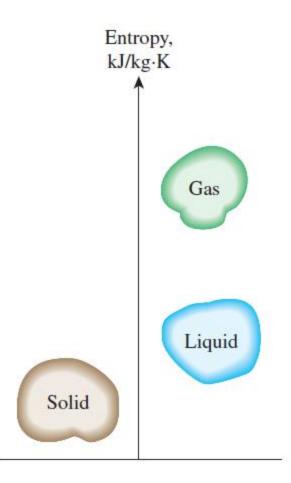
$$W_{\text{net,out}} = Q_H - Q_L$$



**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).

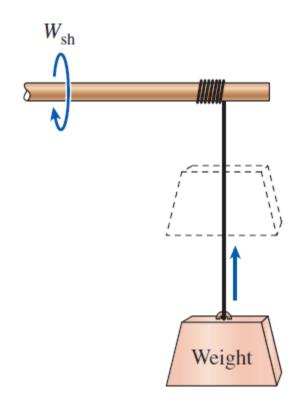
Pure crystal 
$$T = 0 \text{ K}$$
  
Entropy = 0





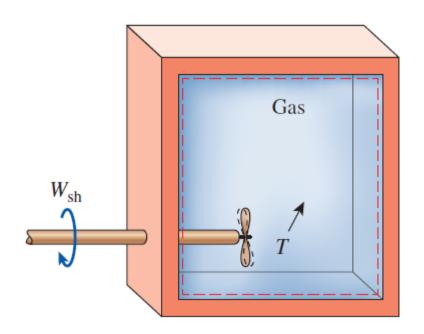
#### FIGURE 7-22

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



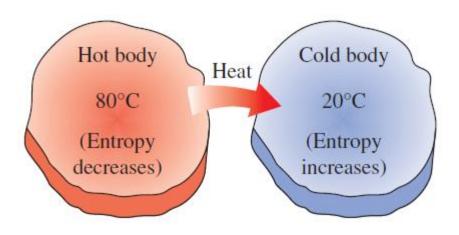
#### FIGURE 7-23

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

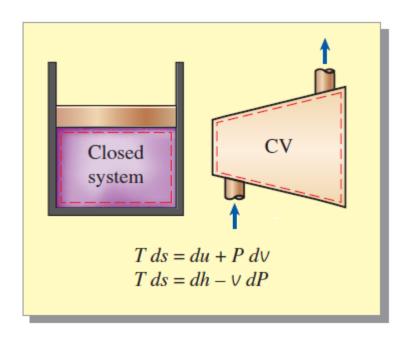
The paddle-wheel work done on a gas increases the level of disorder (entropy) of the gas, and thus energy is degraded during this process.



#### 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 <u>T ds</u> RELATIONS



#### FIGURE 7–27

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

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

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

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

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

$$T \, ds = du + P \, dV \qquad (kJ/kg)$$
the first  $T \, ds$ , or  $Gibbs \, equation$ 

$$h = u + PV$$

$$dh = du + P \, dV + V \, dP$$

$$T \, ds = du + P \, dV$$

$$T \, ds = du + P \, dV$$

$$ds = \frac{du}{T} + \frac{P \ dv}{T}$$
 Differential changes 
$$ds = \frac{dh}{T} - \frac{v \ dP}{T}$$
 of other properties

the second *Tds equation* 

### Summary

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