

Thermodynamics: An Engineering Approach
8th Edition

Yunus A. Çengel, Michael A. Boles
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CHAPTER 7

ENTROPY

Vaibhav Arghode, Department of Aerospace Engineering
Indian Institute of Technology Kanpur

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, incompressible substances, and ideal gases
- Examine a special class of idealized processes, called *isentropic processes*, and develop the property relations for these processes
- Derive the reversible steady-flow work relations
- Develop the isentropic efficiencies for various steady-flow devices
- Introduce and apply the entropy balance to various systems

CLAUSIUS INEQUALITY

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

Clausius
inequality

- *The cyclic integral of $\delta Q/T$ for a closed system is always less than or equal to zero*
- This inequality is valid for all cycles, reversible or irreversible
- The symbol \oint (integral symbol with a circle in the middle) is used to indicate that the integration is performed over the entire cycle
- Any heat transfer to or from a closed system can be considered to consist of differential amounts of heat transfer (δQ)
- The cyclic integral of $\delta Q/T$ can be viewed as the sum of all these ***differential amounts of heat transfer (δQ)*** divided by the ***temperature (T) at the system boundary*** through which δQ takes place

CLAUSIUS INEQUALITY

- Consider closed system connected to a thermal energy reservoir at a constant thermodynamic (absolute) temperature T_R **through a reversible cyclic device (e.g. Carnot engine / refrigerator)**
- The cyclic device produces work δW_{rev} while receiving heat δQ_R from the reservoir and rejecting heat δQ to the closed system **whose temperature at that part of the boundary is T** (a variable)
- The closed system produces work δW_{sys} as a result of this heat transfer. Note that the **state of the system will change in this process**

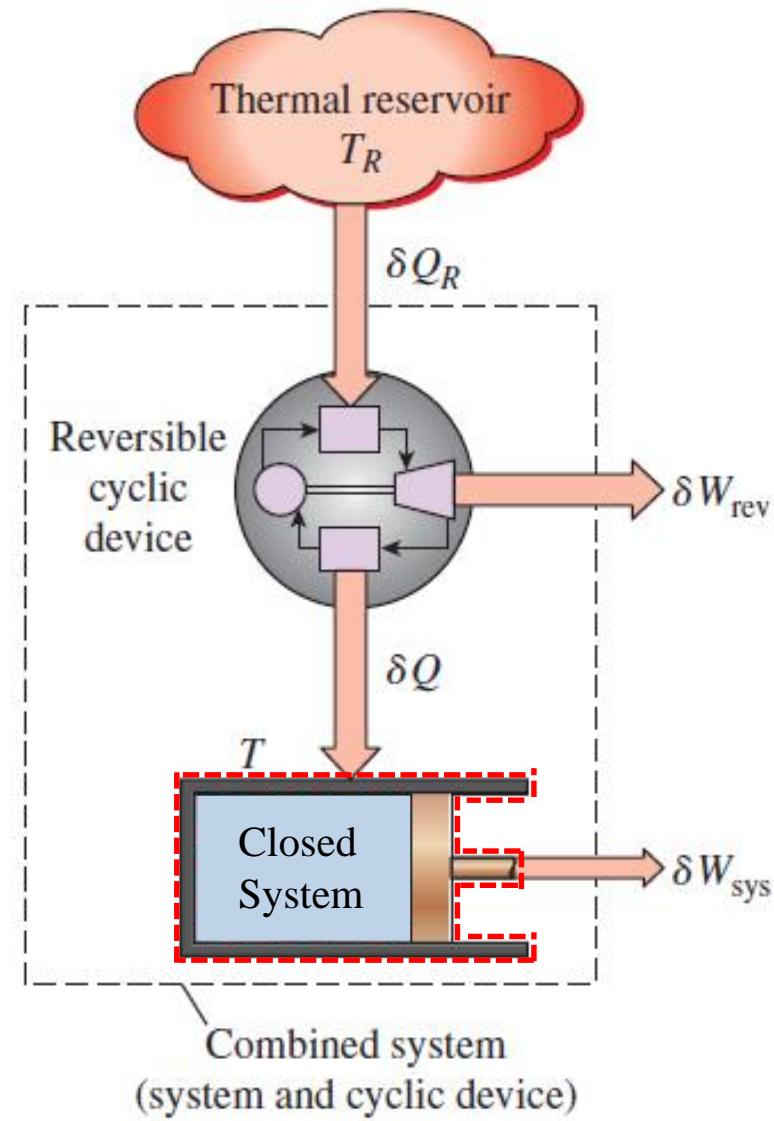


FIGURE 7–1

The system considered in the development of the Clausius inequality.

CLAUSIUS INEQUALITY

- Applying energy balance to the **combined system** identified by dashed lines:

$$\delta W_C = \delta Q_R - dE_C$$

- δW_C is the total work of the **combined system** ($\delta W_{\text{rev}} + \delta W_{\text{sys}}$) and dE_C is the change in the total energy of the **combined system**

$$\frac{\delta Q_R}{T_R} = \frac{\delta Q}{T} \quad \text{for reversible cyclic device}$$

- The sign of δQ is determined *with respect to the system* (positive if **to** the **system**) and sign of δQ_R is determined *with respect to the reversible cyclic device*

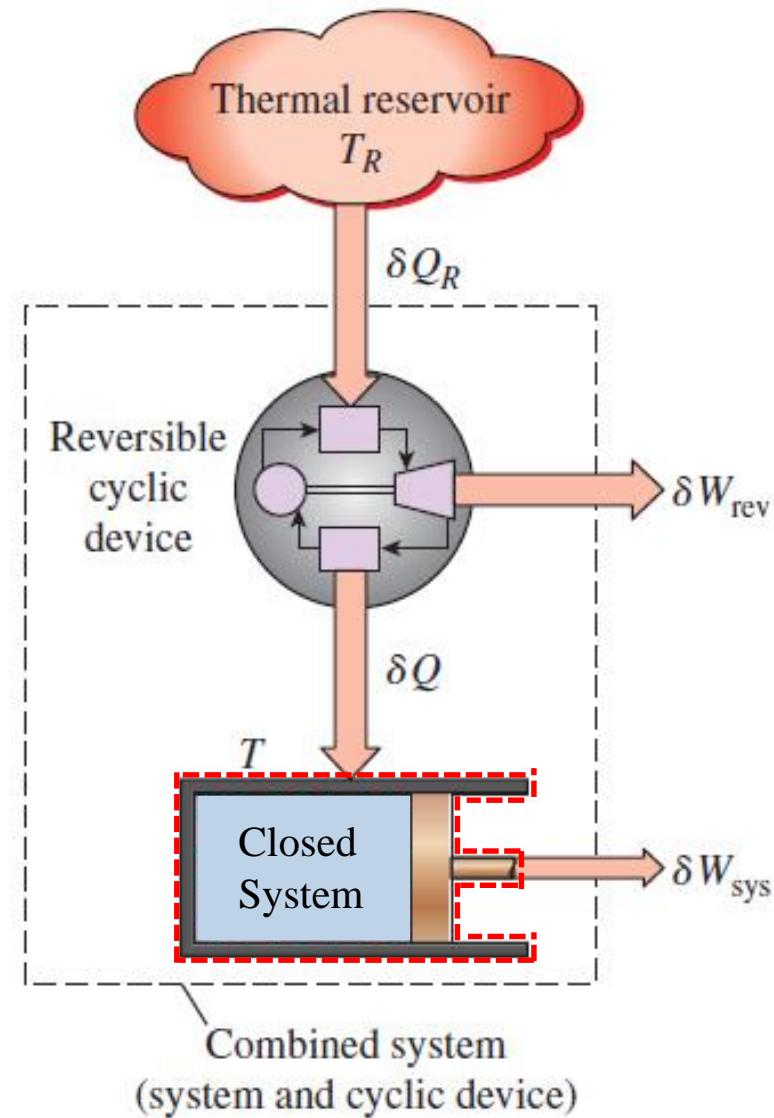


FIGURE 7–1

The system considered in the development of the Clausius inequality.

CLAUSIUS INEQUALITY

- Eliminating δQ_R :

$$\delta W_C = T_R \frac{\delta Q}{T} - dE_C$$

- Now we **let the system undergo a cycle** while the **cyclic device undergoes an integral number of cycles**
- Note that the **cyclic integral of dE_C is zero** ($\oint dE_C = 0$) (the net change in the energy of a system, which is a property, will be zero during a cycle)

$$W_C = T_R \oint \frac{\delta Q}{T}$$

- Here W_C is the cyclic integral of δW_C and it represents the **net work of the combined cycle** ($W_C = \oint \delta W_C$)

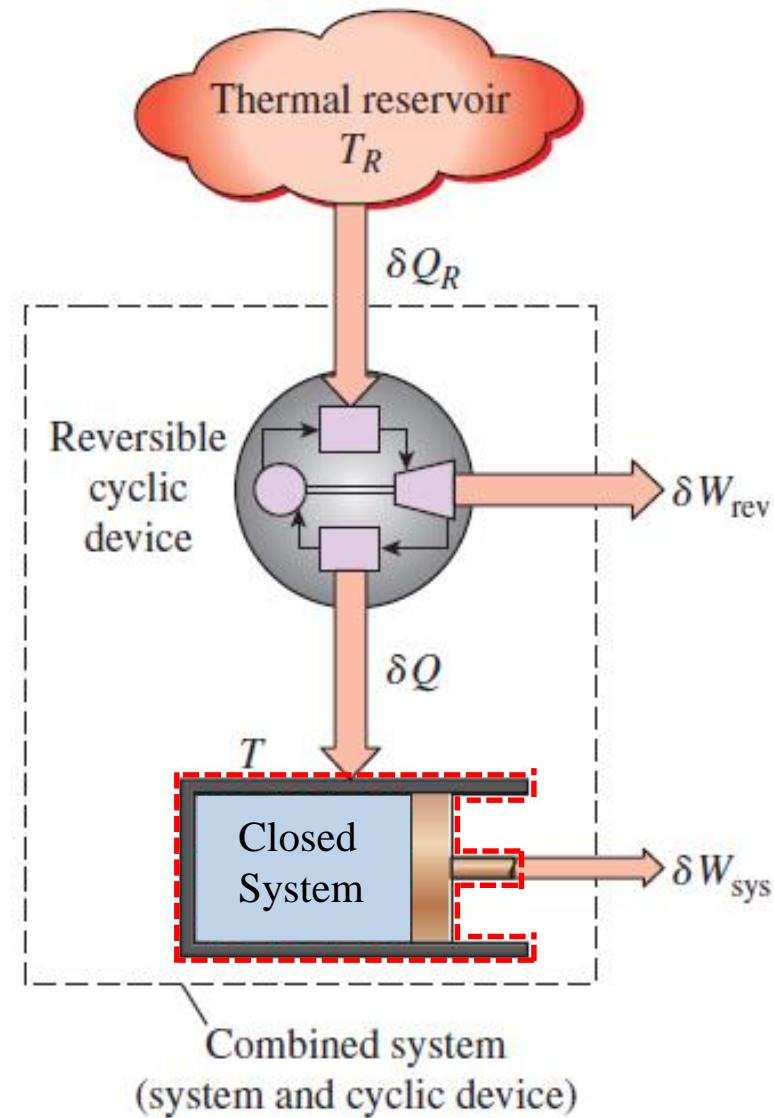


FIGURE 7–1

The system considered in the development of the Clausius inequality.

CLAUSIUS INEQUALITY

- It appears that the combined system is exchanging heat with a single thermal energy reservoir while involving (producing or consuming) work W_C during a cycle
- Kelvin-Planck statement of the second law: *no system can produce a net amount of work while operating in a cycle and exchanging heat with a single thermal energy reservoir*

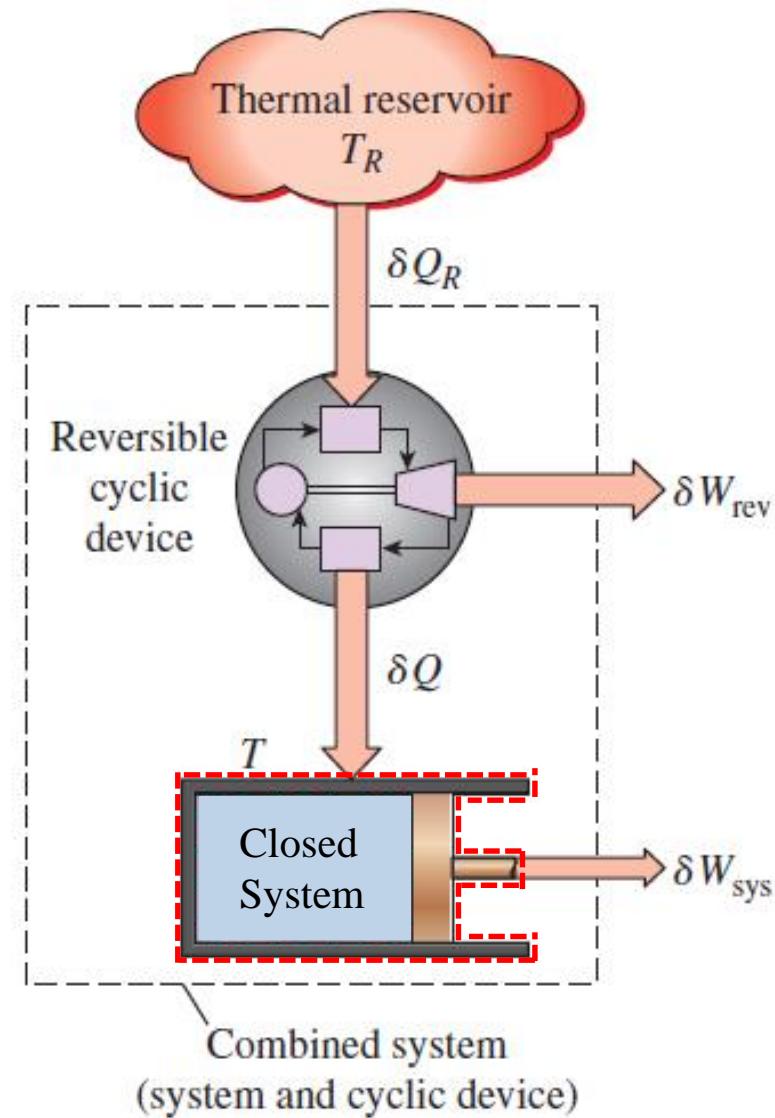


FIGURE 7–1

The system considered in the development of the Clausius inequality.

CLAUSIUS INEQUALITY

$$W_C = T_R \oint \frac{\delta Q}{T}$$

- Based on the Kelvin-Planck statement, this **combined system cannot produce any work** (W_C cannot be positive) *operating on a cycle* as it is exchanging heat with only one reservoir. Though, *it can consume work while transferring all of that energy in the form of heat* to a single reservoir. i.e. $W_C \leq 0$
- Note that T_R (thermodynamic temperature) is positive

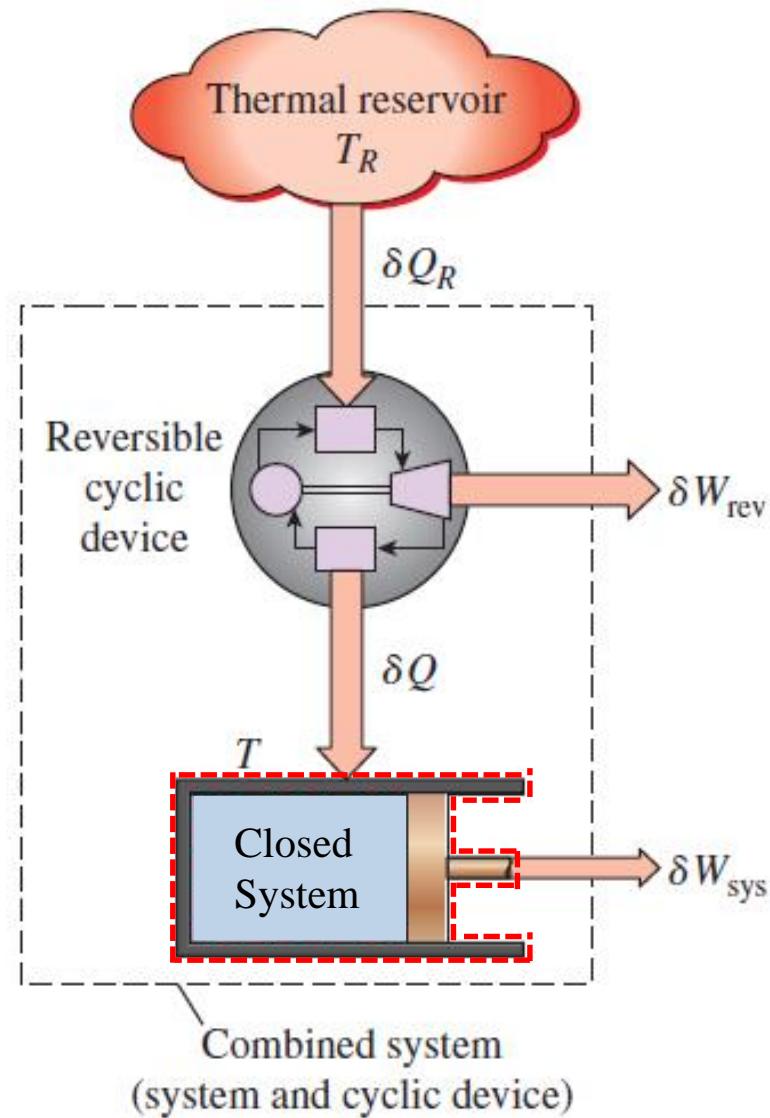


FIGURE 7–1

The system considered in the development of the Clausius inequality.

CLAUSIUS INEQUALITY

- Hence, we must have:

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

Clausius
inequality

- This inequality is valid for all thermodynamic cycles, reversible or irreversible, including refrigeration cycles*

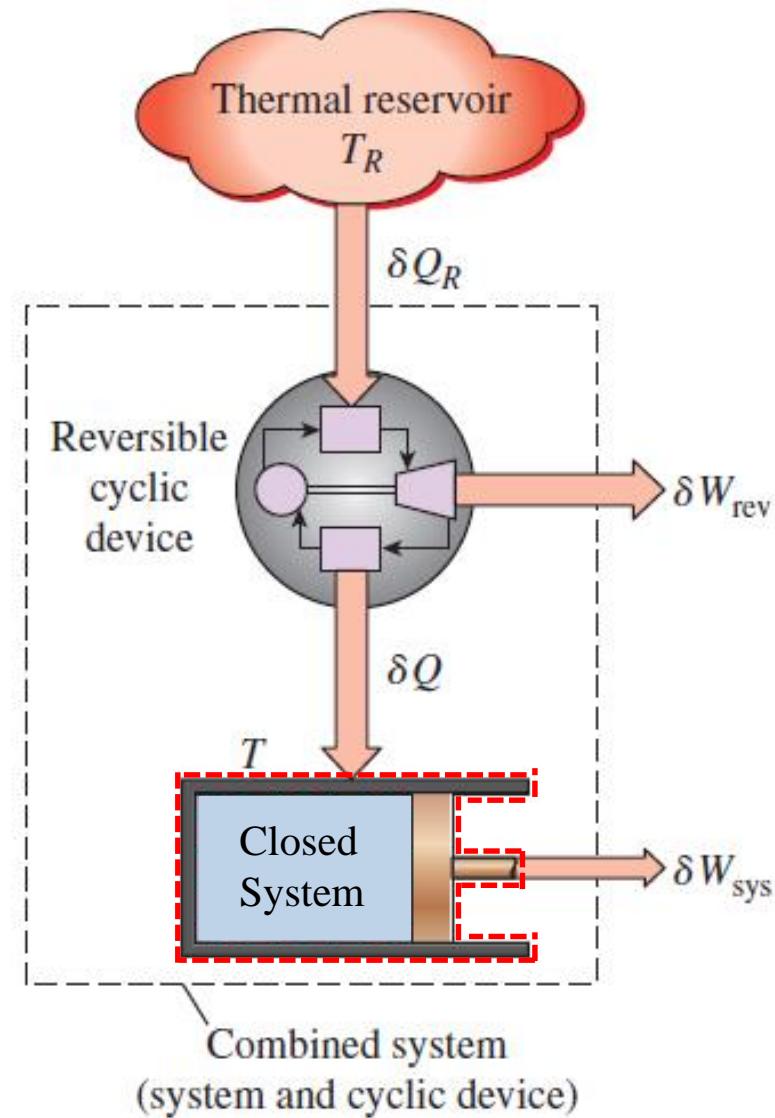


FIGURE 7–1

The system considered in the development of the Clausius inequality.

CLAUSIUS INEQUALITY

- If no irreversibilities occur within the **system** boundaries, this also means that no irreversibilities occur within the **combined system** as the only other component is the reversible cyclic device.
- Also the **heat exchange with the reservoir is also reversible** as we have used a reversible cyclic device to exchange heat with the thermal reservoir
- This means that if the cycle undergone by the **system** is **internally reversible** then the **combined cycle is totally reversible**

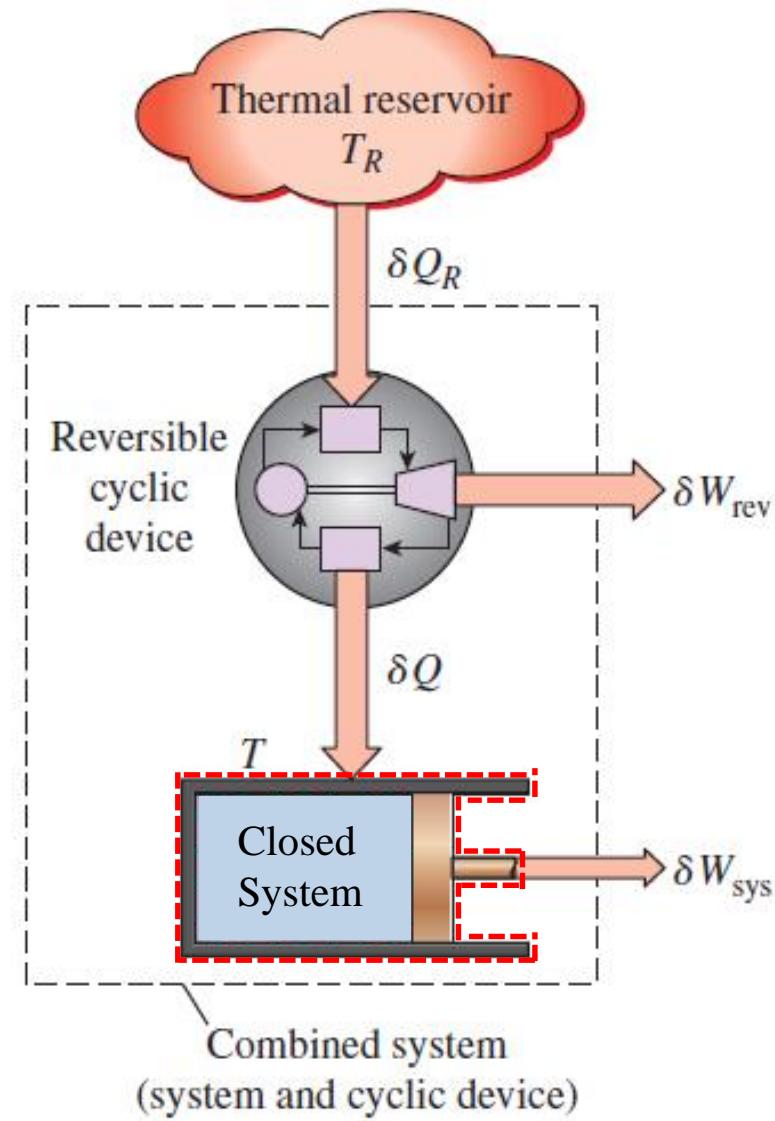


FIGURE 7–1

The system considered in the development of the Clausius inequality.

INTERNAL REVERSIBLE CYCLE

- For the case of *internally reversible cycle* of the *system*, the *combined cycle* can be reversed. In the *reversed cycle* case, all the quantities have the same magnitude but the opposite sign, therefore *the work W_C which could not be a positive quantity in the regular case, cannot be a negative quantity in the reversed case* (i.e. $W_{C,int\ rev} = 0$)

$$W_C = T_R \oint \frac{\delta Q}{T}$$

$W_C \leq 0$ for all thermodynamic cycles
 $W_C = 0$ for internally reversible cycles

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

for internally reversible cycles

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

for all cycles

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

ENTROPY

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

for internally reversible cycles

- A **quantity whose cyclic integral is zero** depends on the state of the closed system only and not the process path, and thus it is a **property**

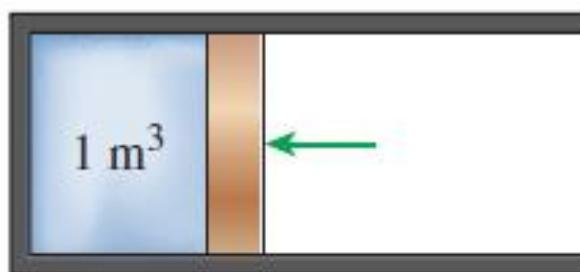
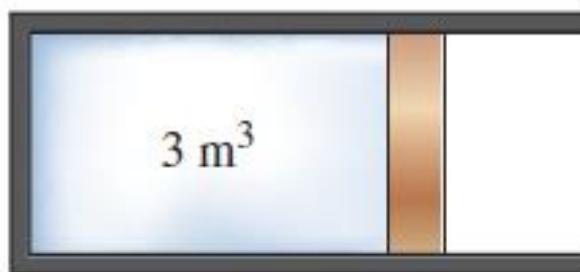
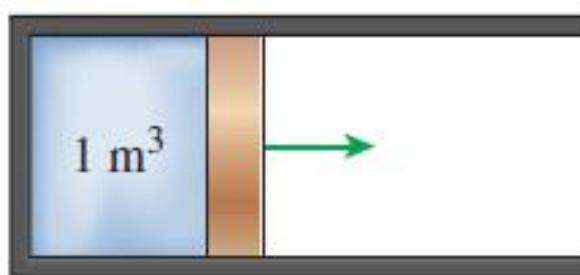
e.g. $\oint dV = 0$

volume is a property

- Therefore, the quantity $(\delta Q/T)_{\text{int rev}}$ must represent a **property** in the differential form. Clausius realized in 1865 that he had discovered a new thermodynamic property, and he chose to name this property **entropy**. It is designated S and is defined as:

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

formal definition of entropy



$$\oint dV = \Delta V_{\text{cycle}} = 0$$

FIGURE 7–2

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

ENTROPY

- Entropy (S) is an extensive property of a system and sometimes referred to as total entropy and has the unit (kJ/K)
- Entropy per unit mass (specific entropy), designated s , is an intensive property and has the unit (kJ/kg-K)
- The entropy change of a closed system during a process can be determined by integrating between the initial and the final state

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

- Notice that we have actually defined the change in entropy instead of entropy itself

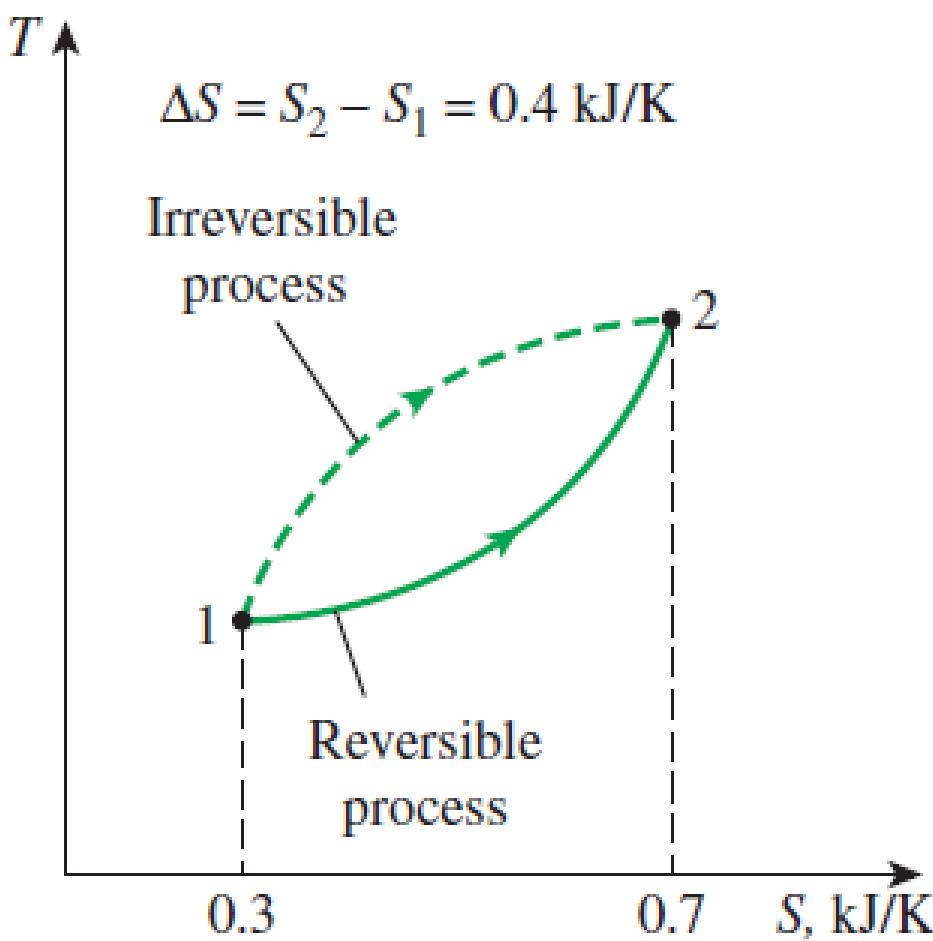


FIGURE 7–3

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

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

- *The integral of $\delta Q/T$ gives us the value of entropy change only if the integration is carried out along an internally reversible path between two states*
- The integral of $\delta Q/T$ along an irreversible path is not a property, and in general, different values will be obtained when the integration is carried out along different irreversible paths
- Therefore, even for irreversible processes, the entropy change should be determined by carrying out this integration along some convenient imaginary reversible path between the specified states

A Special Case: Internally Reversible Isothermal Heat Transfer Processes

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

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

- Where T_0 is the constant temperature of the system and Q is the heat transfer for the internally reversible process
- *This equation is particularly useful for determining the entropy changes of thermal energy reservoirs*
- Heat transfer to a closed system increases its entropy whereas heat transfer from a closed system decreases it
- *In fact, losing heat is the only way the entropy of a closed system can be decreased*

Entropy Change during an Isothermal Process

A piston–cylinder device contains a liquid–vapor mixture of water at 300 K. 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.

Assumptions No irreversibilities occur within the system boundaries during the process.

Analysis We take the *entire water* (liquid + vapor) in the cylinder as the system

$$\Delta S_{\text{sys, isothermal}} = \frac{Q}{T_{\text{sys}}} = \frac{750 \text{ kJ}}{300 \text{ K}} = 2.5 \text{ kJ/K}$$

Discussion Note that the entropy change of the system is positive, as expected, since heat transfer is to the system.

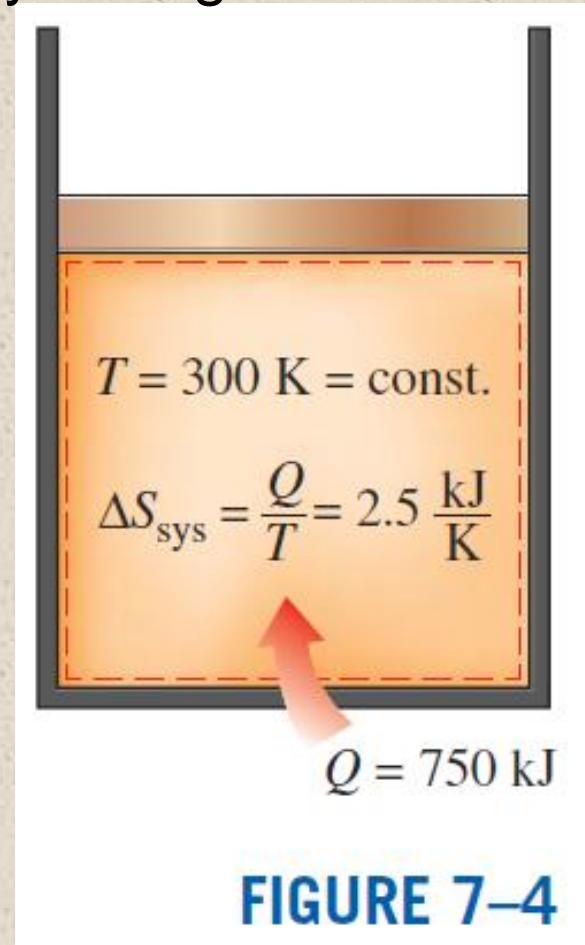
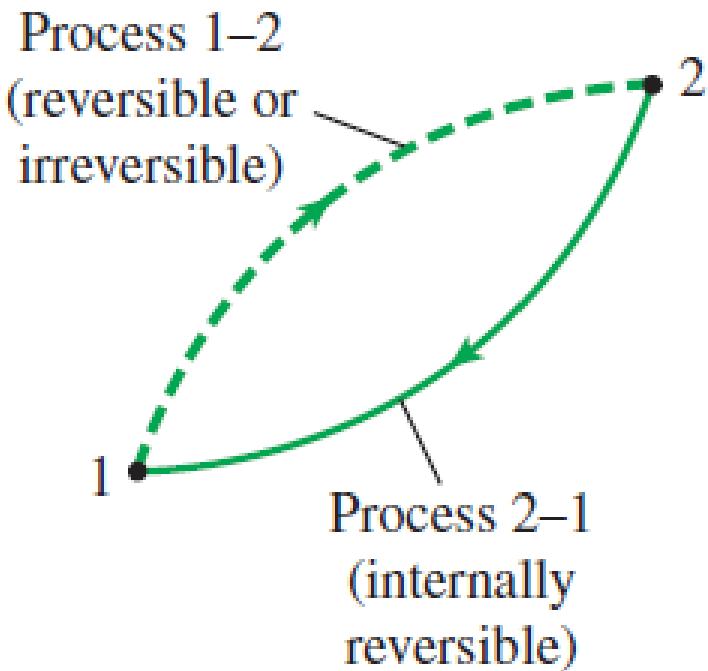


FIGURE 7–4

CHANGE IN ENTROPY OF THE SYSTEM



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

Clausius inequality

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

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

$$S_2 - S_1 \geq \int_1^2 \frac{\delta Q}{T}$$

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

differential form

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

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

CHANGE IN ENTROPY OF THE SYSTEM

$$S_2 - S_1 \geq \int_1^2 \frac{\delta Q}{T}$$

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

- Note that T in these relations is the **thermodynamic temperature** at the **system boundary** where **differential heat δQ is transferred** to the system from the surroundings
- The quantity $\Delta S = S_2 - S_1$ represents the **entropy change** of the closed system. For an internally reversible process, it becomes equal to $\int_1^2 \delta Q/T$, **which represents entropy transfer with heat**
- Hence, for an internally reversible process **entropy change (ΔS)** of the closed system is equal to the **entropy transfer with heat ($\int_1^2 \delta Q/T$)** to the system

ENTROPY GENERATION

$$S_2 - S_1 \geq \int_1^2 \frac{\delta Q}{T}$$

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

- The **entropy change** of a closed system during an **irreversible process** is always greater than the integral of $\delta Q/T$ (**entropy transfer with heat**)
- Some entropy is **generated** or *created* in the system during an **irreversible process**, and this generation is entirely due to the presence of **irreversibilities**

$$\Delta S_{\text{sys}} = S_2 - S_1 = \underbrace{\int_1^2 \frac{\delta Q}{T}}_{\substack{\text{entropy} \\ \text{transfer} \\ \text{with heat to} \\ \text{the system}}} + \underbrace{S_{\text{gen}}}_{\substack{\text{entropy} \\ \text{generated in} \\ \text{the system}}}$$

- The value of entropy generation S_{gen} depends on the process, and thus **S_{gen} is not a property of the system**

The entropy generation S_{gen} is always a **positive** quantity or zero

THE INCREASE OF ENTROPY PRINCIPLE

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

- For an isolated system (or even for an **adiabatic** closed system), the heat transfer is zero ($\delta Q = 0$):

$$\Delta S_{isolated} = S_2 - S_1 \geq 0$$

also true for **adiabatic closed system**

- *Entropy of an isolated system* (or even for an **adiabatic** closed system) *during a process always increases or, in the limiting case of a reversible process remains constant* (in other words it never decreases), this is known as **the increase of entropy principle**
- In absence of any heat transfer to or from the closed system, entropy change of the system is only due to **irreversibilities** present in the system, and their effect is **always to increase entropy** of the system

(Isolated)

- Entropy is an extensive property, thus the total entropy of a system is equal to the sum of entropies of the parts of the system

- *A system and its surroundings can be viewed as the two subsystems of an isolated system*

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

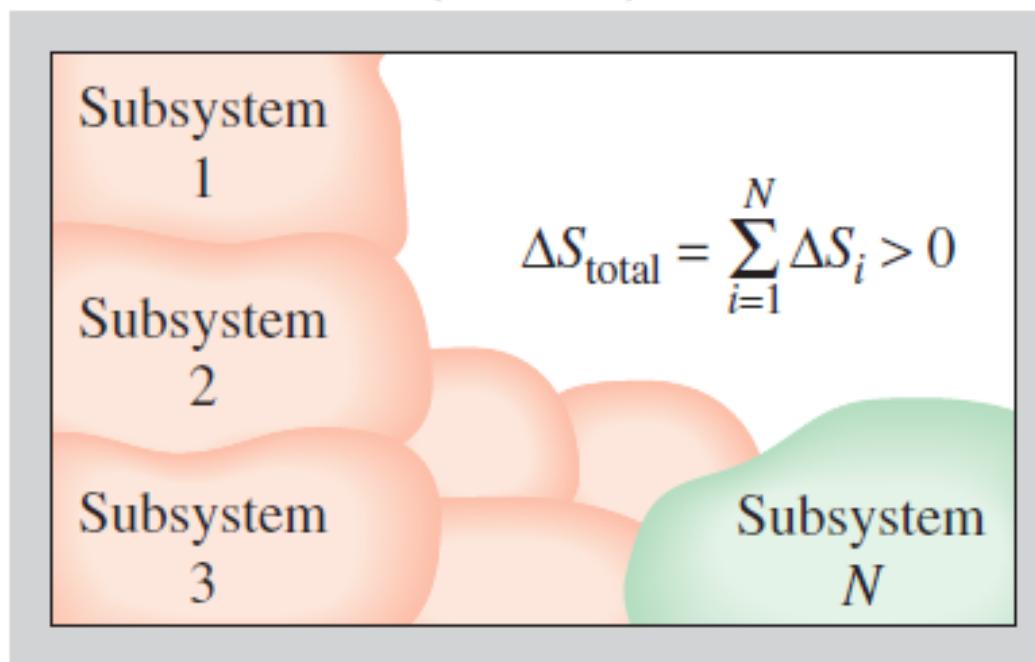


FIGURE 7–6

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

- ΔS_{surr} refers to the change in the entropy of the surroundings as a result of the occurrence of the process under consideration

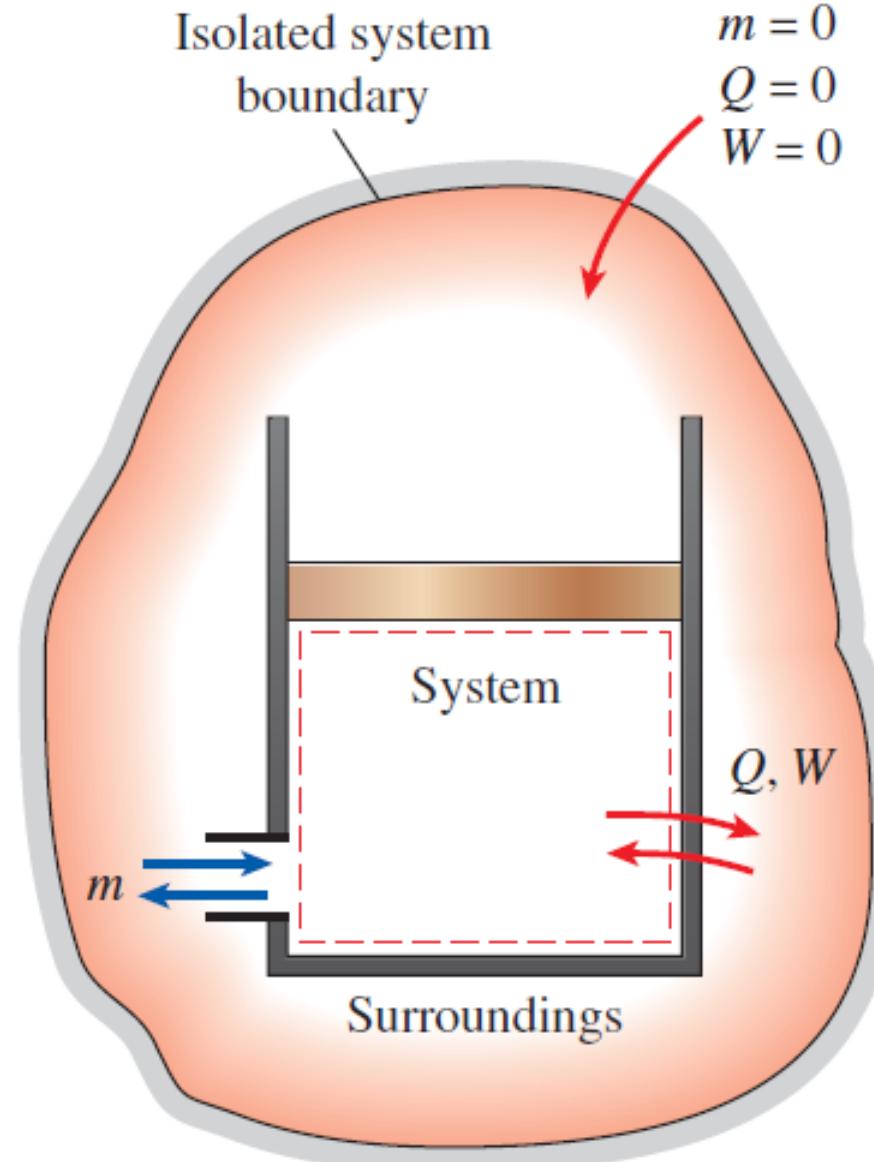


FIGURE 7-7

A system and its surroundings form an isolated system.

THE INCREASE OF ENTROPY PRINCIPLE

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

0, isolated system
isolated system

isolated system

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

system + surroundings

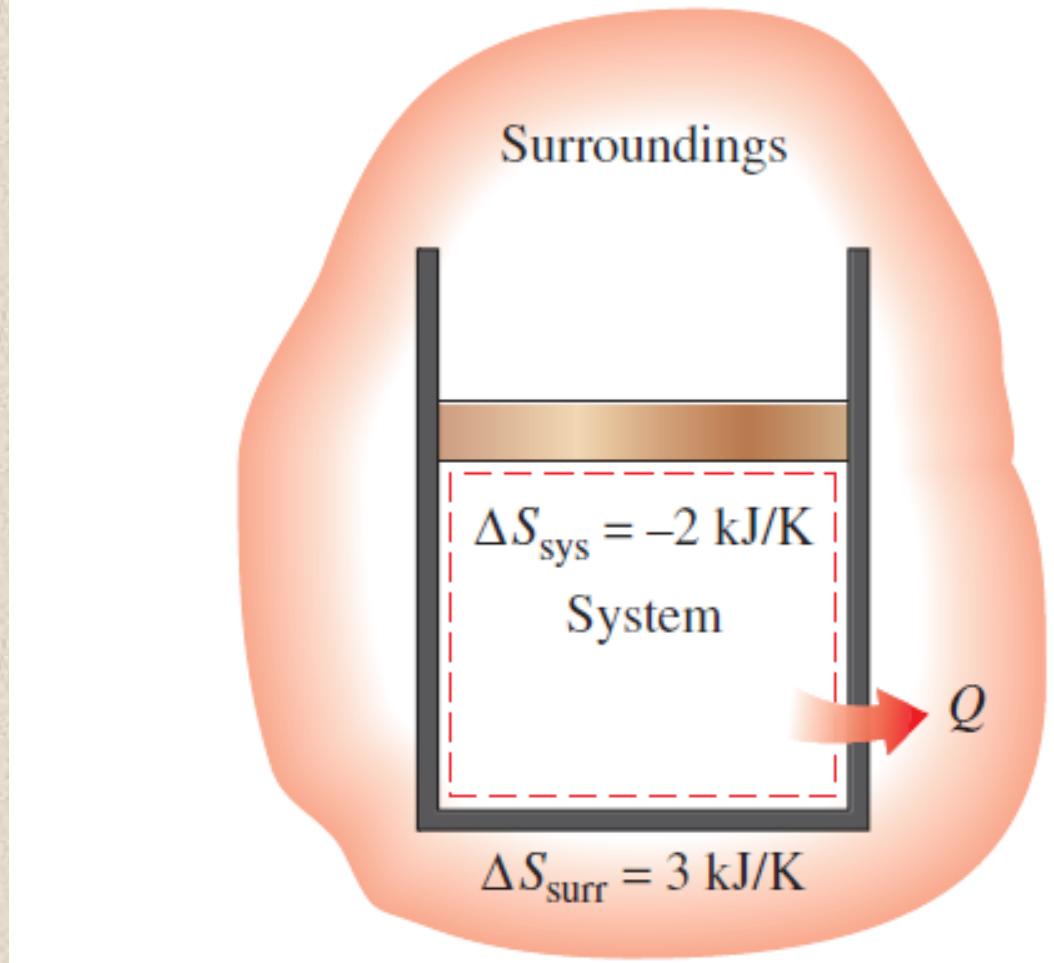
$$S_{\text{gen}} \begin{cases} > 0 & \text{Irreversible process} \\ = 0 & \text{Reversible process} \\ < 0 & \text{Impossible process} \end{cases}$$

The increase of entropy principle

- **Entropy generated during a process** is equal to the entropy generated in the **system** plus entropy generated in the **surroundings**
- Note that a **reversible process** (also called totally reversible process) is **both internally and externally reversible**, hence, for such a process **no entropy is generated either in the system or the surroundings**

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

- The increase in entropy principle dictates that the *entropy of an isolated system increases until the entropy of the system reaches a maximum value*
- At that point, the system is said to have reached an ***equilibrium state*** since the increase of entropy principle prohibits the system from undergoing any change of state that results in decrease in entropy



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

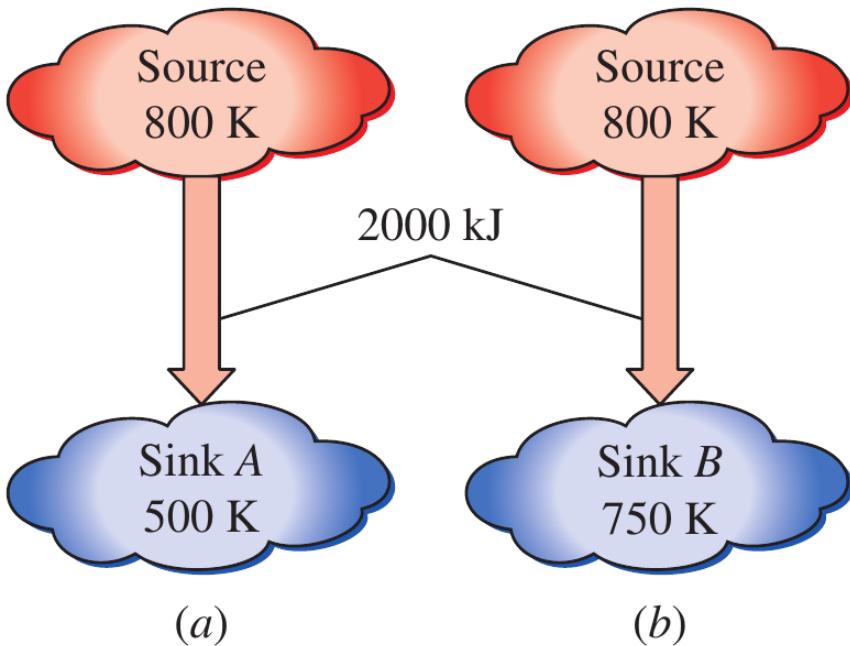
FIGURE 7–8

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

Some Remarks about Entropy

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 PROCESSES



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

$$\Delta S_{\text{source}} = \frac{Q_{\text{source}}}{T_{\text{source}}} = \frac{-2000 \text{ kJ}}{800 \text{ K}} = -2.5 \text{ kJ/K}$$

Sink A

$$\Delta S_{\text{sink}} = \frac{Q_{\text{sink}}}{T_{\text{sink}}} = \frac{2000 \text{ kJ}}{500 \text{ K}} = +4.0 \text{ kJ/K}$$

FIGURE 7–9 $S_{\text{gen}} = \Delta S_{\text{total}} = \Delta S_{\text{source}} + \Delta S_{\text{sink}} = (-2.5 + 4.0) \text{ kJ/K} = 1.5 \text{ kJ/K}$

Schematic for Example 7–2.

In the limit of T_{sink} approaching T_{source} , $S_{\text{gen}} = 0$ (reversible heat addition)

Sink B

$$\Delta S_{\text{source}} = -2.5 \text{ kJ/k}$$

$$\Delta S_{\text{sink}} = +2.7 \text{ kJ/K}$$

$S_{\text{gen}} = \Delta S_{\text{total}} = (-2.5 + 2.7) \text{ kJ/K} = 0.2 \text{ kJ/K}$

ENTROPY 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*
- Using a suitable reference state, the entropies of substances are evaluated from measurable property data following rather involved computations
- The results are tabulated in the same manner as the other properties such as v, u, and h
- The entropy values in the property tables are given relative to an arbitrary reference state. In steam tables the entropy of saturated liquid s_f at 0.01°C is assigned value of zero. For refrigerant-134a, the zero value is assigned to saturated liquid at -40°C.

ENTROPY CHANGE OF PURE SUBSTANCES

The value of entropy at a specified state is determined just like any other property

Saturated mixture region

$$s = s_f + x s_{fg} \quad (\text{kJ/kg}\cdot\text{K})$$

Compressed liquid

$$s_{@T,P} \cong s_{f@T} \quad (\text{kJ/kg}\cdot\text{K})$$

or use tables if available

Superheated vapor

use tables or use ideal gas relations if IGL is applicable

Entropy change of a closed system

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

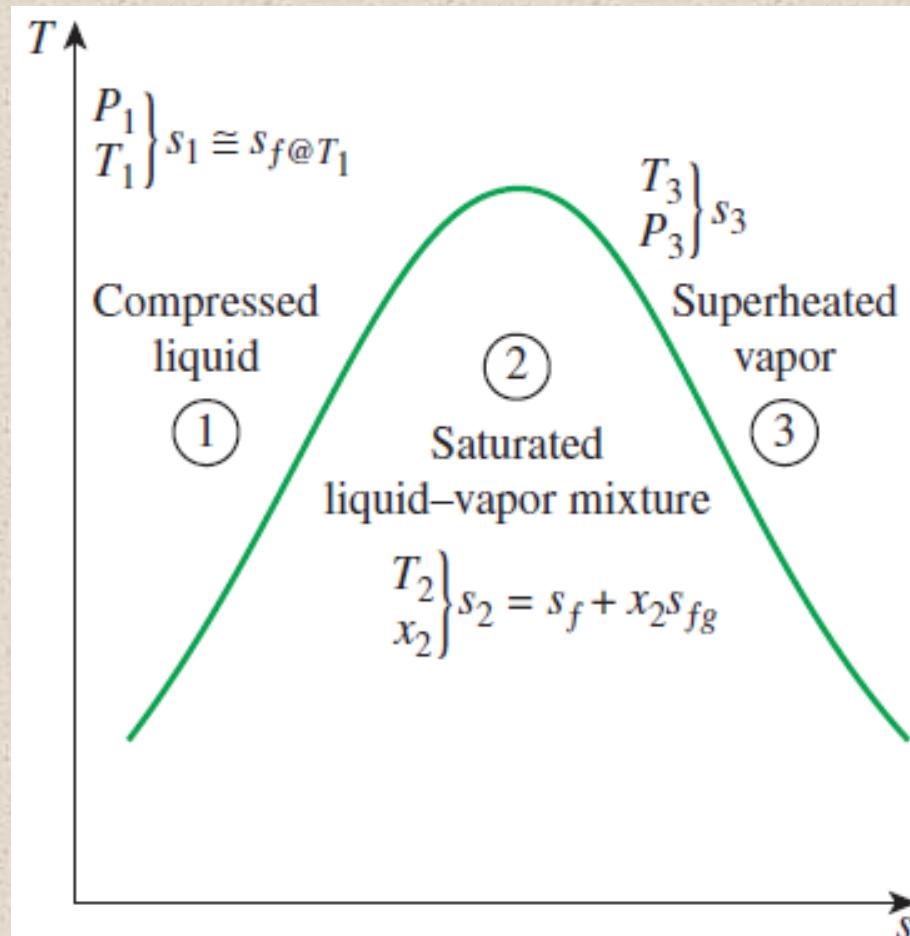


FIGURE 7–10

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

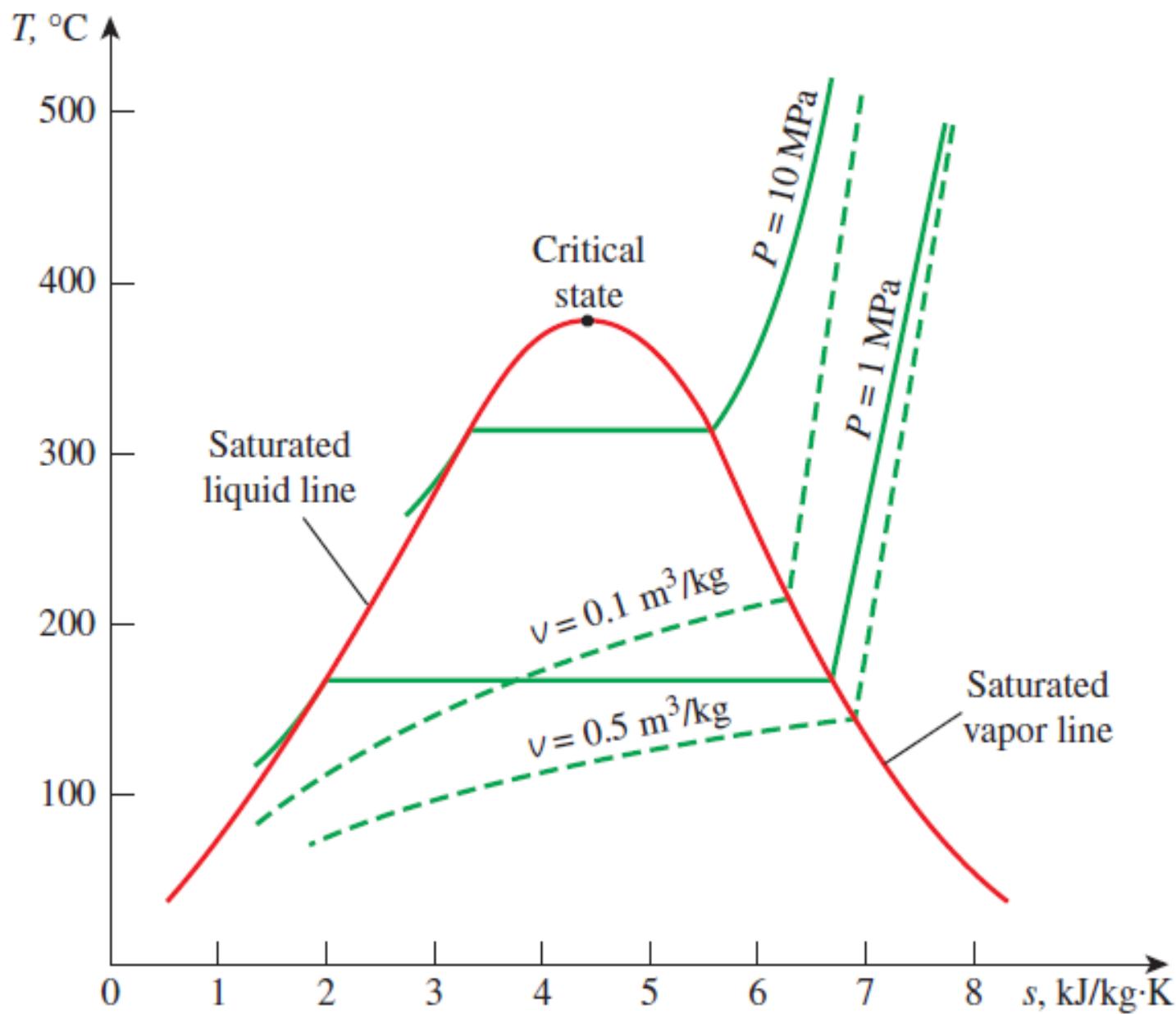


FIGURE 7-11

Schematic of the T - s diagram for water.

Entropy Change of a Substance in a Tank

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

Analysis We take the refrigerant in the tank as the system

State 1

$$\left. \begin{array}{l} P_1 = 140 \text{ kPa} \\ T_1 = 20^\circ\text{C} \end{array} \right\} \quad \left. \begin{array}{l} s_1 = 1.0625 \text{ kJ/kg}\cdot\text{K} \\ v_1 = 0.16544 \text{ m}^3/\text{kg} \end{array} \right.$$

State 2

$$\left. \begin{array}{l} P_2 = 100 \text{ kPa} \\ (v_2 = v_1) \end{array} \right\} \quad \left. \begin{array}{l} v_f = 0.0007258 \text{ m}^3/\text{kg} \\ v_g = 0.19255 \text{ m}^3/\text{kg} \end{array} \right.$$

$$x_2 = \frac{v_2 - v_f}{v_{fg}} = 0.859$$

$$s_2 = s_f + x_2 s_{fg} = 0.8278 \text{ kJ/kg}\cdot\text{K}$$

$$\Delta S = m(s_2 - s_1) = -1.173 \text{ kJ/K}$$

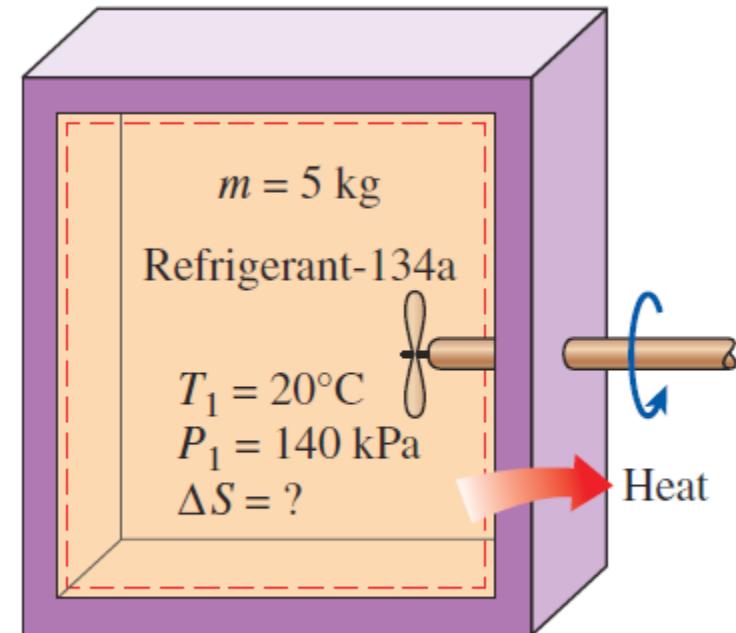


FIGURE 7-12

TABLE A-13

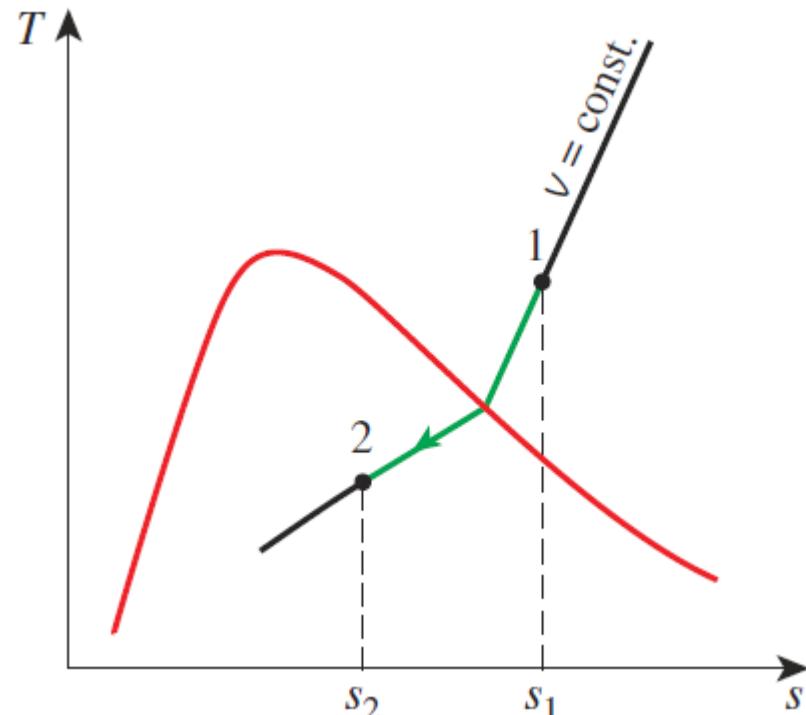
Superheated refrigerant-134a

T °C	v m^3/kg	u kJ/kg	h kJ/kg	s $\text{kJ/kg}\cdot\text{K}$
$P = 0.14 \text{ MPa } (T_{\text{sat}} = -18.77^\circ\text{C})$				
Sat.	0.14020	219.56	239.19	0.9447
-20	0.14605	225.93	246.37	0.9724
-10	0.15263	233.25	254.61	1.0032
0	0.15908	240.68	262.95	1.0331
10	0.16544	248.24	271.40	1.0625
20	0.17172	255.95	279.99	1.0913
30	0.17794	263.80	288.72	1.1196



TABLE A-12

Saturated refrigerant-134a—Pressure table



Press., P kPa	Sat. temp., T_{sat} °C	Specific volume, m^3/kg		Internal energy, kJ/kg		Enthalpy, kJ/kg		Entropy, $\text{kJ/kg}\cdot\text{K}$				
		Sat. liquid, v_f	Sat. vapor, v_g	Sat. liquid, u_f	Evap., u_{fg}	Sat. vapor, u_g	Sat. liquid, h_f	Evap., h_{fg}	Sat. vapor, h_g	Sat. liquid, s_f	Evap., s_{fg}	Sat. vapor, s_g
60	-36.95	0.0007097	0.31108	3.795	205.34	209.13	3.837	223.96	227.80	0.01633	0.94812	0.96445
70	-33.87	0.0007143	0.26921	7.672	203.23	210.90	7.722	222.02	229.74	0.03264	0.92783	0.96047
80	-31.13	0.0007184	0.23749	11.14	201.33	212.48	11.20	220.27	231.47	0.04707	0.91009	0.95716
90	-28.65	0.0007222	0.21261	14.30	199.60	213.90	14.36	218.67	233.04	0.06003	0.89431	0.95434
100	-26.37	0.0007258	0.19255	17.19	198.01	215.21	17.27	217.19	234.46	0.07182	0.88008	0.95191
120	-22.32	0.0007323	0.16216	22.38	195.15	217.53	22.47	214.52	236.99	0.09269	0.85520	0.94789
140	-18.77	0.0007381	0.14020	26.96	192.60	219.56	27.06	212.13	239.19	0.11080	0.83387	0.94467
160	-15.60	0.0007435	0.12355	31.06	190.31	221.37	31.18	209.96	241.14	0.12686	0.81517	0.94202
180	-12.73	0.0007485	0.11049	34.81	188.20	223.01	34.94	207.95	242.90	0.14131	0.79848	0.93979
200	-10.09	0.0007532	0.099951	38.26	186.25	224.51	38.41	206.09	244.50	0.15449	0.78339	0.93788

Entropy Change during an Iso-baric Process

A piston–cylinder device initially contains 1.5 kg of liquid water at 150 kPa and 20°C. The water is now heated at constant pressure by the addition of 4000 kJ of heat. Determine the entropy change of the water during this process.

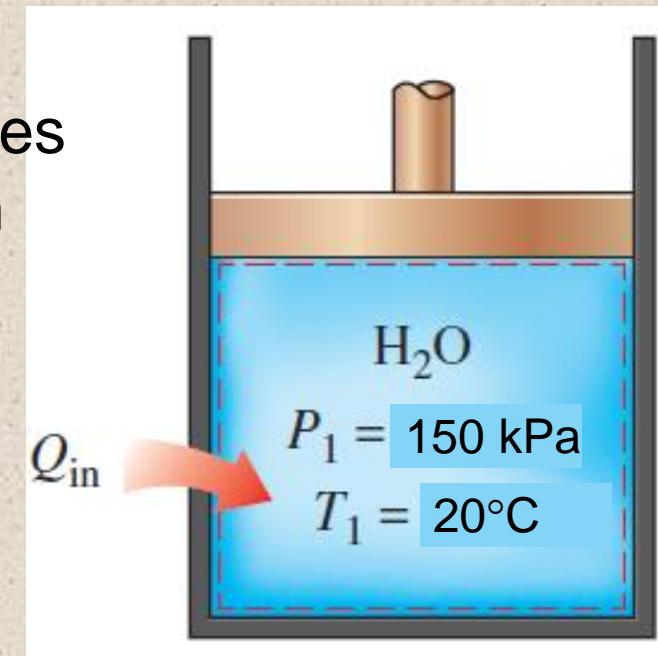
Assumptions 1 The tank is stationary and thus the kinetic and potential energy changes are zero 2 The process is quasi-equilibrium

Analysis We take the water in the cylinder as the system

$$\text{State 1: } \left. \begin{array}{l} P_1 = 150 \text{ kPa} \\ T_1 = 20^\circ\text{C} \end{array} \right\} \quad \left. \begin{array}{l} s_1 \approx s_f @ 20^\circ\text{C} = 0.2965 \text{ kJ/kg-K} \\ h_1 \approx h_f @ 20^\circ\text{C} = 83.915 \text{ kJ/kg} \end{array} \right\}$$

$$\text{State 2: } \left. \begin{array}{l} P_2 = 150 \text{ kPa} \\ h_2 = 2750.6 \text{ kJ/kg} \end{array} \right\} \quad s_2 = 7.3674 \text{ kJ/kg-K}$$

$$\Delta S = m(s_2 - s_1) = 10.61 \text{ kJ/K}$$



$$Q_{in} - W_b = \Delta U$$
$$Q_{in} = \Delta H$$

$$Q_{in} = m(h_2 - h_1)$$

$$h_2 = 2750.6 \text{ kJ/kg}$$

TABLE A-6

REQUIRES INTERPOLATION (for $P = 150 \text{ kPa}$)

Superheated water

T °C	v m^3/kg	u kJ/kg	h kJ/kg	s $\text{kJ/kg}\cdot\text{K}$
$P = 0.10 \text{ MPa} (99.61^\circ\text{C})$				
Sat. [†]	1.6941	2505.6	2675.0	7.3589
50				
100	1.6959	2506.2	2675.8	7.3611
150	1.9367	2582.9	2776.6	7.6148
200	2.1724	2658.2	2875.5	7.8356
250	2.4062	2733.9	2974.5	8.0346

T °C	v m^3/kg	u kJ/kg	h kJ/kg	s $\text{kJ/kg}\cdot\text{K}$
$P = 0.20 \text{ MPa} (120.21^\circ\text{C})$				
Sat.	0.88578	2529.1	2706.3	7.1270
150	0.95986	2577.1	2769.1	7.2810
200	1.08049	2654.6	2870.7	7.5081
250	1.19890	2731.4	2971.2	7.7100

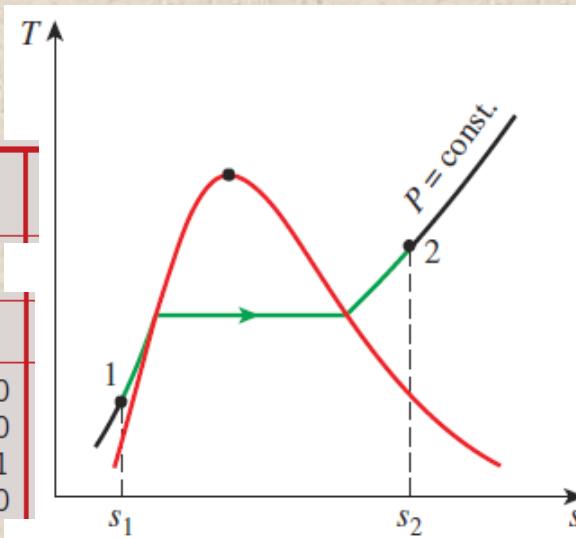


TABLE A-4

Saturated water—Temperature table

Temp., T °C	Specific volume, m^3/kg			Internal energy, kJ/kg			Enthalpy, kJ/kg			Entropy, $\text{kJ/kg}\cdot\text{K}$			
	Sat. press., P_{sat} kPa	Sat. liquid, v_f	Sat. vapor, v_g	Sat. liquid, u_f	Sat. Evap., u_{fg}	Sat. vapor, u_g	Sat. liquid, h_f	Sat. Evap., h_{fg}	Sat. vapor, h_g	Sat. liquid, s_f	Sat. Evap., s_{fg}	Sat. vapor, s_g	
	0.01	0.6117	0.001000	206.00	0.000	2374.9	2374.9	0.001	2500.9	2500.9	0.0000	9.1556	9.1556
5	0.8725	0.001000	147.03		21.019	2360.8	2381.8	21.020	2489.1	2510.1	0.0763	8.9487	9.0249
10	1.2281	0.001000	106.32		42.020	2346.6	2388.7	42.022	2477.2	2519.2	0.1511	8.7488	8.8999
15	1.7057	0.001001	77.885		62.980	2332.5	2395.5	62.982	2465.4	2528.3	0.2245	8.5559	8.7803
20	2.3392	0.001002	57.762		83.913	2318.4	2402.3	83.915	2453.5	2537.4	0.2965	8.3696	8.6661
25	3.1698	0.001003	43.340		104.83	2304.3	2409.1	104.83	2441.7	2546.5	0.3672	8.1895	8.5567
30	4.2469	0.001004	32.879		125.73	2290.2	2415.9	125.74	2429.8	2555.6	0.4368	8.0152	8.4520
35	5.6291	0.001006	25.205		146.63	2276.0	2422.7	146.64	2417.9	2564.6	0.5051	7.8466	8.3517
40	7.3851	0.001008	19.515		167.53	2261.9	2429.4	167.53	2406.0	2573.5	0.5724	7.6832	8.2556
45	9.5953	0.001010	15.251		188.43	2247.7	2436.1	188.44	2394.0	2582.4	0.6386	7.5247	8.1633

ISENTROPIC PROCESSES

- Entropy of a fixed mass (closed system) does not change during a process that is ***internally reversible and adiabatic***
- If no irreversibilities are present inside an adiabatic, steady flow, open system (control volume), the entropy of the fluid at the inlet and outlet will be same
- A process during which the entropy remains constant is called an ***isentropic process***

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

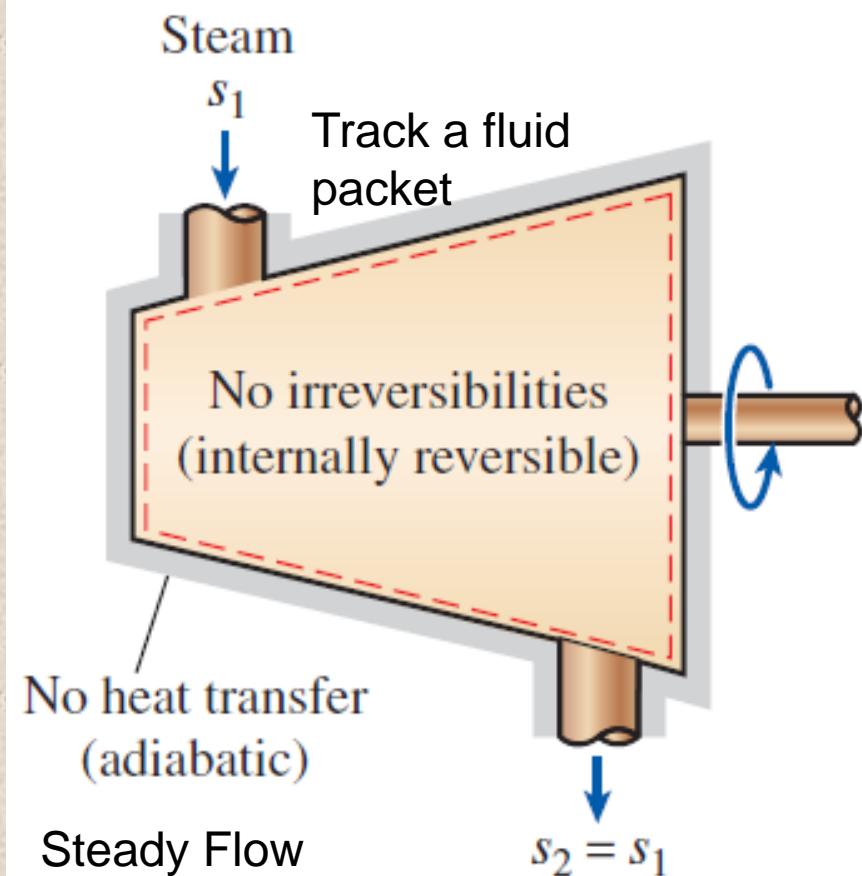


FIGURE 7–14

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

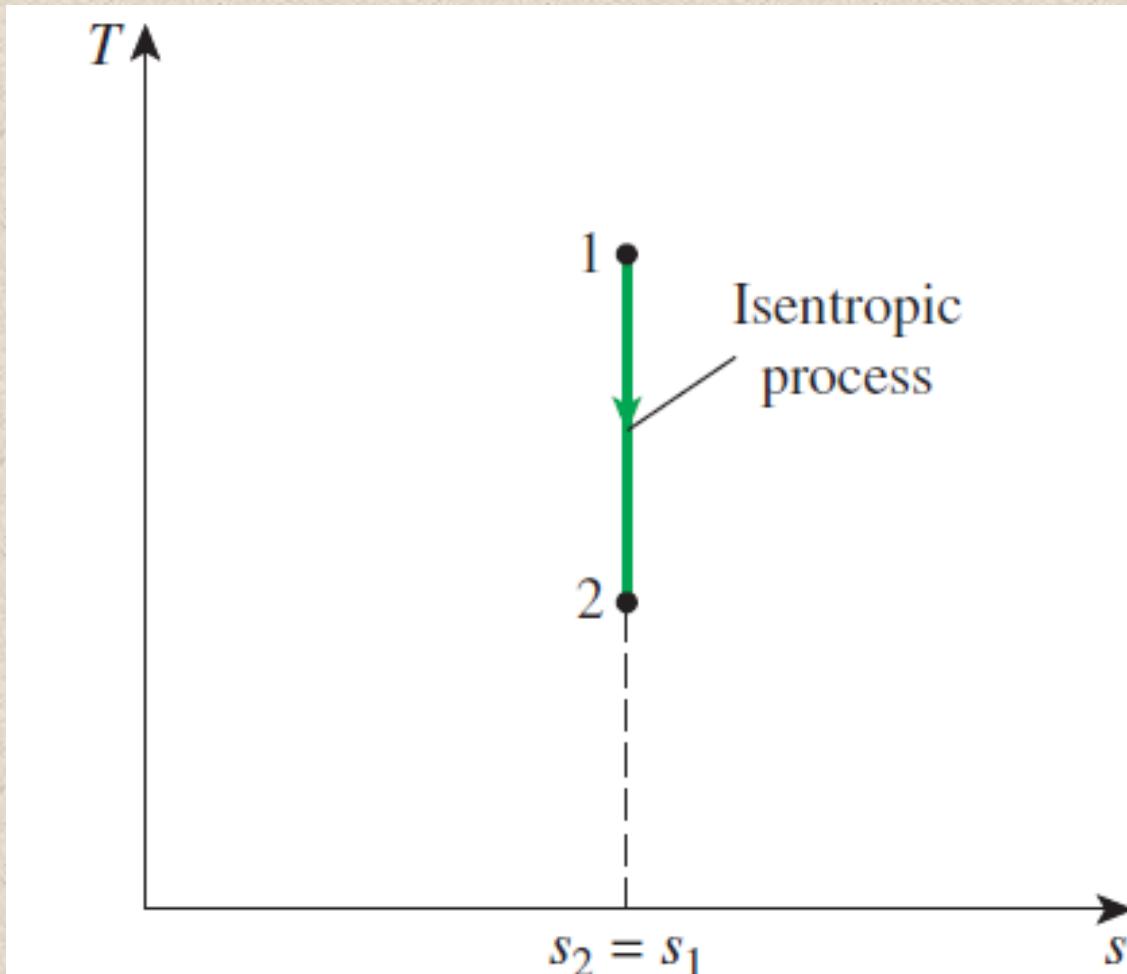


FIGURE 7-17

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

ISENTROPIC PROCESSES

- It should be recognized that *a reversible adiabatic process is necessarily isentropic ($s_2 = s_1$)*
- But an isentropic process is not necessarily a reversible adiabatic process (for example, the entropy increase of a substance during a process as a result of irreversibilities may be offset by a decrease in entropy as a result of heat losses)
- However, *the term isentropic process is customarily used in thermodynamics to imply an internally reversible adiabatic process*

ISENTROPIC EXPANSION OF STEAM IN A TURBINE

Steam enters an adiabatic turbine at 5 MPa and 450°C and leaves at a pressure of 1.4 MPa. Determine the work output of the turbine per unit mass of steam if the process is reversible.

Analysis We take the *turbine* as the system. This is a *control volume* since mass crosses the system boundary during the process.

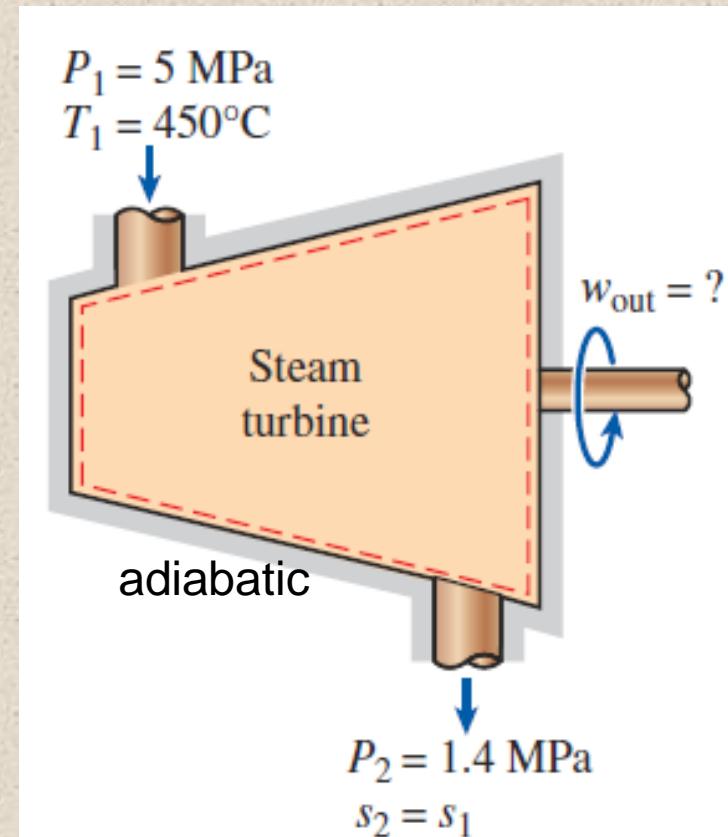
The process is reversible and adiabatic, thus isentropic. Therefore, $s_2 = s_1$

$$\text{State 1: } \left. \begin{array}{l} P_1 = 5 \text{ MPa} \\ T_1 = 450^\circ\text{C} \end{array} \right\} \quad \left. \begin{array}{l} h_1 = 3317.2 \text{ kJ/kg} \\ s_1 = 6.8210 \text{ kJ/kg}\cdot\text{K} \end{array} \right.$$

$$\text{State 2: } \left. \begin{array}{l} P_2 = 1.4 \text{ MPa} \\ s_2 = s_1 \end{array} \right\} \quad h_2 = 2967.4 \text{ kJ/kg}$$

$$\dot{W}_{\text{out}} = \dot{m}(h_1 - h_2) \quad (\text{since } \dot{Q} = 0, \text{ke} \approx \text{pe} \approx 0)$$

$$w_{\text{out}} = h_1 - h_2 = 3317.2 - 2967.4 = 349.8 \text{ kJ/kg}$$

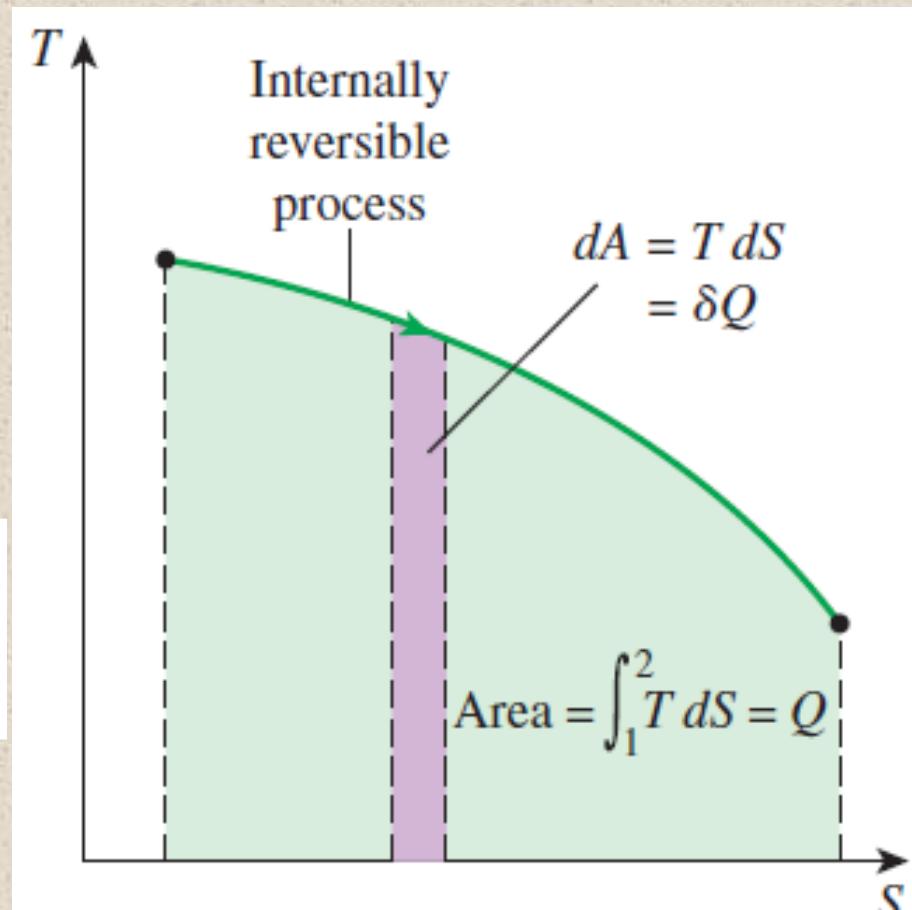


TEMPERATURE-ENTROPY DIAGRAM

- On a T - S diagram, ***the area under the process curve represents the heat transfer for internally reversible processes***
- The area has no meaning for irreversible processes***

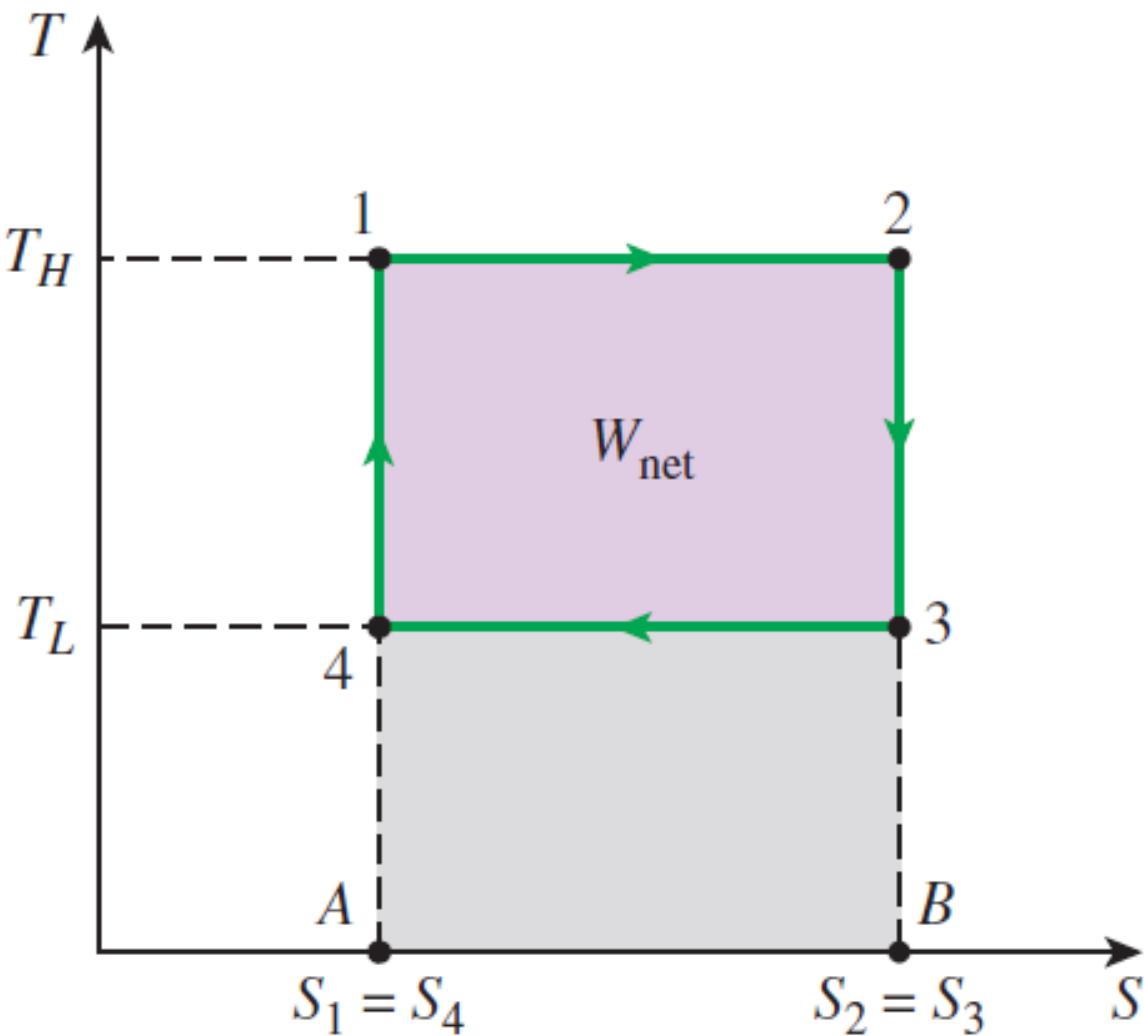
$$\delta Q_{\text{int rev}} = T \, dS \quad Q_{\text{int rev}} = \int_1^2 T \, dS$$

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



Internally reversible isothermal process:

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



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

FIGURE 7–19

The T - S diagram of a Carnot cycle

PROPERTY DIAGRAMS INVOLVING ENTROPY

- Enthalpy-entropy ($h-s$) diagram is quite useful in the analysis of adiabatic steady flow devices such as turbines, compressors, and nozzles.
- **Enthalpy** is a primary property in the first law analysis of the adiabatic steady flow devices
- **Entropy** accounts for irreversibilities during adiabatic processes

Mollier diagram:
The $h-s$ diagram

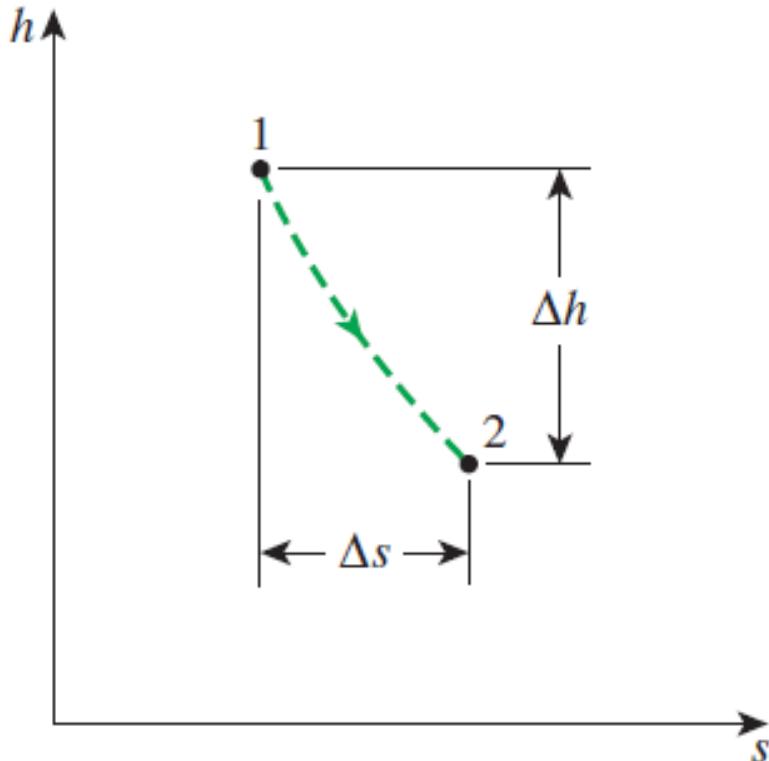


FIGURE 7–18

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.

WHAT IS ENTROPY?

- Entropy can be viewed as a *measure of molecular disorder*, or molecular randomness
- As a system becomes more disordered, *the position of the molecules become less predictable* and the entropy increases
- Entropy of a substance is lowest in the solid phase and highest in the gas phase

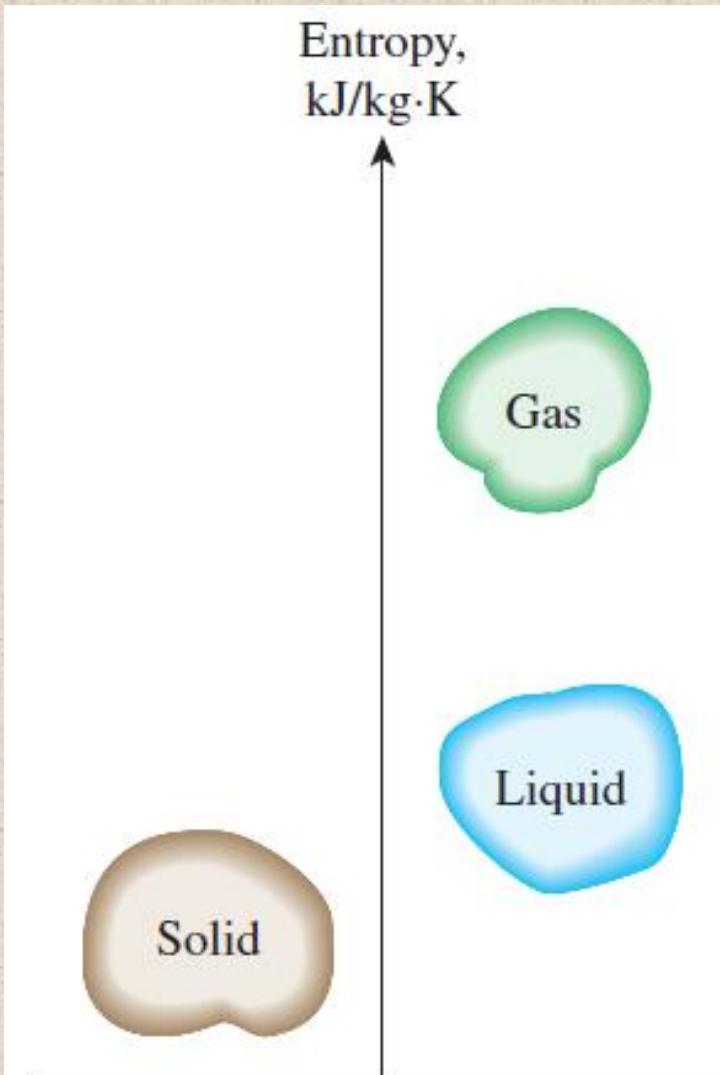


FIGURE 7–20

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

WHAT IS ENTROPY?

- In the **solid** phase the molecules of a substance continually oscillate about their equilibrium position, but they cannot move relative to each other, and *their position at any instant can be predicted with good certainty*
- In the **gas** phase, the molecules move about at random, collide with each other, and change direction, associated with this *molecular chaos* is a high value of entropy

The entropy of a pure crystalline substance at absolute zero temperature is zero since there is no uncertainty about the state of the molecules at that instant (**the third law of thermodynamics**)

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



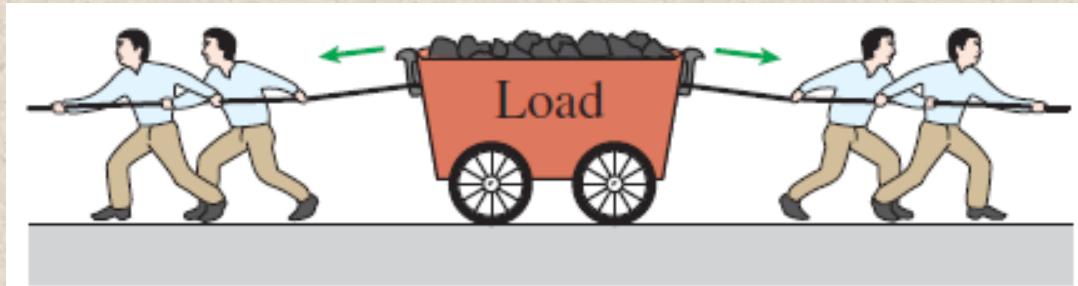


FIGURE 7–22

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

- Molecules in the gas phase possess a considerable amount of kinetic energy. However, we know that no matter how large their kinetic energies are, the gas molecules do not rotate a paddle wheel inserted into the container and produce work
- This is because the gas molecules, and the energy they posses, are disorganized

- The energy of the molecules in a rotating shaft is completely organized since the molecules of the shaft are rotating in the same direction together.
- *This organized energy can be readily be used to perform useful tasks (work)*
- Being an organized form of energy, work is free of disorder or randomness and thus free of entropy
- ***There is no entropy transfer associated with energy transfer as work***

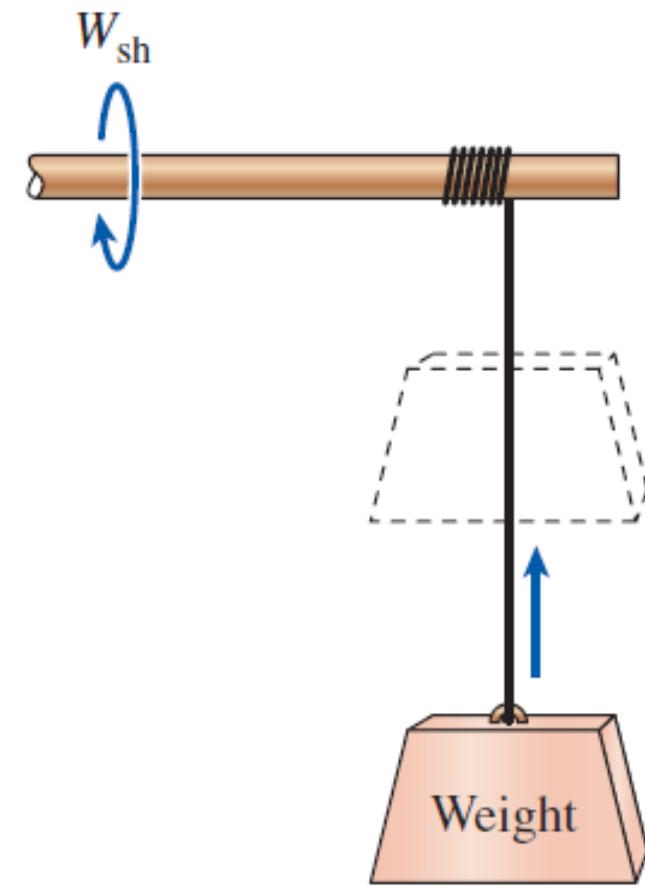


FIGURE 7–23
In the absence of friction, raising a weight by a rotating shaft does not create any disorder (entropy), and thus energy is not degraded during this process.

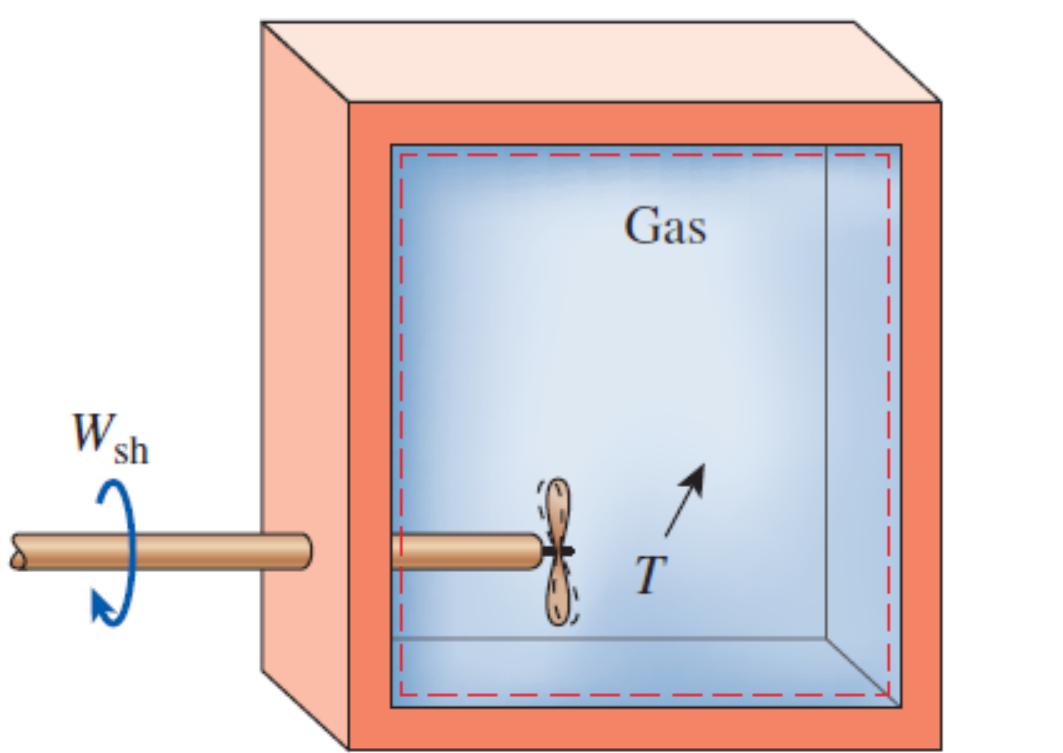


FIGURE 7–24

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.

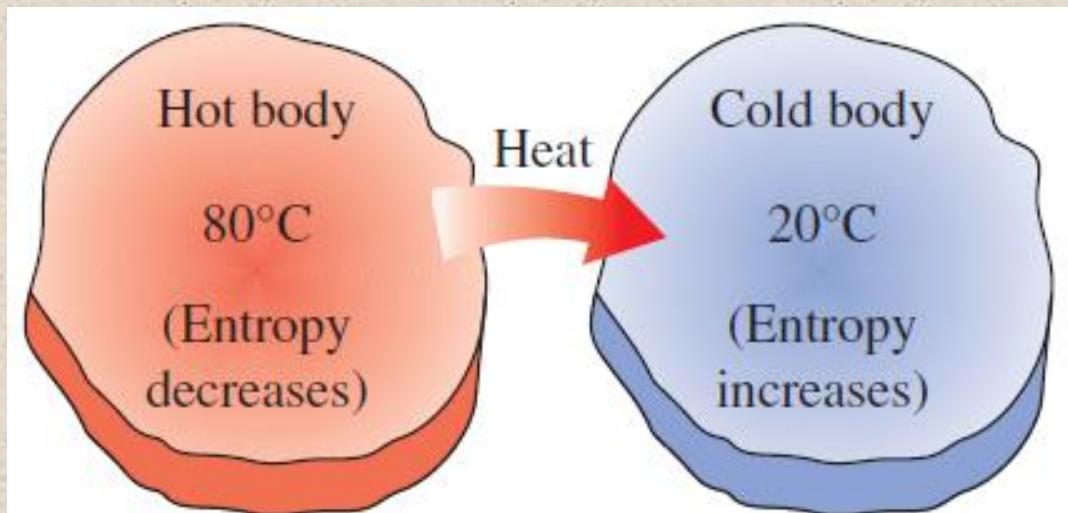


FIGURE 7–25

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

Consider a **closed stationary system** containing a simple compressible substance undergoing an **internally reversible process**

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

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

The only type of work interaction a simple compressible stationary system may involve as it undergoes an **internally reversible** process is the **boundary work**

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

boundary work for a simple compressible stationary system

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

the first $T ds$, or Gibbs equation

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

$$h = u + Pv$$

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

the second $T ds$ equation

$T ds$ relations are extremely valuable since they **relate entropy changes of a system to the changes in other properties**

$T ds$ relations are property relations and therefore are **independent of the type of the processes**

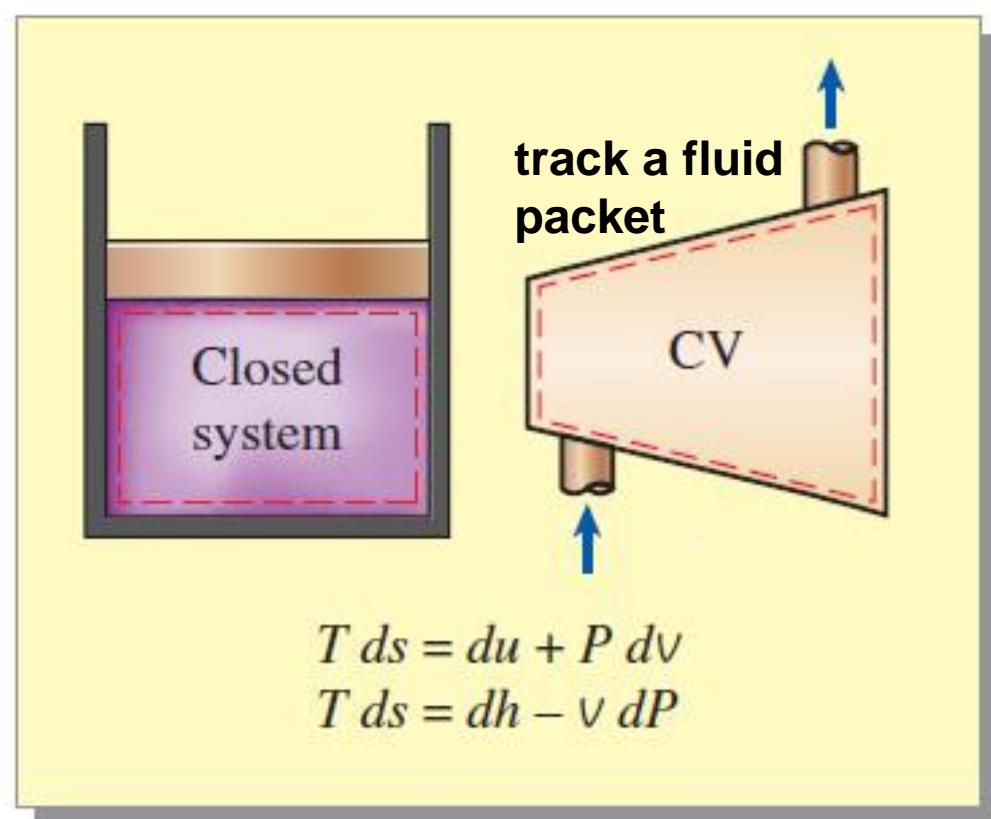


FIGURE 7–27

The $T ds$ relations are valid for both reversible and irreversible processes

THE $T ds$ RELATIONS

- These Tds relations are developed with an internally reversible process in mind since the entropy change between two states must be evaluated along a reversible path
- *However, the results obtained are valid for both **reversible** and **irreversible** processes since entropy is a property and the change in property between two states is independent of the type of process the system undergoes*

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

differential changes in entropy in terms of other properties

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

ENTROPY CHANGE OF LIQUIDS AND SOLIDS

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

Since $dv \cong 0$ for liquids and solids

$$ds = \frac{du}{T} = \frac{c dT}{T}$$

since $c_p = c_v = c$ and $du = c dT$

Liquids and solids can be approximated as *incompressible substances* since their specific volumes remain nearly constant during a process.

Liquids, solids: $s_2 - s_1 = \int_1^2 c(T) \frac{dT}{T} \cong c_{\text{avg}} \ln \frac{T_2}{T_1}$ (kJ/kg · K)

For an isentropic process of an incompressible substance

Isentropic: $s_2 - s_1 = c_{\text{avg}} \ln \frac{T_2}{T_1} = 0 \rightarrow T_2 = T_1$

THE ENTROPY CHANGE OF IDEAL GASES

From the first $T ds$ relation

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

$$ds = c_v \frac{dT}{T} + R \frac{dv}{v} \quad du = c_v dT \quad P = RT/v$$

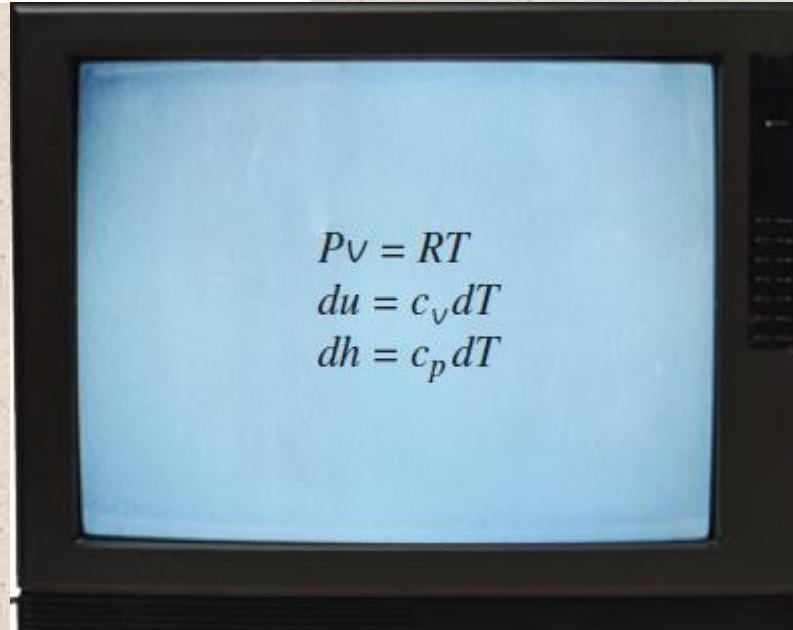
$$s_2 - s_1 = \int_1^2 c_v(T) \frac{dT}{T} + R \ln \frac{v_2}{v_1}$$

From the second $T ds$ relation

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

$$ds = c_p \frac{dT}{T} - R \frac{dP}{P} \quad dh = c_p dT \quad v = RT/P$$

$$s_2 - s_1 = \int_1^2 c_p(T) \frac{dT}{T} - R \ln \frac{P_2}{P_1}$$



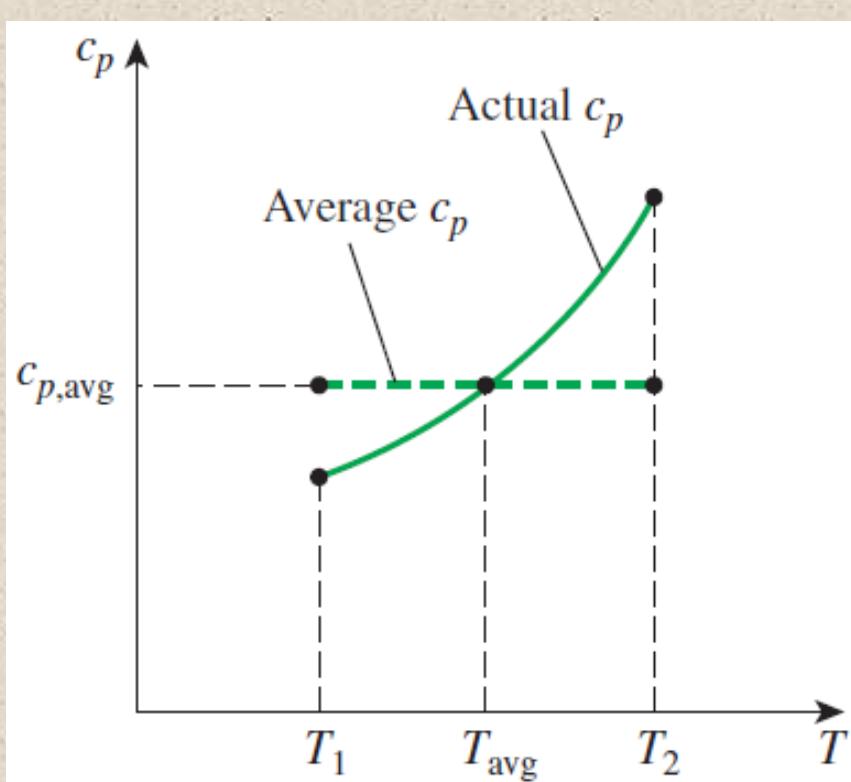
Constant Specific Heats (Approximate Analysis)

$$s_2 - s_1 = \int_1^2 c_v(T) \frac{dT}{T} + R \ln \frac{v_2}{v_1}$$

$$\rightarrow s_2 - s_1 = c_{v,\text{avg}} \ln \frac{T_2}{T_1} + R \ln \frac{v_2}{v_1}$$

$$s_2 - s_1 = \int_1^2 c_p(T) \frac{dT}{T} - R \ln \frac{P_2}{P_1}$$

$$\rightarrow s_2 - s_1 = c_{p,\text{avg}} \ln \frac{T_2}{T_1} - R \ln \frac{P_2}{P_1}$$



(kJ/kg · K)

FIGURE 7–31

Under the constant-specific-heat assumption, the specific heat is assumed to be constant at some average value.

Constant Specific Heats (Approximate Analysis)

Entropy change of an ideal gas on a unit–mole basis

$$\bar{s}_2 - \bar{s}_1 = \bar{c}_{v,\text{avg}} \ln \frac{T_2}{T_1} + R_u \ln \frac{v_2}{v_1} \quad (\text{kJ}/\text{kmol} \cdot \text{K})$$

$$\bar{s}_2 - \bar{s}_1 = \bar{c}_{p,\text{avg}} \ln \frac{T_2}{T_1} - R_u \ln \frac{P_2}{P_1} \quad (\text{kJ}/\text{kmol} \cdot \text{K})$$

Variable Specific Heats (Exact Analysis, Ideal Gas)

We choose absolute zero as the reference temperature and define a function s° as

$$s^\circ = \int_0^T c_p(T) \frac{dT}{T}$$

$$\int_1^2 c_p(T) \frac{dT}{T} = s_2^\circ - s_1^\circ$$

On a unit-mass basis

$$s_2 - s_1 = s_2^\circ - s_1^\circ - R \ln \frac{P_2}{P_1} \quad (\text{kJ/kg} \cdot \text{K})$$

On a unit-mole basis

$$\bar{s}_2 - \bar{s}_1 = \bar{s}_2^\circ - \bar{s}_1^\circ - R_u \ln \frac{P_2}{P_1} \quad (\text{kJ/kmol} \cdot \text{K})$$

	<u>T, K</u>	<u>$s^\circ, \text{kJ/kg} \cdot \text{K}$</u>
300	1.70203	
310	1.73498	
320	1.76690	
⋮	⋮	⋮
		(Table A-17)

FIGURE 7–32

The entropy of an ideal gas depends on both T and P . The function s° represents only the temperature-dependent part of entropy.

Air

$$P_1 = 100 \text{ kPa} \quad T_1 = 290 \text{ K}$$

$$P_2 = 600 \text{ kPa} \quad T_2 = 330 \text{ K}$$

$$\begin{aligned}s_2 - s_1 &= s_2^\circ - s_1^\circ - R \ln \frac{P_2}{P_1} \\&= -0.3844 \text{ kJ/kg}\cdot\text{K}\end{aligned}$$

$$\begin{aligned}s_2 - s_1 &= c_{p,\text{avg}} \ln \frac{T_2}{T_1} - R \ln \frac{P_2}{P_1} \\&= -0.3842 \text{ kJ/kg}\cdot\text{K}\end{aligned}$$



FIGURE 7–34

For small temperature differences, the exact and approximate relations for entropy changes of ideal gases give almost identical results.

TABLE A-17

Ideal-gas properties of air

<i>T</i> K	<i>h</i> kJ/kg	<i>P_r</i>	<i>u</i> kJ/kg	<i>v_r</i>	<i>s°</i> kJ/kg·K
200	199.97	0.3363	142.56	1707.0	1.29559
210	209.97	0.3987	149.69	1512.0	1.34444
220	219.97	0.4690	156.82	1346.0	1.39105
230	230.02	0.5477	164.00	1205.0	1.43557
240	240.02	0.6355	171.13	1084.0	1.47824
250	250.05	0.7329	178.28	979.0	1.51917
260	260.09	0.8405	185.45	887.8	1.55848
270	270.11	0.9590	192.60	808.0	1.59634
280	280.13	1.0889	199.75	738.0	1.63279
285	285.14	1.1584	203.33	706.1	1.65055
290	290.16	1.2311	206.91	676.1	1.66802
295	295.17	1.3068	210.49	647.9	1.68515
298	298.18	1.3543	212.64	631.9	1.69528
300	300.19	1.3860	214.07	621.2	1.70203
305	305.22	1.4686	217.67	596.0	1.71865
310	310.24	1.5546	221.25	572.3	1.73498
315	315.27	1.6442	224.85	549.8	1.75106
320	320.29	1.7375	228.42	528.6	1.76690
325	325.31	1.8345	232.02	508.4	1.78249
330	330.34	1.9352	235.61	489.4	1.79783

ISENTROPIC PROCESSES OF IDEAL GASES

CONSTANT SPECIFIC HEATS (APPROXIMATE ANALYSIS)

$$s_2 - s_1 = c_{v,\text{avg}} \ln \frac{T_2}{T_1} + R \ln \frac{V_2}{V_1}$$

setting this eq. equal to zero, we get

$$\ln \frac{T_2}{T_1} = -\frac{R}{c_v} \ln \frac{V_2}{V_1}$$

$$\ln \frac{T_2}{T_1} = \ln \left(\frac{V_1}{V_2} \right)^{R/c_v}$$

$$R = c_p - c_v, k = c_p/c_v$$

$$\text{and thus } R/c_v = k - 1$$

$$TV^{k-1} = \text{constant}$$

$$TP^{(1-k)/k} = \text{constant}$$

$$PV^k = \text{constant}$$

$$\left(\frac{T_2}{T_1} \right)_{s=\text{const.}} = \left(\frac{V_1}{V_2} \right)^{k-1}$$

$$\left(\frac{T_2}{T_1} \right)_{s=\text{const.}} = \left(\frac{P_2}{P_1} \right)^{(k-1)/k}$$

$$\left(\frac{P_2}{P_1} \right)_{s=\text{const.}} = \left(\frac{V_1}{V_2} \right)^k$$

$$\left(\frac{T_2}{T_1}\right)_{s=\text{const.}} = \left(\frac{P_2}{P_1}\right)^{(k-1)/k} = \left(\frac{v_1}{v_2}\right)^{k-1}$$

Valid for *ideal gas
 *isentropic process
 *constant specific heats

FIGURE 7–35

The isentropic relations of ideal gases are valid for the isentropic processes of ideal gases only.

ISENTROPIC PROCESSES OF IDEAL GASES

Variable Specific Heats (Exact Analysis)

$$s_2 - s_1 = s_2^\circ - s_1^\circ - R \ln \frac{P_2}{P_1} \quad (\text{kJ/kg} \cdot \text{K})$$

$$0 = s_2^\circ - s_1^\circ - R \ln \frac{P_2}{P_1} \quad s_2^\circ = s_1^\circ + R \ln \frac{P_2}{P_1}$$

Relative Pressure and Relative Specific Volume

$$\frac{P_2}{P_1} = \exp \frac{s_2^\circ - s_1^\circ}{R} \quad \text{Define: } \exp(s^\circ/R) \text{ as the relative pressure } P_r$$

$$\frac{P_2}{P_1} = \frac{\exp(s_2^\circ / R)}{\exp(s_1^\circ / R)} \quad \left(\frac{P_2}{P_1} \right)_{s=\text{const.}} = \frac{P_{r2}}{P_{r1}}$$

$$\frac{P_1 v_1}{T_1} = \frac{P_2 v_2}{T_2} \rightarrow \frac{v_2}{v_1} = \frac{T_2}{T_1} \frac{P_1}{P_2} = \frac{T_2}{T_1} \frac{P_{r1}}{P_{r2}} = \frac{T_2/P_{r2}}{T_1/P_{r1}}$$

$$\left(\frac{v_2}{v_1} \right)_{s=\text{const.}} = \frac{v_{r2}}{v_{r1}} \quad \text{Define: } T/P_r \text{ as the relative specific volume } v_r$$

P_r (dimensionless) and v_r are *functions of temperature only* and are tabulated against temperature (Table A17 for air)

These relations are strictly valid for *isentropic processes of ideal gas* only are used to account for *variation in specific heats with temperature*

Process: isentropic

Given: P_1 , T_1 , and P_2

Find: T_2

$$\frac{T}{P_r}$$

$$T_2 \xleftarrow{\text{read}} P_{r2} = \frac{P_2}{P_1} P_{r1} \quad T_1 \xrightarrow{\text{read}} P_{r1}$$

Process: isentropic

Given: v_1 , T_1 , and v_2

Find: T_2

$$\frac{T}{v_r}$$

$$T_2 \xleftarrow{\text{read}} v_{r2} = \frac{v_2}{v_1} v_{r1} \quad T_1 \xrightarrow{\text{read}} v_{r1}$$

Example: Isentropic Processes of Ideal Gases

Air is compressed in a car engine from 228°C and 95 kPa in a reversible and adiabatic (isentropic) manner. If the compression ratio V_1/V_2 of this engine is 8, determine the final temperature of the air.

For closed system

$$\frac{V_2}{V_1} = \frac{v_2}{v_1}$$

Solution (considering temperature dependent specific heats)

At $T_1 = 295$ K:

$$v_{r1} = 647.9$$

$$v_{r2} = v_{r1} \left(\frac{v_2}{v_1} \right) = (647.9) \left(\frac{1}{8} \right) = 80.99 \rightarrow T_2 = 662.7 \text{ K}$$

Alternative solution (considering constant specific heats)

$$\left(\frac{T_2}{T_1} \right)_{s=\text{const.}} = \left(\frac{v_1}{v_2} \right)^{k-1}$$

$$T_2 = (295 \text{ K})(8)^{1.391 - 1} = 665.2 \text{ K}$$

TABLE A-17

Ideal-gas properties of air

<i>T</i> K	<i>h</i> kJ/kg	<i>P_r</i>	<i>u</i> kJ/kg	<i>v_r</i>	<i>s^o</i> kJ/kg·K	<i>T</i> K	<i>h</i> kJ/kg	<i>P_r</i>	<i>u</i> kJ/kg	<i>v_r</i>	<i>s^o</i> kJ/kg·K
200	199.97	0.3363	142.56	1707.0	1.29559	580	586.04	14.38	419.55	115.7	2.37348
210	209.97	0.3987	149.69	1512.0	1.34444	590	596.52	15.31	427.15	110.6	2.39140
220	219.97	0.4690	156.82	1346.0	1.39105	600	607.02	16.28	434.78	105.8	2.40902
230	230.02	0.5477	164.00	1205.0	1.43557	610	617.53	17.30	442.42	101.2	2.42644
240	240.02	0.6355	171.13	1084.0	1.47824	620	628.07	18.36	450.09	96.92	2.44356
250	250.05	0.7329	178.28	979.0	1.51917	630	638.63	19.84	457.78	92.84	2.46048
260	260.09	0.8405	185.45	887.8	1.55848	640	649.22	20.64	465.50	88.99	2.47716
270	270.11	0.9590	192.60	808.0	1.59634	650	659.84	21.86	473.25	85.34	2.49364
280	280.13	1.0889	199.75	738.0	1.63279	660	670.47	23.13	481.01	81.89	2.50985
285	285.14	1.1584	203.33	706.1	1.65055	670	681.14	24.46	488.81	78.61	2.52589
290	290.16	1.2311	206.91	676.1	1.66802	680	691.82	25.85	496.62	75.50	2.54175
295	295.17	1.3068	210.49	647.9	1.68515	690	702.52	27.29	504.45	72.56	2.55731
298	298.18	1.3543	212.64	631.9	1.69528	700	713.27	28.80	512.33	69.76	2.57277
300	300.19	1.3860	214.07	621.2	1.70203	710	724.04	30.38	520.23	67.07	2.58810
305	305.22	1.4686	217.67	596.0	1.71865	720	734.82	32.02	528.14	64.53	2.60319



REVERSIBLE STEADY-FLOW WORK

$$\delta q_{\text{int rev}} - \delta w_{\text{int rev}} = dh + dke + dpe$$

energy balance for steady flow system undergoing an internally reversible process

$$\delta q_{\text{int rev}} = T ds \quad (\text{Eq. 7-16}) \}$$

$$T ds = dh - v dP \quad (\text{Eq. 7-24}) \}$$

$$\delta q_{\text{int rev}} = dh - v dP$$

$$-\delta w_{\text{int rev}} = v dP + dke + dpe$$

$$w_{\text{int rev}} = - \int_1^2 v dP - \Delta ke - \Delta pe$$

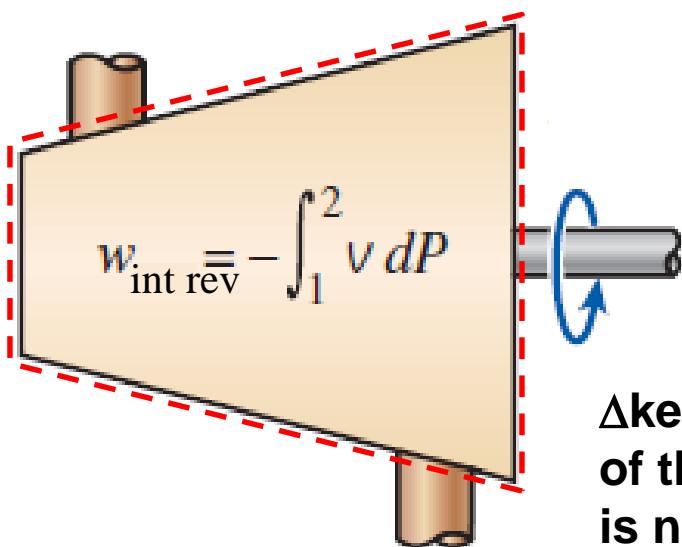
note that **1** represents the **inlet** state and **2** represents the **exit** state of the fluid flowing through the steady flow system

$$w_{\text{int rev}} = - \int_1^2 v dP$$

If the change in kinetic and potential energies of the fluid are negligible

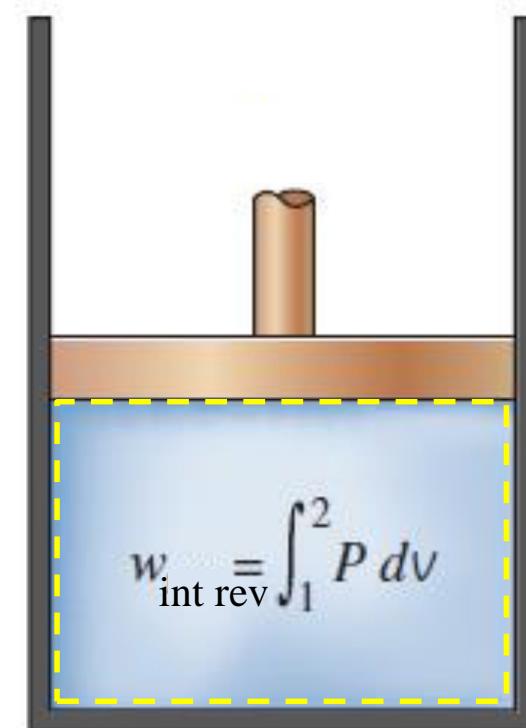
Work output associated with an **internally reversible process** in a steady flow system

REVERSIBLE STEADY-FLOW WORK



(a) Steady-flow system

Δ_{ke} and Δ_{pe} of the fluid is neglected



(b) Closed system

The larger the specific volume, the larger the reversible work produced or consumed by the steady-flow system

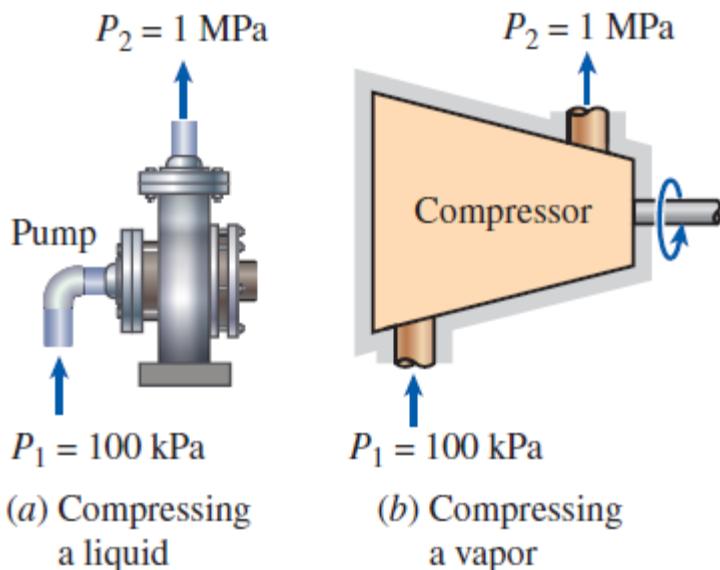
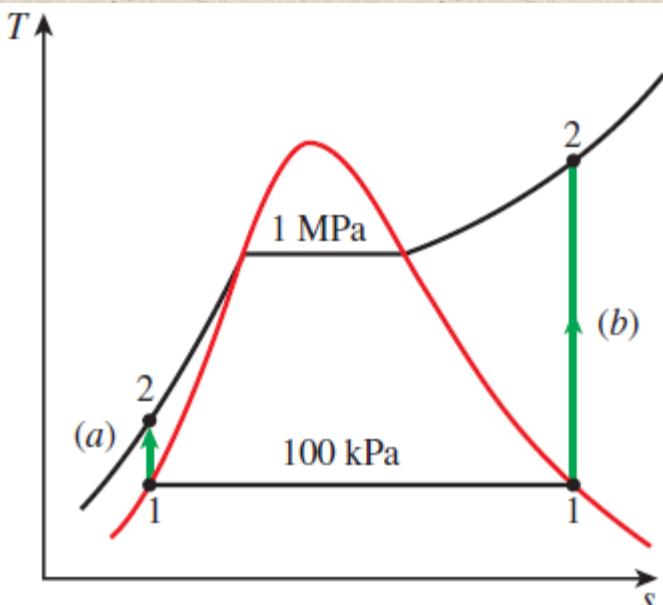
REVERSIBLE STEADY-FLOW WORK FOR INCOMPRESSIBLE WORKING FLUID

$$w_{\text{int rev}} = - \int_1^2 v dP - \Delta \text{ke} - \Delta \text{pe}$$

$$w_{\text{int rev}} = -v(P_2 - P_1) - \Delta \text{ke} - \Delta \text{pe}$$

For the steady flow of a liquid through an open system (control volume) having no irreversibilities inside it, which involves no work interactions (e.g. a pipe section), the work term is zero (**Bernoulli equation**):

$$v(P_2 - P_1) + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1) = 0$$



EXAMPLE: Compressing a Substance in the Liquid versus Gas Phases

Case A: Compressing saturated liquid

$$\begin{aligned}
 w_{\text{rev,in}} &= \int_1^2 v dP \cong v_1 (P_2 - P_1) & v_1 &= v_f @ 100 \text{ kPa} \\
 &= (0.001043 \text{ m}^3/\text{kg})[(1000 - 100) \text{ kPa}] \left(\frac{1 \text{ kJ}}{1 \text{ kPa} \cdot \text{m}^3} \right) \\
 &= \mathbf{0.94 \text{ kJ/kg}}
 \end{aligned}$$

Case B: Compressing saturated vapor

$$\begin{aligned}
 Tds &= dh - v dP \quad (\text{Eq. 7-24}) \\
 ds &= 0 \quad (\text{isentropic process})
 \end{aligned} \quad \left. \begin{array}{l} v dP = dh \\ \end{array} \right\}$$

$$\begin{aligned}
 \text{State 1: } & P_1 = 100 \text{ kPa} \} & h_1 &= 2675.0 \text{ kJ/kg} \\
 & (\text{sat. vapor}) \} & s_1 &= 7.3589 \text{ kJ/kg} \cdot \text{K}
 \end{aligned}$$

$$\begin{aligned}
 \text{State 2: } & P_2 = 1 \text{ MPa} \} & h_2 &= 3194.5 \text{ kJ/kg} \\
 & s_2 = s_1 \}
 \end{aligned}$$

$$w_{\text{rev,in}} = \int_1^2 v dP = \int_1^2 dh = h_2 - h_1$$

$$w_{\text{rev,in}} = (3194.5 - 2675.0) \text{ kJ/kg} = \mathbf{519.5 \text{ kJ/kg}}$$

TABLE A-5

Saturated water—Pressure table

Press., P kPa	Sat. T_{sat} °C	Specific volume, m³/kg			Internal energy, kJ/kg			Enthalpy, kJ/kg			Entropy, kJ/kg·K		
		Sat. liquid, v_f	Sat. vapor, v_g	Sat. u_f	Sat. liquid, u_{fg}	Sat. vapor, u_g	Sat. liquid, h_f	Sat. Evap., h_{fg}	Sat. vapor, h_g	Sat. liquid, s_f	Sat. Evap., s_{fg}	Sat. vapor, s_g	
1.0	6.97	0.001000	129.19	29.302	2355.2	2384.5	29.303	2484.4	2513.7	0.1059	8.8690	8.9749	
1.5	13.02	0.001001	87.964	54.686	2338.1	2392.8	54.688	2470.1	2524.7	0.1956	8.6314	8.8270	
2.0	17.50	0.001001	66.990	73.431	2325.5	2398.9	73.433	2459.5	2532.9	0.2606	8.4621	8.7227	
2.5	21.08	0.001002	54.242	88.422	2315.4	2403.8	88.424	2451.0	2539.4	0.3118	8.3302	8.6421	
3.0	24.08	0.001003	45.654	100.98	2306.9	2407.9	100.98	2443.9	2544.8	0.3543	8.2222	8.5765	
4.0	28.96	0.001004	34.791	121.39	2293.1	2414.5	121.39	2432.3	2553.7	0.4224	8.0510	8.4734	
5.0	32.87	0.001005	28.185	137.75	2282.1	2419.8	137.75	2423.0	2560.7	0.4762	7.9176	8.3938	
7.5	40.29	0.001008	19.233	168.74	2261.1	2429.8	168.75	2405.3	2574.0	0.5763	7.6738	8.2501	
10	45.81	0.001010	14.670	191.79	2245.4	2437.2	191.81	2392.1	2583.9	0.6492	7.4996	8.1488	
15	53.97	0.001014	10.020	225.93	2222.1	2448.0	225.94	2372.3	2598.3	0.7549	7.2522	8.0071	
20	60.06	0.001017	7.6481	251.40	2204.6	2456.0	251.42	2357.5	2608.9	0.8320	7.0752	7.9073	
25	64.96	0.001020	6.2034	271.93	2190.4	2462.4	271.96	2345.5	2617.5	0.8932	6.9370	7.8302	
30	69.09	0.001022	5.2287	289.24	2178.5	2467.7	289.27	2335.3	2624.6	0.9441	6.8234	7.7675	
40	75.86	0.001026	3.9933	317.58	2158.8	2476.3	317.62	2318.4	2636.1	1.0261	6.6430	7.6691	
50	81.32	0.001030	3.2403	340.49	2142.7	2483.2	340.54	2304.7	2645.2	1.0912	6.5019	7.5931	
75	91.76	0.001037	2.2172	384.36	2111.8	2496.1	384.44	2278.0	2662.4	1.2132	6.2426	7.4558	
100	99.61	0.001043	1.6941	417.40	2088.2	2505.6	417.51	2257.5	2675.0	1.3028	6.0562	7.3589	
101.325	99.97	0.001043	1.6734	418.95	2087.0	2506.0	419.06	2256.5	2675.6	1.3069	6.0476	7.3545	
125	105.97	0.001048	1.3750	444.23	2068.8	2513.0	444.36	2240.6	2684.9	1.3741	5.9100	7.2841	
150	111.35	0.001053	1.1594	466.97	2052.3	2519.2	467.13	2226.0	2693.1	1.4337	5.7894	7.2231	

TABLE A-6

Superheated water (*Concluded*)

<i>T</i> °C	<i>v</i> m ³ /kg	<i>u</i> kJ/kg	<i>h</i> kJ/kg	<i>s</i> kJ/kg·K
<i>P</i> = 1.00 MPa (179.88°C)				
Sat.	0.19437	2582.8	2777.1	6.5850
200	0.20602	2622.3	2828.3	6.6956
250	0.23275	2710.4	2943.1	6.9265
300	0.25799	2793.7	3051.6	7.1246
350	0.28250	2875.7	3158.2	7.3029
400	0.30661	2957.9	3264.5	7.4670
500	0.35411	3125.0	3479.1	7.7642
600	0.40111	3297.5	3698.6	8.0311
700	0.44783	3476.3	3924.1	8.2755
800	0.49438	3661.7	4156.1	8.5024
900	0.54083	3853.9	4394.8	8.7150
1000	0.58721	4052.7	4640.0	8.9155
1100	0.63354	4257.9	4891.4	9.1057
1200	0.67983	4469.0	5148.9	9.2866
1300	0.72610	4685.8	5411.9	9.4593



Proof that Steady-Flow Systems Deliver the Most and Consume the Least Work when the Process Is Internally Reversible (no irreversibilities inside the system)

Taking heat input and work output to be positive:

$$\delta q_{\text{act}} - \delta w_{\text{act}} = dh + dke + dpe \quad \text{Actual}$$

$$\delta q_{\text{int rev}} - \delta w_{\text{int rev}} = dh + dke + dpe \quad \text{Internally Reversible}$$

$$\delta q_{\text{act}} - \delta w_{\text{act}} = \delta q_{\text{int rev}} - \delta w_{\text{int rev}}$$

$$\delta w_{\text{int rev}} - \delta w_{\text{act}} = \delta q_{\text{int rev}} - \delta q_{\text{act}}$$

$$\delta q_{\text{int rev}} = T ds \quad ds \geq \frac{\delta q_{\text{act}}}{T}$$

$$\frac{\delta w_{\text{int rev}} - \delta w_{\text{act}}}{T} = ds - \frac{\delta q_{\text{act}}}{T} \geq 0$$

$$\delta w_{\text{int rev}} \geq \delta w_{\text{act}} \quad w_{\text{int rev}} \geq w_{\text{act}}$$

Work producing systems such as turbines (w is positive) delivers most work, and work consuming systems such as pumps and compressors (w is negative) requires least work ***when they operate reversibly*** (no irreversibilities inside them) ***between the same inlet and exit fluid states***

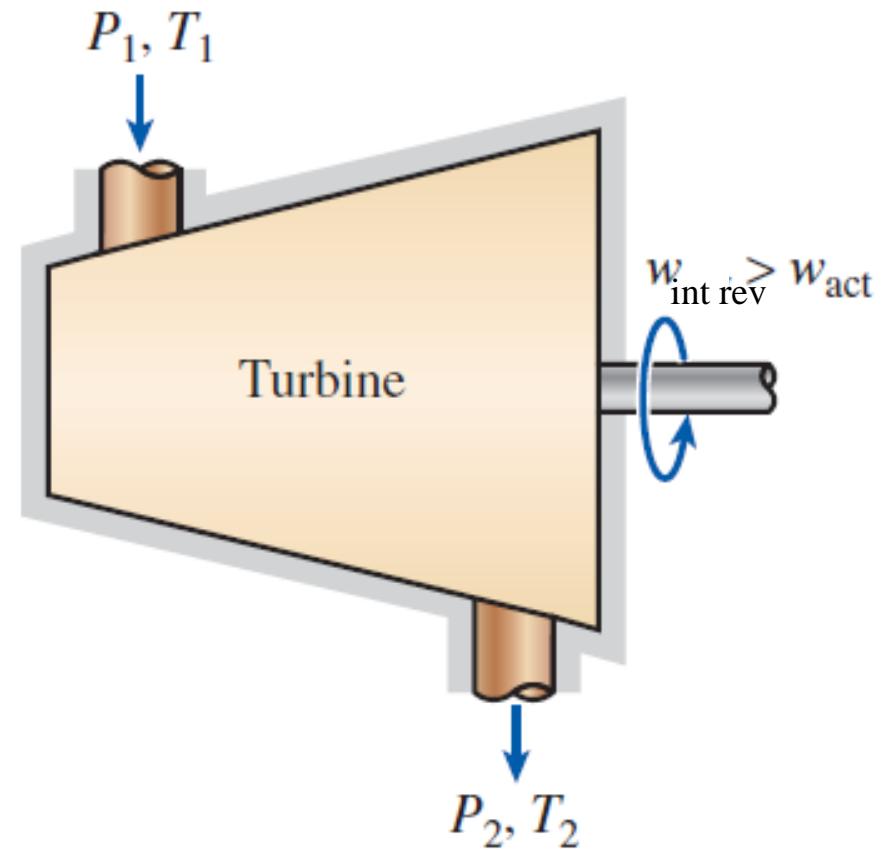


FIGURE 7–43

A reversible turbine delivers more work than an irreversible one if both operate between the same end states.

MINIMIZING THE COMPRESSOR WORK OPERATING BETWEEN THE SAME PRESSURE LEVELS P_1 and P_2

If our objective is to operate between the ***same pressure levels*** (**instead of the same end states**) then the compressor work input can be further reduced by using non-adiabatic processes so as to ***keep the specific volume of the gas as small as possible*** during the compression process

$$w_{\text{int rev, in}} = \int_1^2 v \, dP$$

if the change in kinetic and potential energies of the fluid are negligible

This can be done by maintaining the temperature of the gas as low as possible during the compression process since the specific volume of a gas is proportional to temperature

Therefore, reducing the work input to a compressor requires that the ***gas be cooled as it is compressed***

MINIMIZING THE COMPRESSOR WORK OPERATING BETWEEN THE SAME PRESSURE LEVELS P_1 and P_2

$$w_{\text{int rev, in}} = \int_1^2 v \, dP$$

if the change in kinetic and potential energies of the fluid are negligible

use $v = v(P)$ based on the process and integrate between states 1 (inlet) and 2 (exit)

Isentropic ($Pv^k = \text{constant}$, $n = k$) (no cooling):

$$w_{\text{comp,in}} = \frac{kR(T_2 - T_1)}{k - 1} = \frac{kRT_1}{k - 1} \left[\left(\frac{P_2}{P_1} \right)^{(k-1)/k} - 1 \right]$$

Polytropic ($Pv^n = \text{constant}$, $1 < n < k$) (some cooling):

$$w_{\text{comp,in}} = \frac{nR(T_2 - T_1)}{n - 1} = \frac{nRT_1}{n - 1} \left[\left(\frac{P_2}{P_1} \right)^{(n-1)/n} - 1 \right]$$

Isothermal ($Pv = \text{constant}$, $n = 1$) (high cooling):

$$w_{\text{comp,in}} = RT \ln \frac{P_2}{P_1}$$

MINIMIZING THE COMPRESSOR WORK

$$w_{\text{int rev, in}} = \int_1^2 v \, dP$$

Δke and Δpe of the fluid is neglected

On a P-v diagram, the **area to the left of the process curve** is the integral of $v \, dP$

The adiabatic compression ($Pv^k = \text{constant}$) requires the more work than the isothermal compression ($T = \text{constant}$) if the inlet state is the same and **the exit pressure is same**.

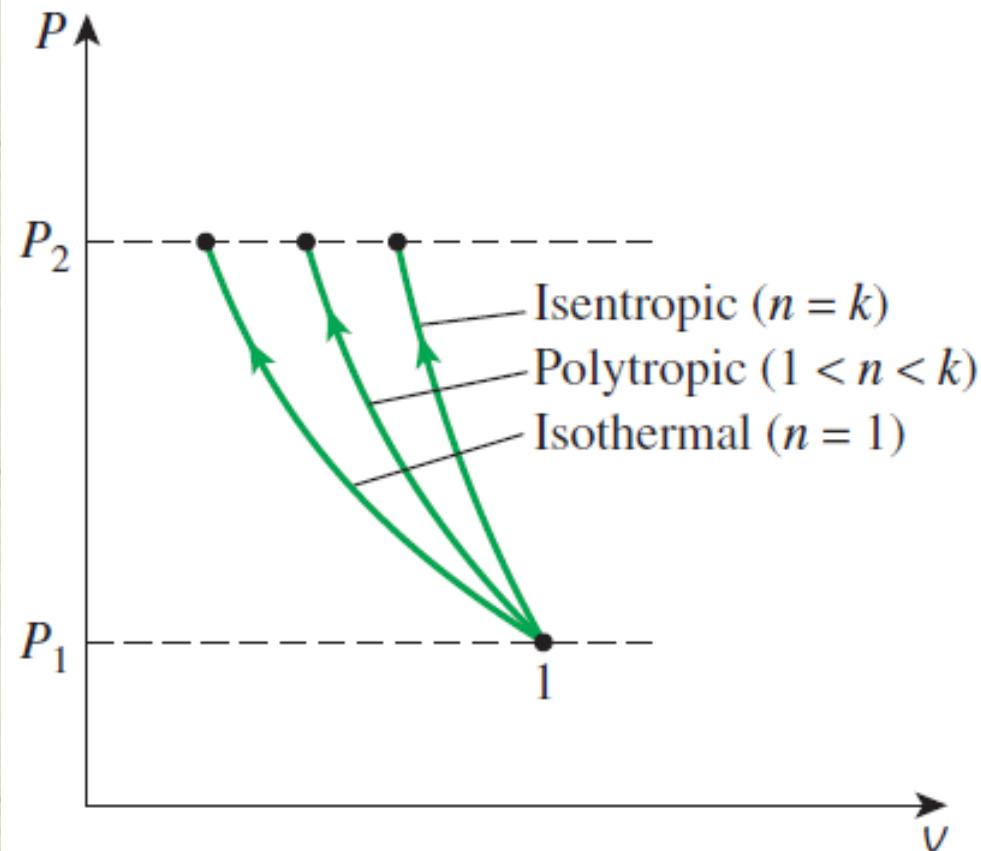


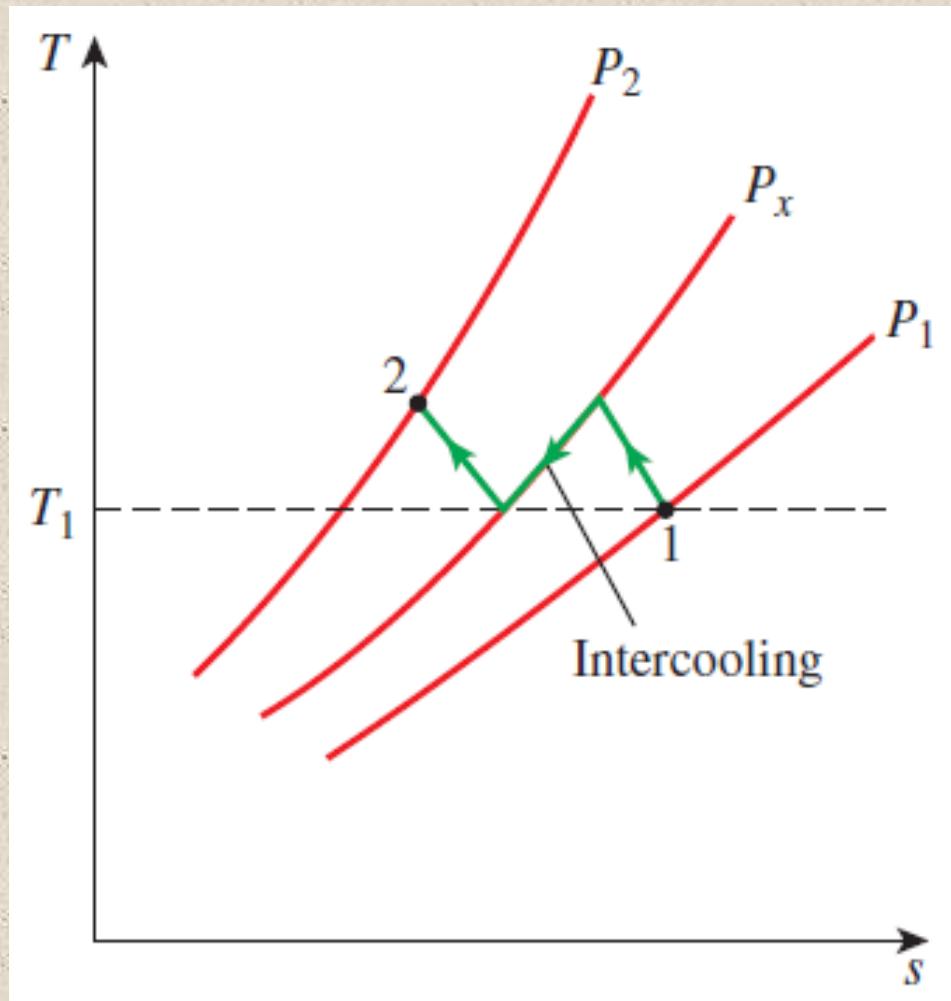
FIGURE 7-44

P-v diagrams of isentropic, polytropic, and isothermal compression processes between the same pressure limits.

Multistage Compression with Intercooling

The gas is compressed in stages and cooled between each stage by passing it through a heat exchanger called an *intercooler*

Ideally, the cooling process takes place at constant pressure, and the gas is cooled to the initial temperature T_1 at each intercooler



Multistage Compression with Intercooling

$$w_{\text{comp,in}} = w_{\text{comp I,in}} + w_{\text{comp II,in}}$$

$$= \frac{nRT_1}{n-1} \left[\left(\frac{P_x}{P_1} \right)^{(n-1)/n} - 1 \right] + \frac{nRT_1}{n-1} \left[\left(\frac{P_2}{P_x} \right)^{(n-1)/n} - 1 \right]$$

Differentiate w.r.t. P_x and set the resulting expression to zero

$$P_x = (P_1 P_2)^{1/2} \quad \text{or} \quad \frac{P_x}{P_1} = \frac{P_2}{P_x}$$

To minimize compression work during two-stage compression, the pressure ratio across each stage of the compressor must be the same

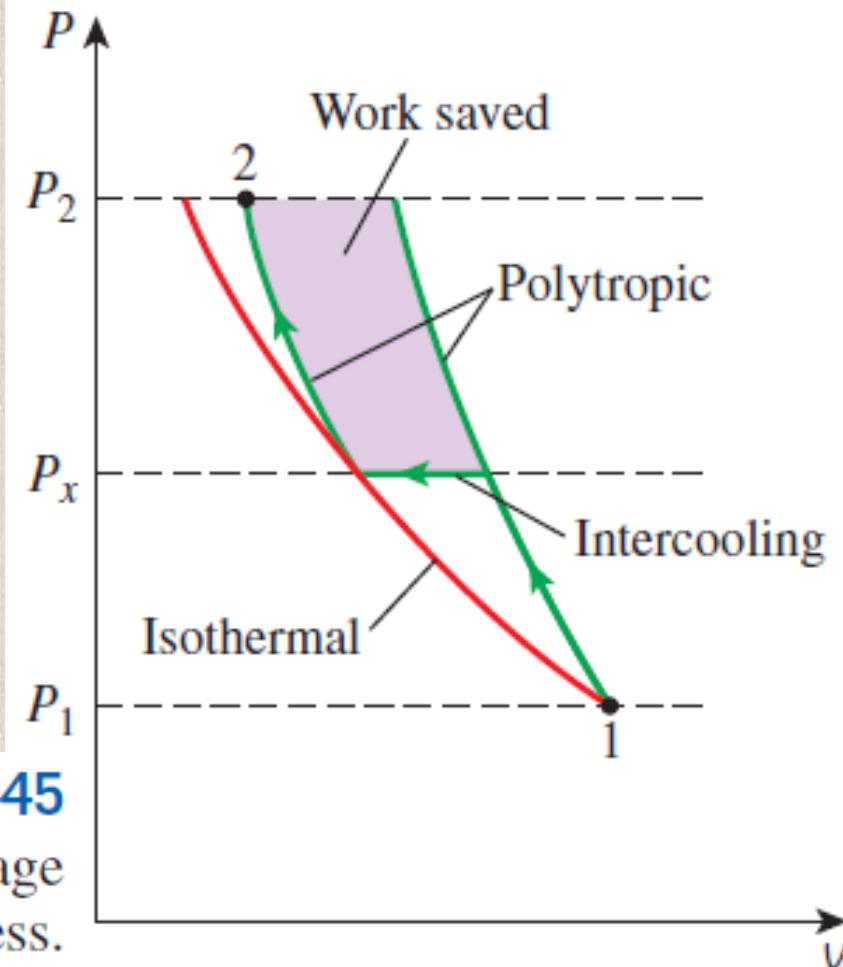


FIGURE 7-45

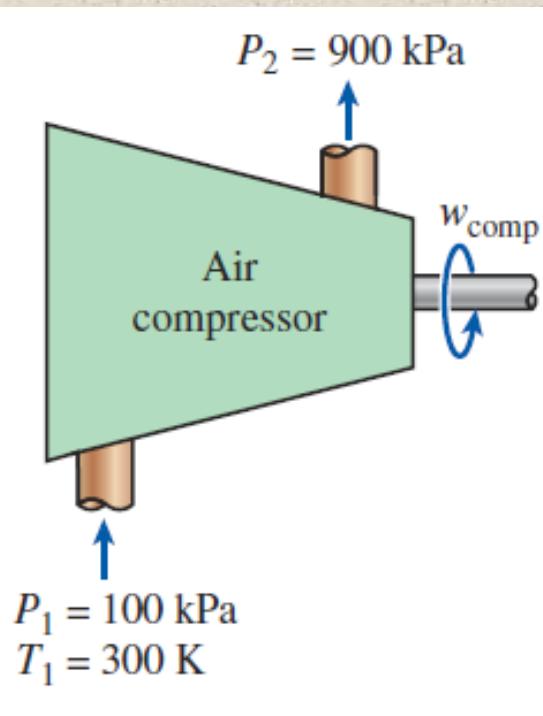
P - v and T - s diagrams for a two-stage steady-flow compression process.

Work Input for Various Compression Process

Air is compressed steadily by a reversible compressor from an inlet state of 100 kPa and 300 K to an exit pressure of 900 kPa. Determine the compressor work per unit mass for (a) isentropic compression with $k = 1.4$, (b) polytropic compression with $n = 1.3$, (c) isothermal compression, and (d) ideal two-stage compression with intercooling with a polytropic exponent of 1.3

(a) Isentropic compression with $k = 1.4$:

$$\begin{aligned} w_{\text{comp,in}} &= \frac{kRT_1}{k - 1} \left[\left(\frac{P_2}{P_1} \right)^{(k-1)/k} - 1 \right] \\ &= \frac{(1.4)(0.287 \text{ kJ/kg}\cdot\text{K})(300 \text{ K})}{1.4 - 1} \left[\left(\frac{900 \text{ kPa}}{100 \text{ kPa}} \right)^{(1.4-1)/1.4} - 1 \right] \\ &= 263.2 \text{ kJ/kg} \end{aligned}$$



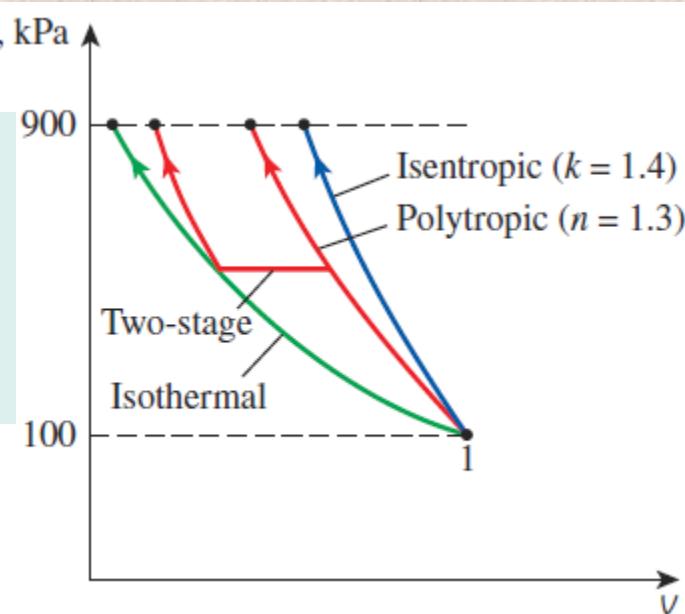
(b) Polytropic compression with $n = 1.3$:

$$\begin{aligned} w_{\text{comp,in}} &= \frac{nRT_1}{n - 1} \left[\left(\frac{P_2}{P_1} \right)^{(n-1)/n} - 1 \right] \\ &= \frac{(1.3)(0.287 \text{ kJ/kg}\cdot\text{K})(300 \text{ K})}{1.3 - 1} \left[\left(\frac{900 \text{ kPa}}{100 \text{ kPa}} \right)^{(1.3-1)/1.3} - 1 \right] \\ &= 246.4 \text{ kJ/kg} \end{aligned}$$

(c) Isothermal compression:

$$w_{\text{comp,in}} = RT \ln \frac{P_2}{P_1} = (0.287 \text{ kJ/kg}\cdot\text{K})(300 \text{ K}) \ln \frac{900 \text{ kPa}}{100 \text{ kPa}}$$

$$= \mathbf{189.2 \text{ kJ/kg}}$$



(d) Ideal two-stage compression with intercooling ($n = 1.3$): In this case, the pressure ratio across each stage is the same, and its value is

$$P_x = (P_1 P_2)^{1/2} = [(100 \text{ kPa})(900 \text{ kPa})]^{1/2} = 300 \text{ kPa}$$

The compressor work across each stage is also the same. Thus the total compressor work is twice the compression work for a single stage:

$$w_{\text{comp,in}} = 2w_{\text{comp I,in}} = 2 \frac{nRT_1}{n - 1} \left[\left(\frac{P_x}{P_1} \right)^{(n-1)/n} - 1 \right]$$

$$= \frac{2(1.3)(0.287 \text{ kJ/kg}\cdot\text{K})(300 \text{ K})}{1.3 - 1} \left[\left(\frac{300 \text{ kPa}}{100 \text{ kPa}} \right)^{(1.3-1)/1.3} - 1 \right]$$

$$= \mathbf{215.3 \text{ kJ/kg}}$$

ISENTROPIC EFFICIENCIES OF ADIABATIC STEADY-FLOW SYSTEMS

Isentropic Efficiency of Adiabatic Turbines

$$\eta_T = \frac{\text{Actual turbine work}}{\text{Isentropic turbine work}} = \frac{w_a}{w_s}$$

same inlet state and same exit pressures for the actual and ideal process

$$\eta_T \cong \frac{h_1 - h_{2a}}{h_1 - h_{2s}}$$

if the change in ke and pe of the fluid are negligible

Ideal process that serve as a suitable model for *adiabatic steady flow systems* is the *isentropic process*

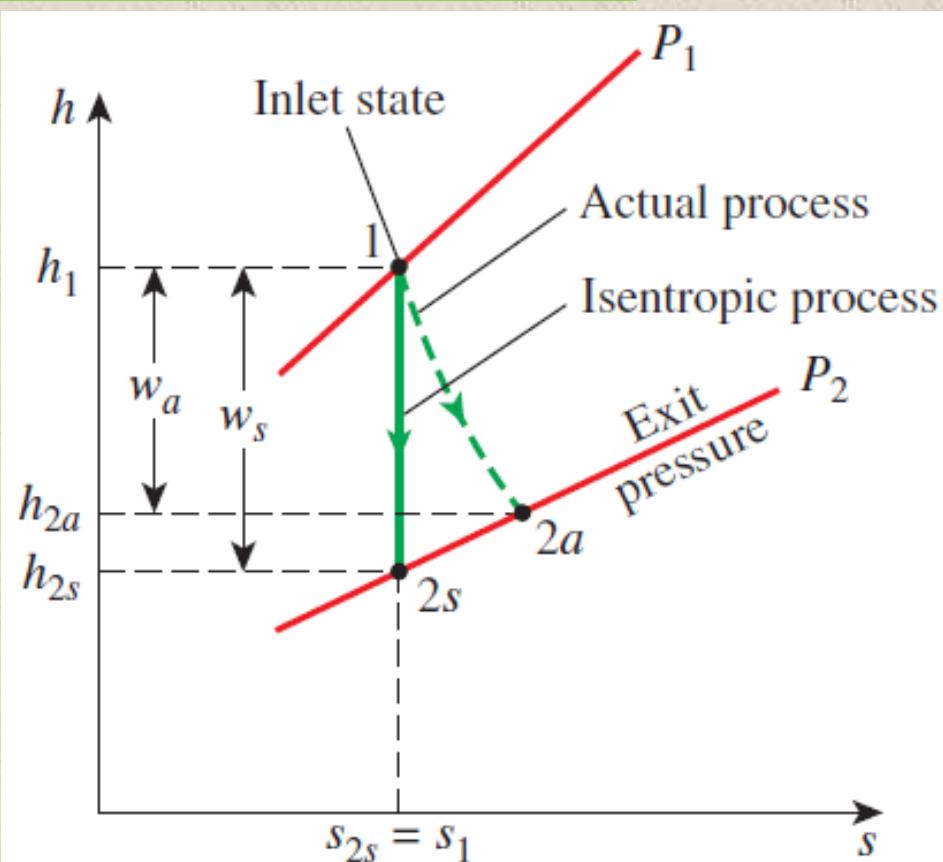
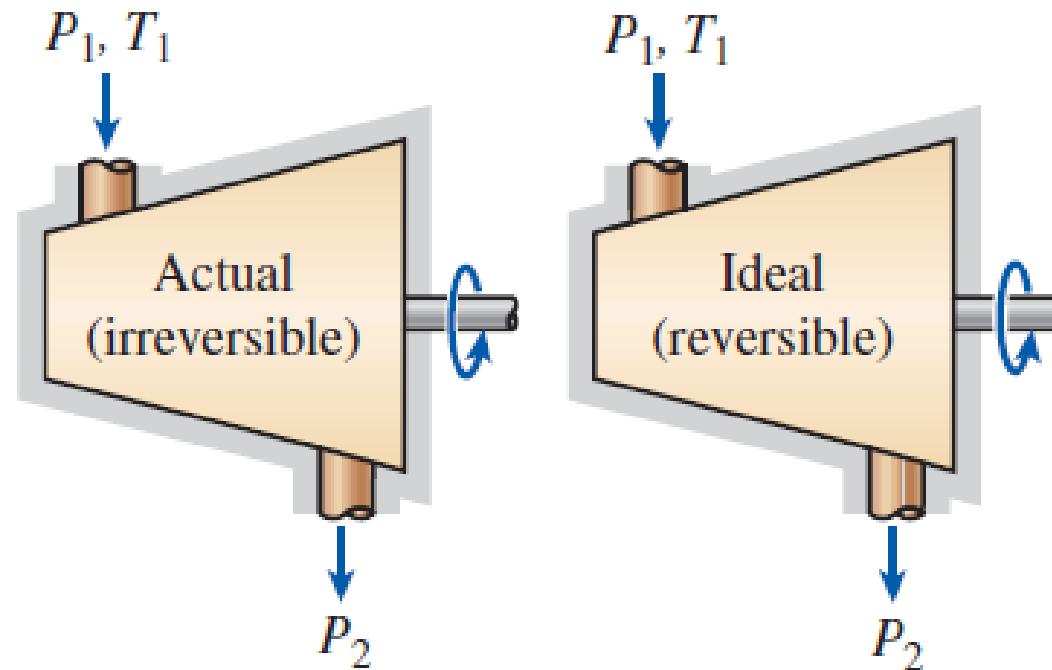


FIGURE 7–48

The *h-s* diagram for the actual and isentropic processes of an adiabatic turbine.



**same inlet state and same
exit pressure for the actual
and ideal process**

$$s_2 = s_1$$

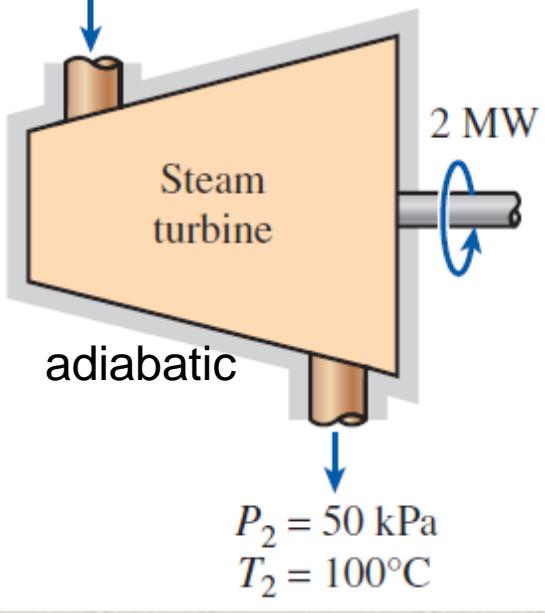
FIGURE 7–47

The isentropic process involves no irreversibilities and serves as the ideal process for adiabatic devices.

$$P_1 = 3 \text{ MPa}$$

$$T_1 = 400^\circ\text{C}$$

$$\eta_T = ?$$



State 1: $\left. \begin{array}{l} P_1 = 3 \text{ MPa} \\ T_1 = 400^\circ\text{C} \end{array} \right\} h_1 = 3231.7 \text{ kJ/kg}$

$s_1 = 6.9235 \text{ kJ/kg}\cdot\text{K}$

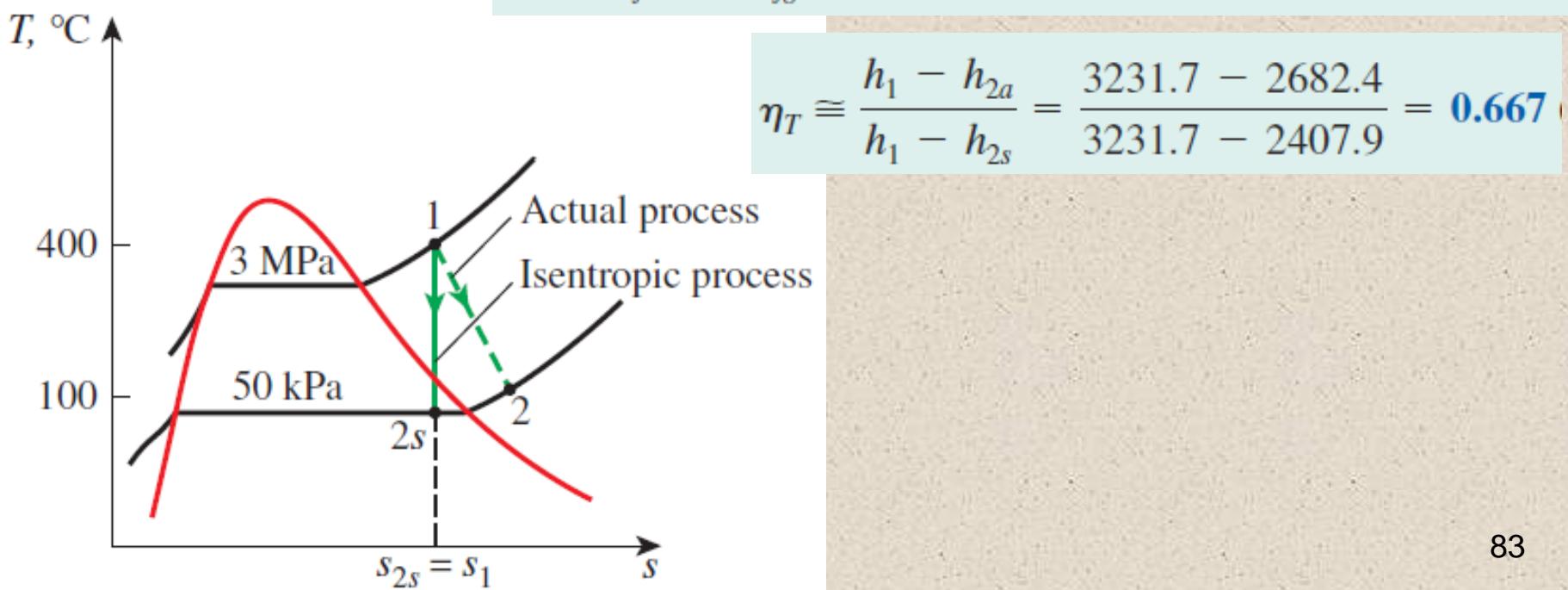
State 2a: $\left. \begin{array}{l} P_{2a} = 50 \text{ kPa} \\ T_{2a} = 100^\circ\text{C} \end{array} \right\} h_{2a} = 2682.4 \text{ kJ/kg}$

State 2s: $P_{2s} = 50 \text{ kPa}$ $\rightarrow s_f = 1.0912 \text{ kJ/kg}\cdot\text{K}$

$(s_{2s} = s_1)$ $s_g = 7.5931 \text{ kJ/kg}\cdot\text{K}$

$$x_{2s} = \frac{s_{2s} - s_f}{s_{fg}} = \frac{6.9235 - 1.0912}{6.5019} = 0.897$$

$$h_{2s} = h_f + x_{2s}h_{fg} = 340.54 + 0.897(2304.7) = 2407.9 \text{ kJ/kg}$$



$$\eta_T \equiv \frac{h_1 - h_{2a}}{h_1 - h_{2s}} = \frac{3231.7 - 2682.4}{3231.7 - 2407.9} = \mathbf{0.667}$$

TABLE A-6

Superheated water (*Concluded*)

T °C	v m ³ /kg	u kJ/kg	h kJ/kg	s kJ/kg·K
$P = 0.05 \text{ MPa} (81.32^\circ\text{C})$				
Sat. [†]	3.2403	2483.2	2645.2	7.5931
50				
100	3.4187	2511.5	2682.4	7.6953
150	3.8897	2585.7	2780.2	7.9413
200	4.3562	2660.0	2877.8	8.1592
250	4.8206	2735.1	2976.2	8.3568
300	5.2841	2811.6	3075.8	8.5387
400	6.2094	2968.9	3279.3	8.8659
500	7.1338	3132.6	3489.3	9.1566
600	8.0577	3303.1	3706.0	9.4201
700	8.9813	3480.6	3929.7	9.6626
800	9.9047	3665.2	4160.4	9.8883
900	10.8280	3856.8	4398.2	10.1000
1000	11.7513	4055.2	4642.7	10.3000
1100	12.6745	4259.9	4893.7	10.4897
1200	13.5977	4470.8	5150.7	10.6704
1300	14.5209	4687.3	5413.3	10.8429

T °C	v m ³ /kg	u kJ/kg	h kJ/kg	s kJ/kg·K
$P = 3.00 \text{ MPa} (233.85^\circ\text{C})$				
Sat.	0.06667	2603.2	2803.2	6.1856
225				
250	0.07063	2644.7	2856.5	6.2893
300	0.08118	2750.8	2994.3	6.5412
350	0.09056	2844.4	3116.1	6.7450
400	0.09938	2933.6	3231.7	6.9235
450	0.10789	3021.2	3344.9	7.0856
500	0.11620	3108.6	3457.2	7.2359
600	0.13245	3285.5	3682.8	7.5103
700	0.14841	3467.0	3912.2	7.7590
800	0.16420	3654.3	4146.9	7.9885
900	0.17988	3847.9	4387.5	8.2028
1000	0.19549	4047.7	4634.2	8.4045
1100	0.21105	4253.6	4886.7	8.5955
1200	0.22658	4465.3	5145.1	8.7771
1300	0.24207	4682.6	5408.8	8.9502

TABLE A-5

Saturated water—Pressure table

Press., <i>P</i> kPa	Specific volume, m ³ /kg		Internal energy, kJ/kg			Enthalpy, kJ/kg			Entropy, kJ/kg·K			
	Sat. temp., <i>T_{sat}</i> °C	Sat. liquid, <i>v_f</i>	Sat. vapor, <i>v_g</i>	Sat. liquid, <i>u_f</i>	Sat. Evap., <i>u_{fg}</i>	Sat. vapor, <i>u_g</i>	Sat. liquid, <i>h_f</i>	Sat. Evap., <i>h_{fg}</i>	Sat. vapor, <i>h_g</i>	Sat. liquid, <i>s_f</i>	Sat. Evap., <i>s_{fg}</i>	Sat. vapor, <i>s_g</i>
1.0	6.97	0.001000	129.19	29.302	2355.2	2384.5	29.303	2484.4	2513.7	0.1059	8.8690	8.9749
1.5	13.02	0.001001	87.964	54.686	2338.1	2392.8	54.688	2470.1	2524.7	0.1956	8.6314	8.8270
2.0	17.50	0.001001	66.990	73.431	2325.5	2398.9	73.433	2459.5	2532.9	0.2606	8.4621	8.7227
2.5	21.08	0.001002	54.242	88.422	2315.4	2403.8	88.424	2451.0	2539.4	0.3118	8.3302	8.6421
3.0	24.08	0.001003	45.654	100.98	2306.9	2407.9	100.98	2443.9	2544.8	0.3543	8.2222	8.5765
4.0	28.96	0.001004	34.791	121.39	2293.1	2414.5	121.39	2432.3	2553.7	0.4224	8.0510	8.4734
5.0	32.87	0.001005	28.185	137.75	2282.1	2419.8	137.75	2423.0	2560.7	0.4762	7.9176	8.3938
7.5	40.29	0.001008	19.233	168.74	2261.1	2429.8	168.75	2405.3	2574.0	0.5763	7.6738	8.2501
10	45.81	0.001010	14.670	191.79	2245.4	2437.2	191.81	2392.1	2583.9	0.6492	7.4996	8.1488
15	53.97	0.001014	10.020	225.93	2222.1	2448.0	225.94	2372.3	2598.3	0.7549	7.2522	8.0071
20	60.06	0.001017	7.6481	251.40	2204.6	2456.0	251.42	2357.5	2608.9	0.8320	7.0752	7.9073
25	64.96	0.001020	6.2034	271.93	2190.4	2462.4	271.96	2345.5	2617.5	0.8932	6.9370	7.8302
30	69.09	0.001022	5.2287	289.24	2178.5	2467.7	289.27	2335.3	2624.6	0.9441	6.8234	7.7675
40	75.86	0.001026	3.9933	317.58	2158.8	2476.3	317.62	2318.4	2636.1	1.0261	6.6430	7.6691
50	81.32	0.001030	3.2403	340.49	2142.7	2483.2	340.54	2304.7	2645.2	1.0912	6.5019	7.5931

Isentropic Efficiencies of Adiabatic Compressors and Pumps

$$\eta_c = \frac{\text{Isentropic compressor work}}{\text{Actual compressor work}} = \frac{w_s}{w_a}$$

same inlet state and same exit pressure
for the actual and ideal process

if the change in k_e and p_e of
the fluid are negligible

$$\eta_c \approx \frac{h_{2s} - h_1}{h_{2a} - h_1} \quad \text{for a compressor}$$

$$\eta_p = \frac{w_s}{w_a} = \frac{v(P_2 - P_1)}{h_{2a} - h_1} \quad \text{for a pump}$$

Ideal process that serve as a
suitable model for *adiabatic*
steady flow systems is the
isentropic process

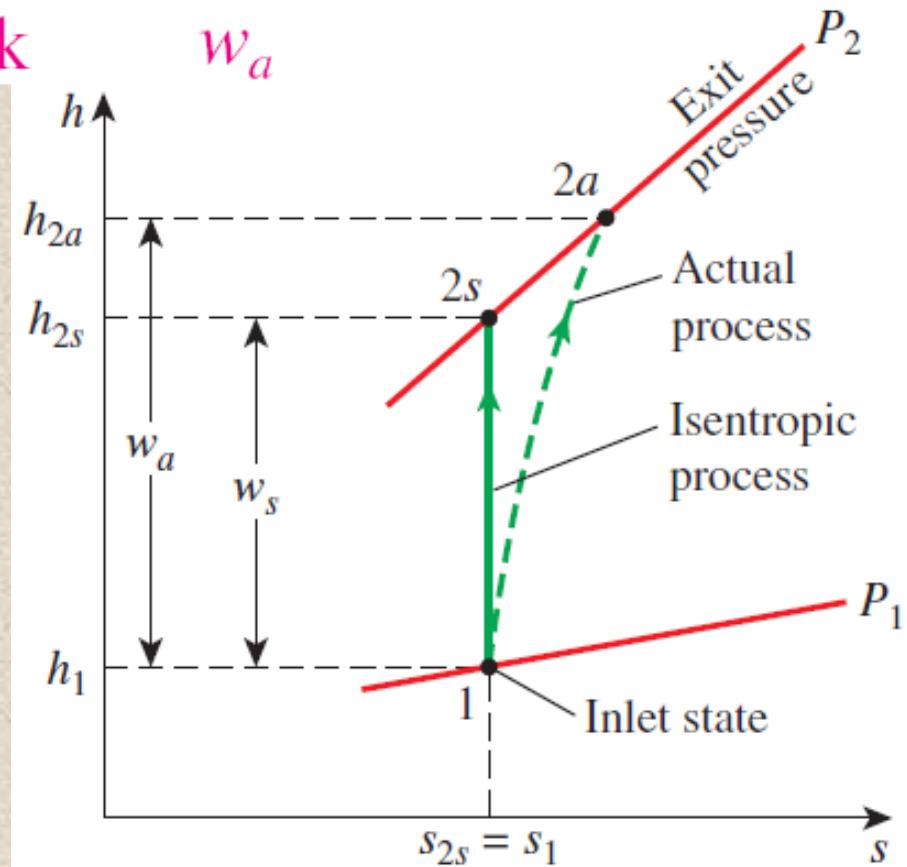


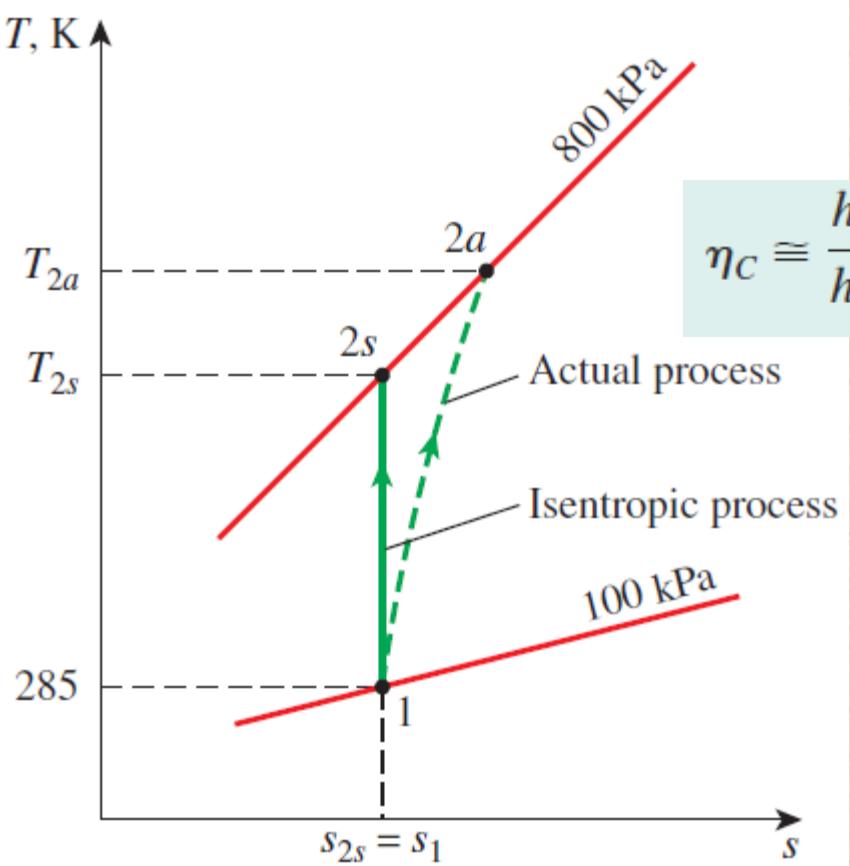
FIGURE 7-50

The *h-s* diagram of the actual and isentropic processes of an adiabatic compressor.

$$T_1 = 285 \text{ K} \rightarrow h_1 = 285.14 \text{ kJ/kg} \\ (P_{r1} = 1.1584)$$

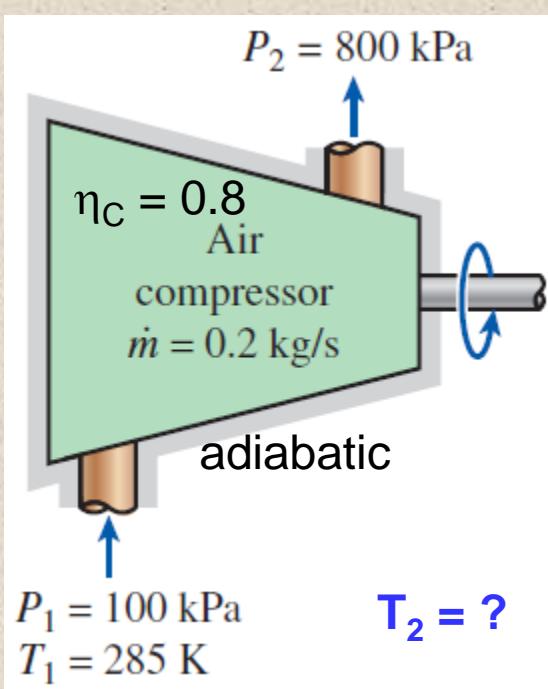
$$P_{r2} = P_{r1} \left(\frac{P_2}{P_1} \right) = 1.1584 \left(\frac{800 \text{ kPa}}{100 \text{ kPa}} \right) = 9.2672$$

$$P_{r2} = 9.2672 \rightarrow h_{2s} = 517.05 \text{ kJ/kg}$$



$$\eta_C \equiv \frac{h_{2s} - h_1}{h_{2a} - h_1} \rightarrow 0.80 = \frac{(517.05 - 285.14) \text{ kJ/kg}}{(h_{2a} - 285.14) \text{ kJ/kg}}$$

$$h_{2a} = 575.03 \text{ kJ/kg} \rightarrow T_{2a} = \mathbf{569.5 \text{ K}}$$



$$\mathbf{T_2 = ?}$$

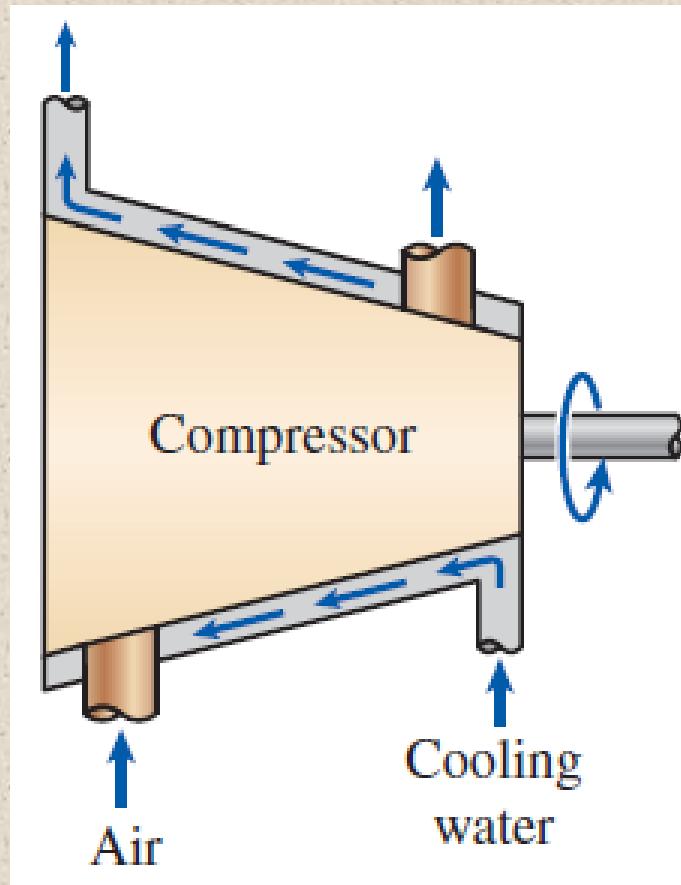
TABLE A-17

Ideal-gas properties of air

<i>T</i> K	<i>h</i> kJ/kg	<i>P_r</i>	<i>u</i> kJ/kg	<i>v_r</i>	<i>s^o</i> kJ/kg·K
250	250.05	0.7329	178.28	979.0	1.51917
260	260.09	0.8405	185.45	887.8	1.55848
270	270.11	0.9590	192.60	808.0	1.59634
280	280.13	1.0889	199.75	738.0	1.63279
285	285.14	1.1584	203.33	706.1	1.65055
290	290.16	1.2311	206.91	676.1	1.66802
295	295.17	1.3068	210.49	647.9	1.68515
298	298.18	1.3543	212.64	631.9	1.69528
300	300.19	1.3860	214.07	621.2	1.70203
305	305.22	1.4686	217.67	596.0	1.71865
490	492.74	7.824	352.08	179.7	2.19876
500	503.02	8.411	359.49	170.6	2.21952
510	513.32	9.031	366.92	162.1	2.23993
520	523.63	9.684	374.36	154.1	2.25997
530	533.98	10.37	381.84	146.7	2.27967
540	544.35	11.10	389.34	139.7	2.29906
550	555.74	11.86	396.86	133.1	2.31809
560	565.17	12.66	404.42	127.0	2.33685
570	575.59	13.50	411.97	121.2	2.35531

In case of cooling, the isentropic efficiency is not suitable as the model process since the ***device is not longer adiabatic*** and the isentropic compressor efficiency as defined is meaningless

A realistic model process for compressors that are intentionally cooled during the compression process is the ***reversible isothermal process***



compressors are sometimes intentionally cooled to minimize the work input

$$\eta_c = \frac{w_t}{w_a} \text{ isothermal efficiency}$$

where w_t and w_a are the required work inputs to the compressor for the reversible isothermal and actual cases

Isentropic Efficiency of Adiabatic Nozzles

$$\eta_N = \frac{\text{Actual KE at nozzle exit}}{\text{Isentropic KE at nozzle exit}} = \frac{V_{2a}^2}{V_{2s}^2}$$

same inlet state and same exit pressure
for the actual and ideal process

If the inlet velocity of the fluid is
small relative to the exit velocity,
the energy balance is

$$h_1 = h_{2a} + \frac{V_{2a}^2}{2} \quad \text{if the change in pe of the fluid is negligible}$$

$$\eta_N \equiv \frac{h_1 - h_{2a}}{h_1 - h_{2s}}$$

Ideal process that serve as a suitable model for *adiabatic steady flow systems* is the **isentropic process**

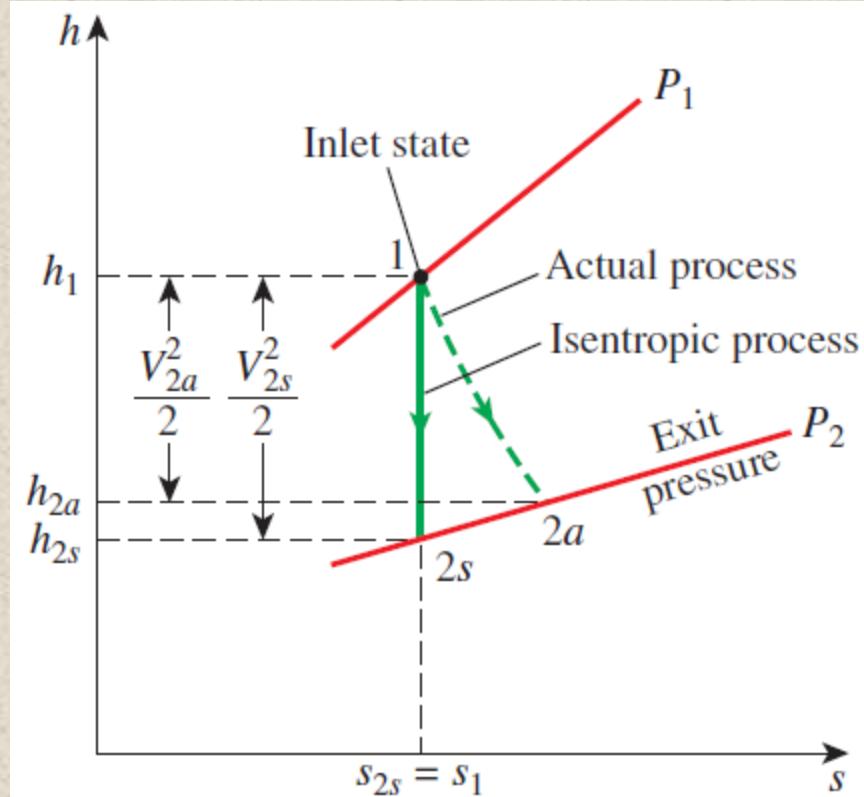
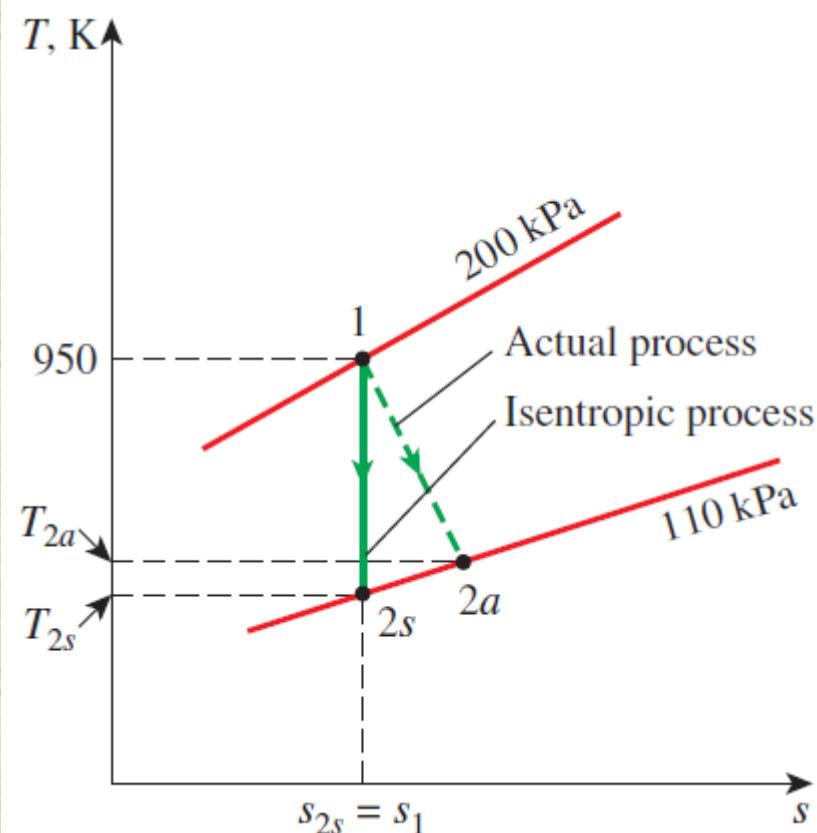


FIGURE 7–53

The *h-s* diagram of the actual and isentropic processes of an adiabatic nozzle.



$$T_{2s} = T_1 \left(\frac{P_{2s}}{P_1} \right)^{(k-1)/k} = (950 \text{ K}) \left(\frac{110 \text{ kPa}}{200 \text{ kPa}} \right)^{0.349/1.349} = 814 \text{ K}$$

$$h_1 + \frac{V_1^2}{2} = h_{2s} + \frac{V_{2s}^2}{2}$$

$$\begin{aligned} V_{2s} &= \sqrt{2(h_1 - h_{2s})} = \sqrt{2c_{p,\text{avg}}(T_1 - T_{2s})} \\ &= \sqrt{2(1.11 \text{ kJ/kg}\cdot\text{K})(950 - 814) \text{ K}} \left(\frac{1000 \text{ m}^2/\text{s}^2}{1 \text{ kJ/kg}} \right) \\ &= 549 \text{ m/s} \end{aligned}$$

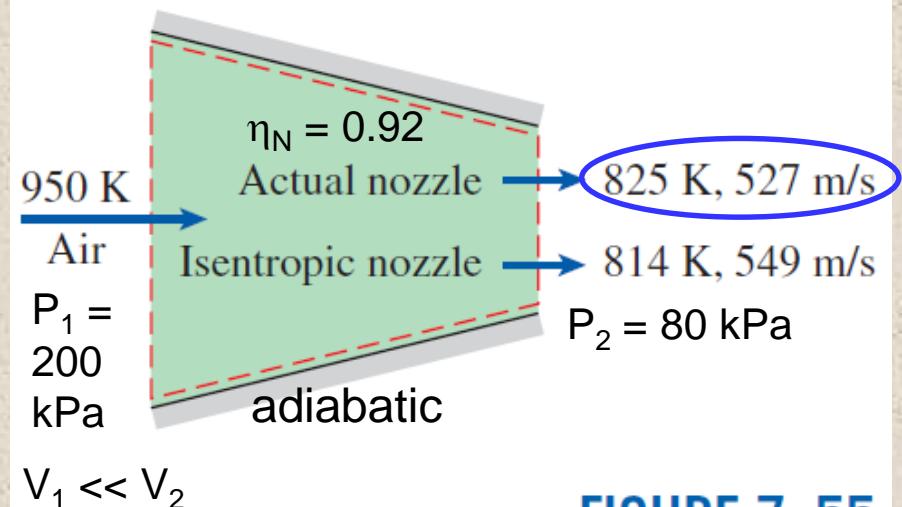


FIGURE 7–55
A substance leaves actual nozzles at a higher temperature (thus a lower velocity) as a result of friction.

$$\eta_N \equiv \frac{h_1 - h_{2a}}{h_1 - h_{2s}} = \frac{c_{p,\text{avg}}(T_1 - T_{2a})}{c_{p,\text{avg}}(T_1 - T_{2s})}$$

$$0.92 = \frac{950 - T_{2a}}{950 - 814} \rightarrow T_{2a} = 825 \text{ K}$$

$$\eta_N = \frac{V_{2a}^2}{V_{2s}^2}$$

$$V_{2a} = \sqrt{\eta_N V_{2s}^2} = \sqrt{0.92(549 \text{ m/s})^2} = 527 \text{ m/s}$$

TABLE A-2

Ideal-gas specific heats of various common gases

(b) At various temperatures

Temperature, K	c_p kJ/kg·K	c_v kJ/kg·K	k
<i>Air</i>			
250	1.003	0.716	1.401
300	1.005	0.718	1.400
350	1.008	0.721	1.398
400	1.013	0.726	1.395
450	1.020	0.733	1.391
500	1.029	0.742	1.387
550	1.040	0.753	1.381
600	1.051	0.764	1.376
650	1.063	0.776	1.370
700	1.075	0.788	1.364
750	1.087	0.800	1.359
800	1.099	0.812	1.354
800	1.121	0.834	1.344
1000	1.142	0.855	1.336

Guessed averaged
temperature = 850 K
so that constant
value of c_p and k can
be used at that
temperature



ENTROPY BALANCE

$$\left(\begin{array}{l} \text{Total} \\ \text{entropy} \\ \text{entering} \end{array} \right) - \left(\begin{array}{l} \text{Total} \\ \text{entropy} \\ \text{leaving} \end{array} \right) + \left(\begin{array}{l} \text{Total} \\ \text{entropy} \\ \text{generated} \end{array} \right) = \left(\begin{array}{l} \text{Change in the} \\ \text{total entropy} \\ \text{of the system} \end{array} \right)$$

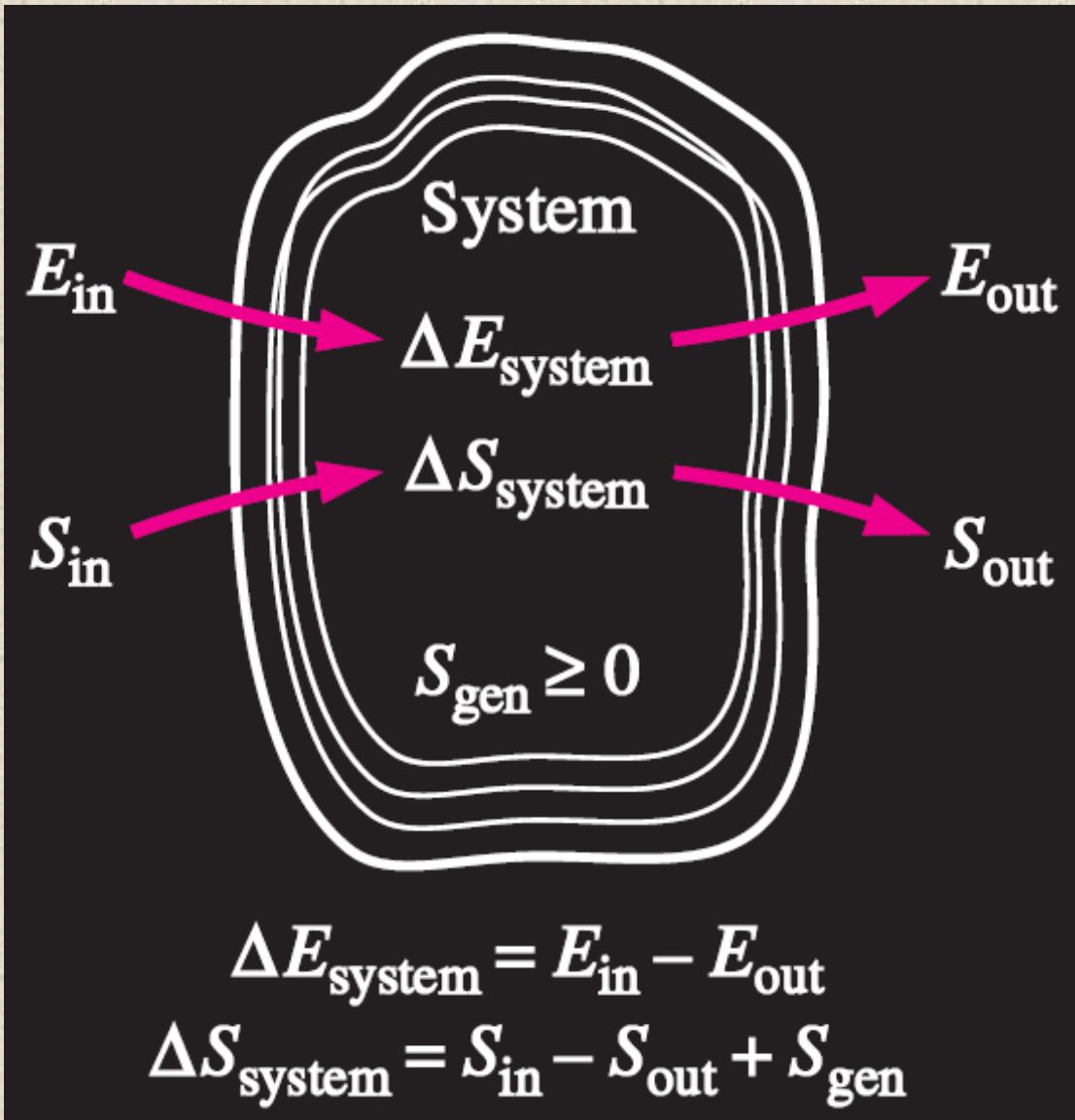
$$S_{\text{in}} - S_{\text{out}} + S_{\text{gen}} = \Delta S_{\text{system}}$$

Entropy Change of a System, ΔS_{system}

$$\Delta S_{\text{system}} = S_{\text{final}} - S_{\text{initial}} = S_2 - S_1$$

When the properties of the system are not uniform

$$S_{\text{system}} = \int s \, \delta m = \int_V s \rho \, dV$$



Mechanisms of Entropy Transfer, S_{in} and S_{out}

Entropy transfer by heat transfer:

$$S_{\text{heat}} = \frac{Q}{T} \quad (T = \text{constant})$$

$$S_{\text{heat}} = \int_1^2 \frac{\delta Q}{T} \cong \sum \frac{Q_k}{T_k}$$

Q_k is the heat transfer through the boundary at temperature T_k at location k

Heat is in essence, a form of disorganized energy, and some disorganization (entropy) will flow with heat

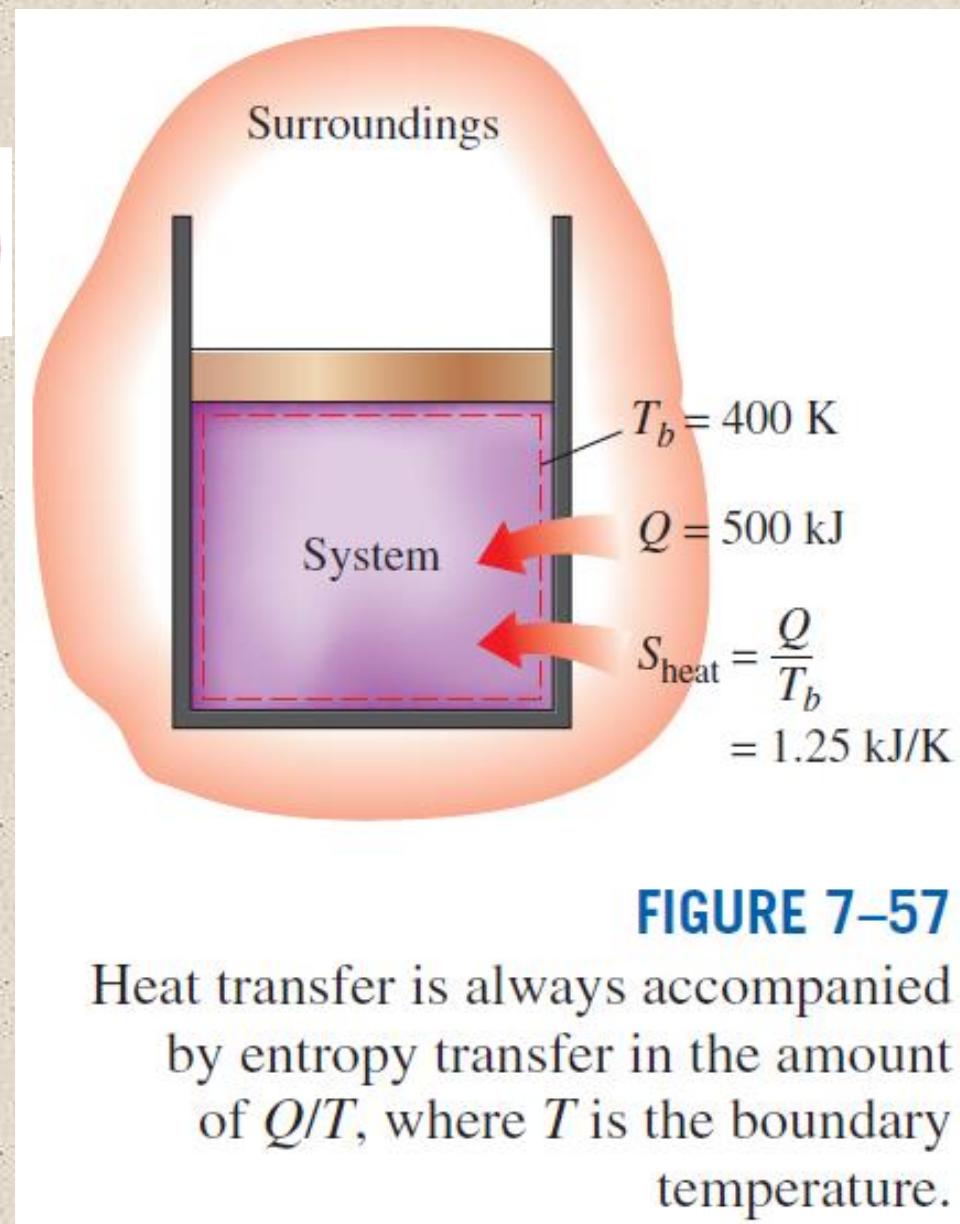
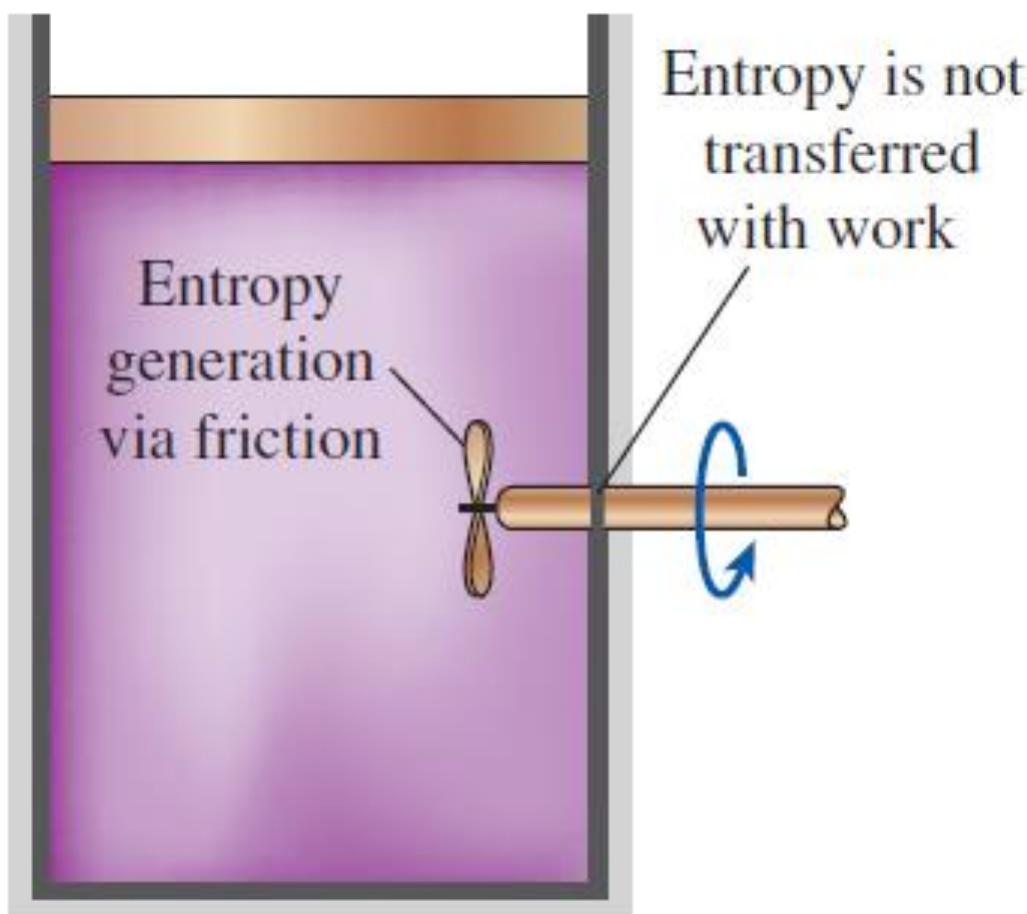


FIGURE 7–57
Heat transfer is always accompanied by entropy transfer in the amount of Q/T , where T is the boundary temperature.

Mechanisms of Entropy Transfer, S_{in} and S_{out}

Entropy transfer by work:

$$S_{\text{work}} = 0$$



For a closed system energy is transferred by both heat and work, whereas **entropy is transferred only by heat**

No entropy accompanies work as it crosses the system boundary. Hence, **no entropy is transferred by work**

But entropy may be generated within the system as work is dissipated into a less useful form of energy

Mechanisms of Entropy Transfer, S_{in} and S_{out}

Entropy transfer by mass flow:

$$\dot{S}_{\text{mass}} = \dot{m}s$$

Entropy is carried into or out of a system by streams of matter as they cross the system boundary

When the properties of the mass change during the process

$$\dot{S}_{\text{mass}} = \int_{A_c} s\rho V_n dA_c$$

$$S_{\text{mass}} = \int s \delta m = \int_{\Delta t} \dot{S}_{\text{mass}} dt$$

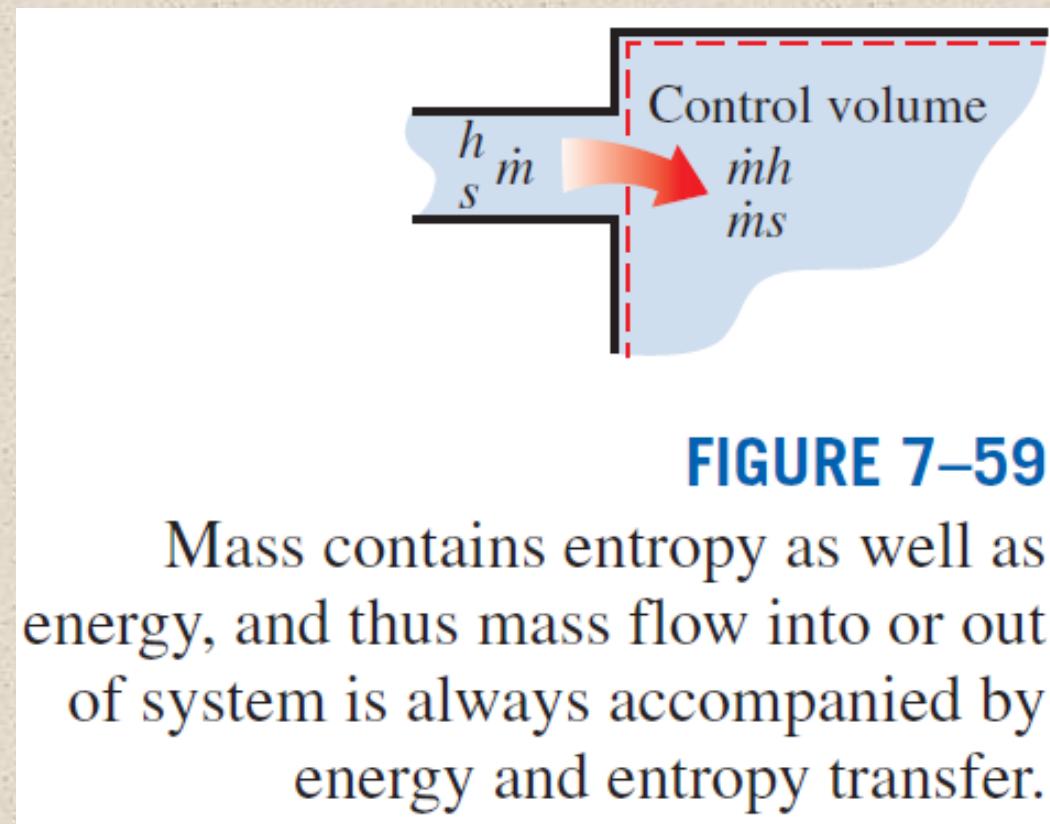
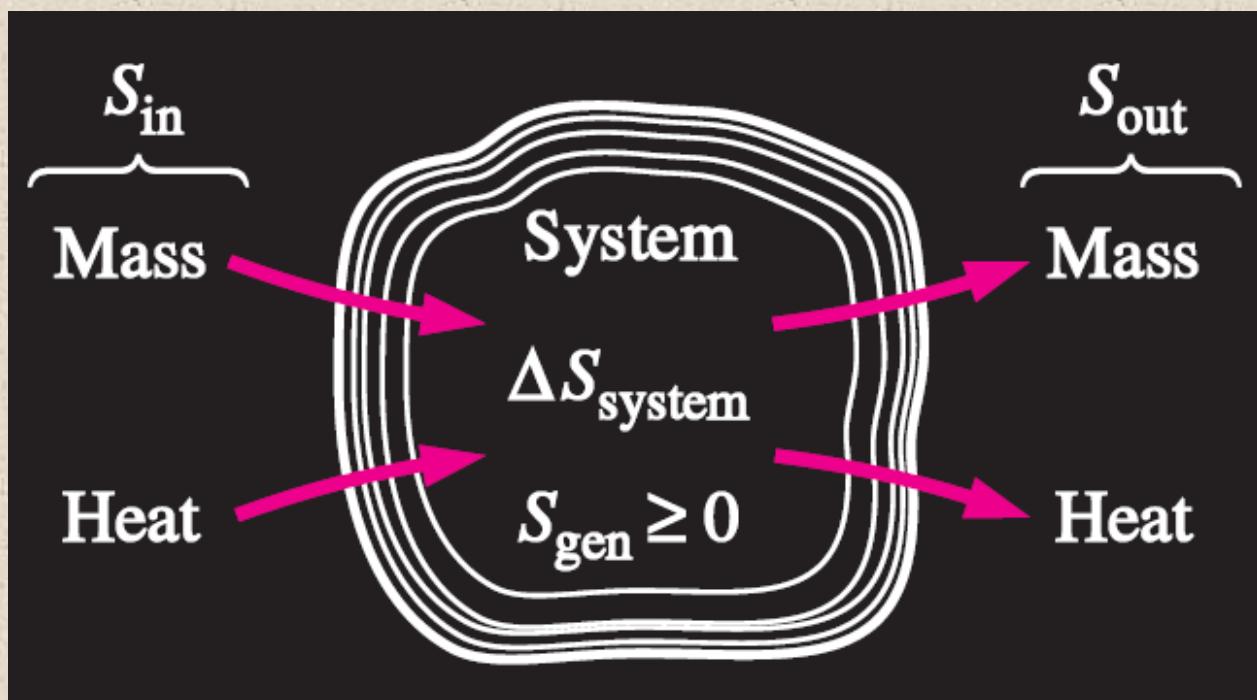


FIGURE 7–59

Mass contains entropy as well as energy, and thus mass flow into or out of system is always accompanied by energy and entropy transfer.



Entropy Balance

- For **any system** undergoing **any process**

$$\underbrace{S_{in} - S_{out}}_{\text{Net entropy transfer by heat and mass}} + \underbrace{S_{gen}}_{\text{Entropy generation}} = \underbrace{\Delta S_{system}}_{\text{Change in entropy}} \quad (\text{kJ/K})$$

$$\underbrace{\dot{S}_{in} - \dot{S}_{out}}_{\text{Rate of net entropy transfer by heat and mass}} + \underbrace{\dot{S}_{gen}}_{\text{Rate of entropy generation}} = \underbrace{dS_{system}/dt}_{\text{Rate of change in entropy}} \quad (\text{kW/K})$$

$$(S_{in} - S_{out}) + s_{gen} = \Delta s_{system} \quad (\text{kJ/kg} \cdot \text{K})$$

- The entropy generation term (**e.g.** S_{gen}) represents **entropy generation within the system boundaries** and it is due to irreversibilities present within the system

Entropy Generation, S_{gen}

- **Irreversibilities** such as friction, mixing, chemical reactions, heat transfer through finite temperature difference, unrestrained expansion, nonquasi-equilibrium compression or expansion, **always causes the entropy of a system to increase**, and entropy generation is a measure of entropy created by such effects during a process
- For an **internally reversible process** (a process that involves no irreversibilities within the system boundaries), **the entropy generation within the system is zero** and thus the entropy change of a system is equal to the entropy transfer
- The entropy transfer by heat Q/T is zero for adiabatic systems, and the entropy transfer by mass m_s is zero for closed systems

Closed Systems

$$\Delta S_{\text{system}} = m(s_2 - s_1)$$

Closed system:

$$\sum \underbrace{\frac{Q_k}{T_k}}_{\text{entropy transfer by heat}} + \underbrace{S_{\text{gen}}}_{\text{entropy generation}} = \Delta S_{\text{system}} = \underbrace{s_2 - s_1}_{\text{entropy change}} \quad (\text{kJ/K})$$

The entropy change of a closed system during a process is equal to the sum of the net entropy transferred through the system boundary by heat transfer and the entropy generated within the system boundaries

Adiabatic closed system: $(Q = 0)$ $S_{\text{gen}} = \Delta S_{\text{adiabatic system}}$

System + Surroundings:

Isolated System: $(Q = 0)$

$$S_{\text{gen}} = \sum \Delta S = \Delta S_{\text{system}} + \Delta S_{\text{surroundings}}$$



System + Surroundings

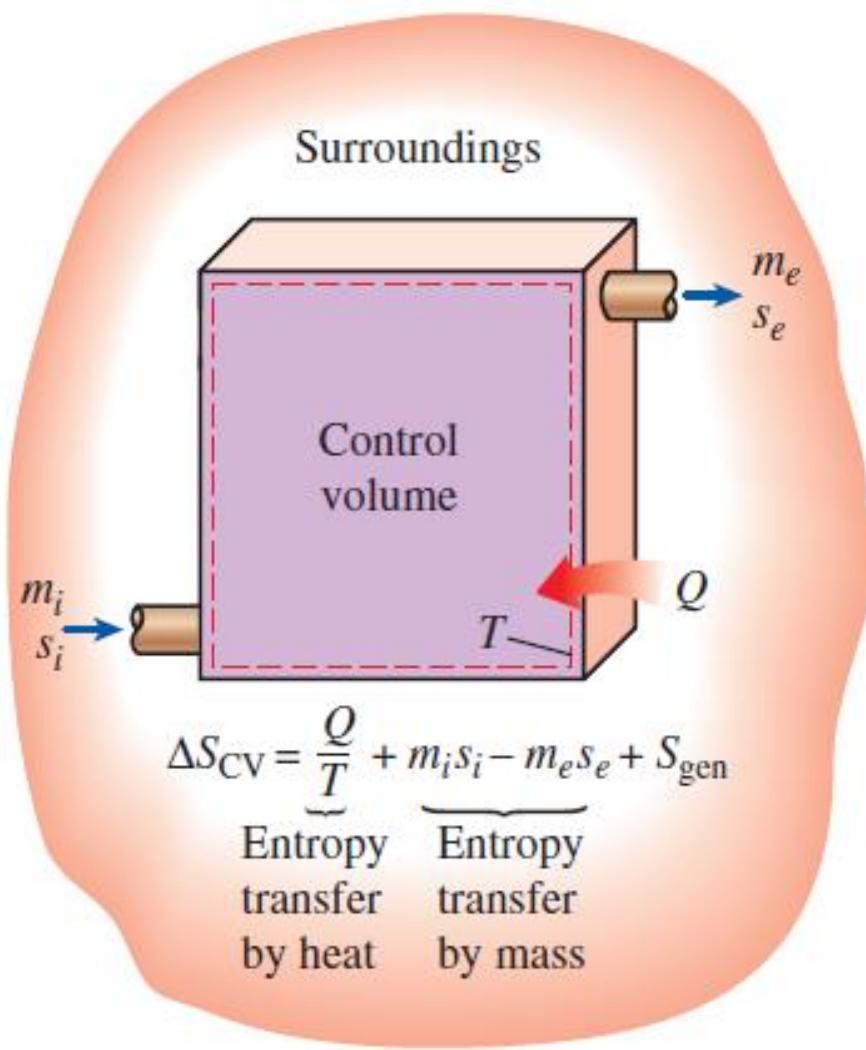


FIGURE 7–62

The entropy of a control volume changes as a result of mass flow as well as heat transfer.

Control Volumes

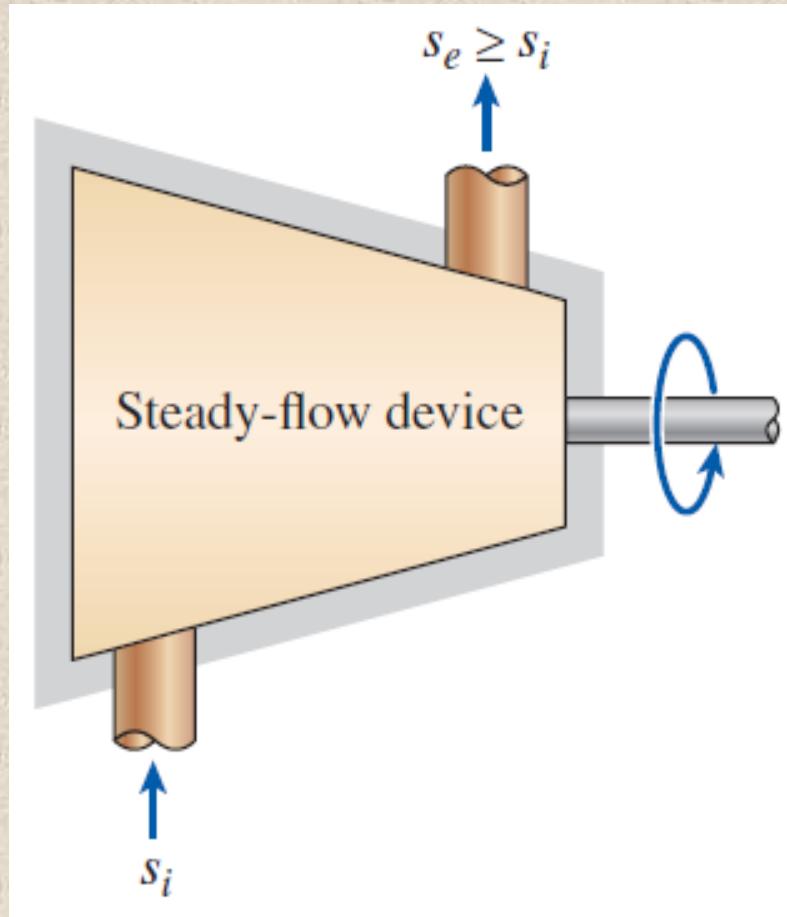
$$\sum \underbrace{\frac{\dot{Q}_k}{T_k}}_{\text{entropy transfer by heat}} + \sum \underbrace{m_i s_i - m_e s_e}_{\text{entropy transfer by mass flow}} + \underbrace{S_{\text{gen}}}_{\text{entropy generation}} = (S_2 - S_1)_{\text{CV}} \quad (\text{kJ/K})$$

$$\sum \frac{\dot{Q}_k}{T_k} + \sum \dot{m}_i s_i - \sum \dot{m}_e s_e + \dot{S}_{\text{gen}} = dS_{\text{CV}}/dt \quad (\text{kW/K})$$

Steady-flow: $\dot{S}_{\text{gen}} = \sum \dot{m}_e s_e - \sum \dot{m}_i s_i - \sum \frac{\dot{Q}_k}{T_k}$

Steady-flow, single-stream: $\dot{S}_{\text{gen}} = \dot{m}(s_e - s_i) - \sum \frac{\dot{Q}_k}{T_k}$

Steady-flow, single-stream, adiabatic: $\dot{S}_{\text{gen}} = \dot{m}(s_e - s_i)$



The entropy of a substance always increases (or remains constant in the case of a reversible process) as it flows through a single-stream, adiabatic, steady-flow system

Entropy balance for heat transfer through a wall

Determine the rate of entropy generation in the wall, and the rate of total entropy generation associated with this heat transfer process

Analysis We first take the *wall* as the system

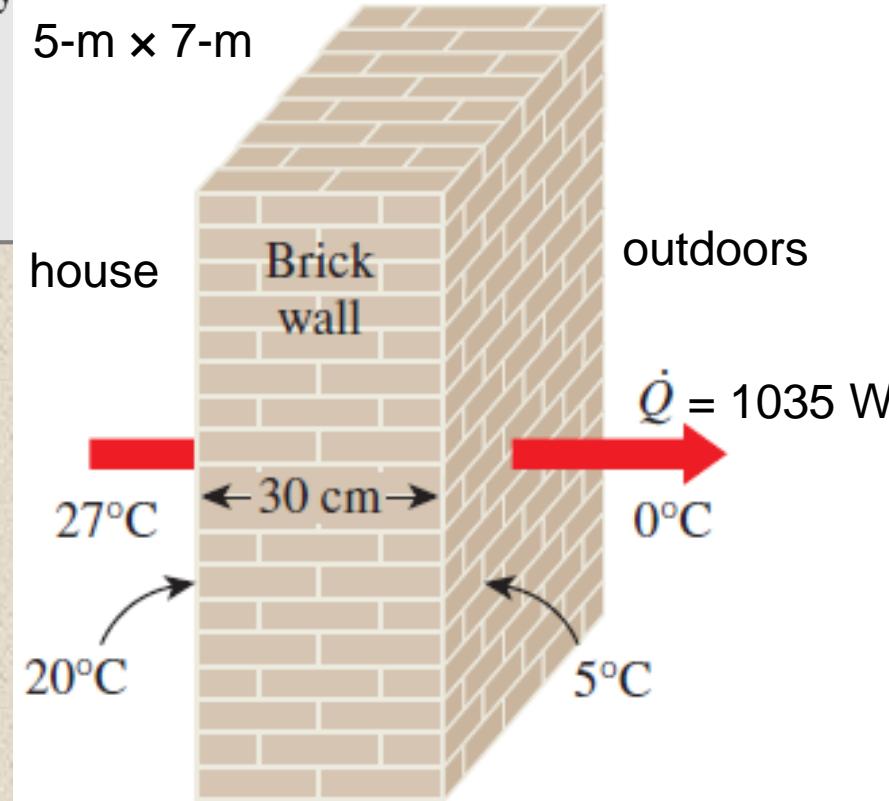
$$\underbrace{\dot{S}_{\text{in}} - \dot{S}_{\text{out}}}_{\text{Rate of net entropy transfer by heat and mass}} + \underbrace{\dot{S}_{\text{gen}}}_{\text{Rate of entropy generation}} = \underbrace{\frac{dS_{\text{system}}}{dt}}_{\substack{0 \text{ (steady)} \\ \text{Rate of change in entropy}}}$$

$$\left(\frac{\dot{Q}}{T}\right)_{\text{in}} - \left(\frac{\dot{Q}}{T}\right)_{\text{out}} + \dot{S}_{\text{gen}} = 0$$

$$\frac{1035 \text{ W}}{293 \text{ K}} - \frac{1035 \text{ W}}{278 \text{ K}} + \dot{S}_{\text{gen}} = 0$$

$$\dot{S}_{\text{gen}} = 0.191 \text{ W/K}$$

Entropy is generated due to heat transfer through finite temperature difference



Entropy balance for heat transfer through a wall

To determine the rate of total entropy generation during this heat transfer process, we extend the system to include regions on both sides of the wall that experience temperature change

$$\underbrace{\dot{S}_{\text{in}} - \dot{S}_{\text{out}}}_{\text{Rate of net entropy transfer by heat and mass}} + \underbrace{\dot{S}_{\text{gen}}}_{\text{Rate of entropy generation}} = \underbrace{\frac{dS_{\text{system}}}{dt}}_{\substack{0 (\text{steady}) \\ \text{Rate of change in entropy}}}$$
$$\left(\frac{\dot{Q}}{T}\right)_{\text{in}} - \left(\frac{\dot{Q}}{T}\right)_{\text{out}} + \dot{S}_{\text{gen}} = 0$$

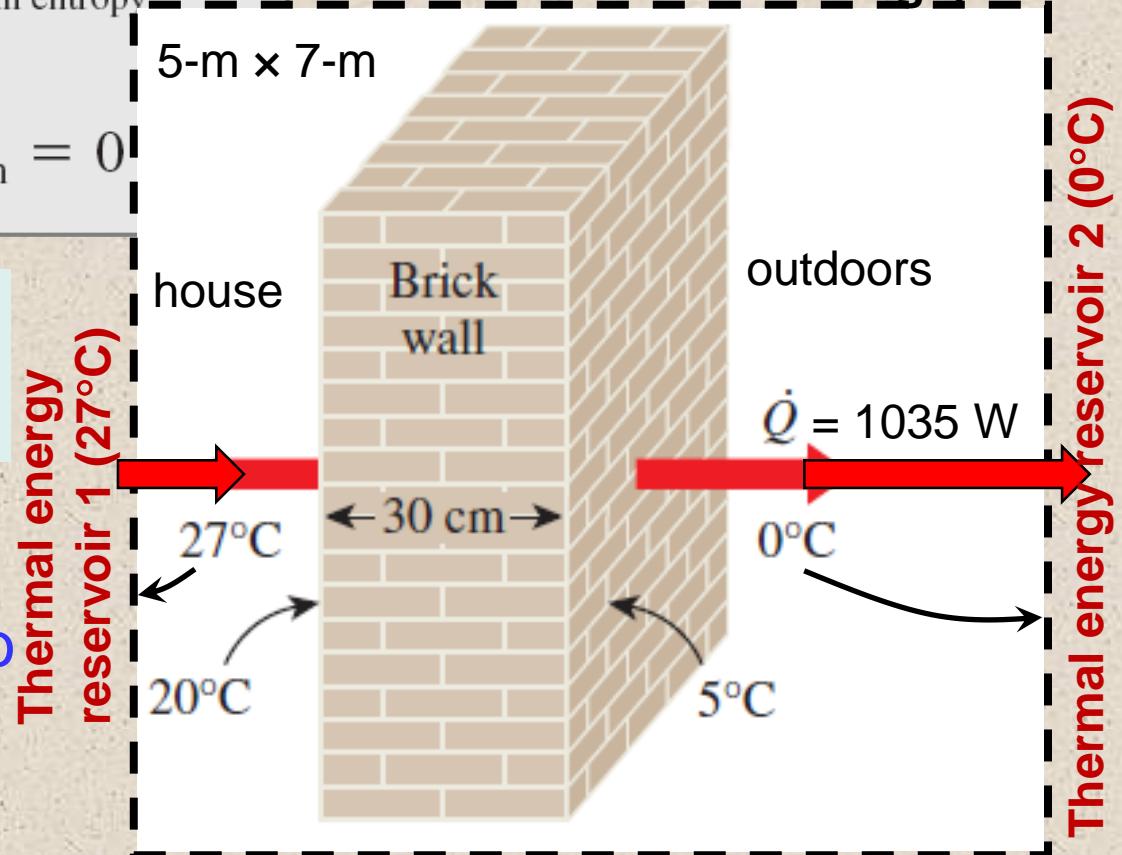
$$\frac{1035 \text{ W}}{300 \text{ K}} - \frac{1035 \text{ W}}{273 \text{ K}} + \dot{S}_{\text{gen,total}} = 0$$

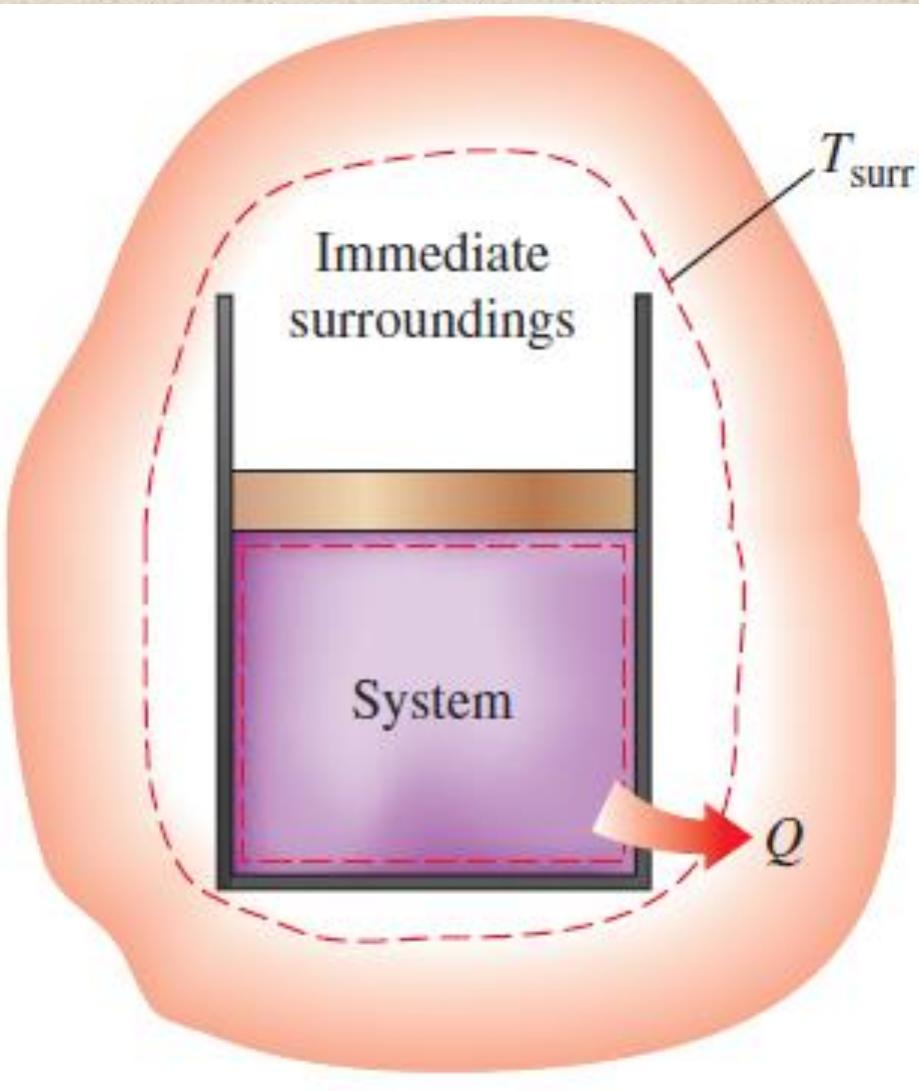
$$\dot{S}_{\text{gen,total}} = 0.341 \text{ W/K}$$

Entropy is generated due to heat transfer through finite temperature difference

This extended system is not an isolated system

Extended system (system + Immediate surroundings)





The **total entropy generated during a process** can be obtained by writing an **entropy balance on an extended system** that includes the system and its **immediate surroundings**

This extended system **need not be an isolated system**

Entropy balance for a throttling process

Determine the entropy generated during this process

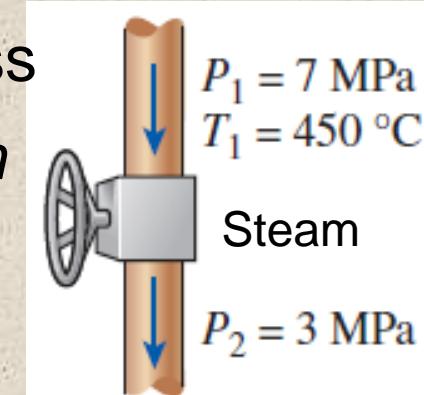
Analysis We take the throttling valve as the system

State 1:

$$\left. \begin{array}{l} P_1 = 7 \text{ MPa} \\ T_1 = 450^\circ\text{C} \end{array} \right\} \quad \left. \begin{array}{l} h_1 = 3288.3 \text{ kJ/kg} \\ s_1 = 6.6353 \text{ kJ/kg}\cdot\text{K} \end{array} \right.$$

State 2:

$$\left. \begin{array}{l} P_2 = 3 \text{ MPa} \\ h_2 = h_1 \end{array} \right\} \quad s_2 = 7.0046 \text{ kJ/kg}\cdot\text{K}$$



$$\underbrace{\dot{S}_{\text{in}} - \dot{S}_{\text{out}}}_{\substack{\text{Rate of net entropy} \\ \text{transfer by heat} \\ \text{and mass}}} + \underbrace{\dot{S}_{\text{gen}}}_{\substack{\text{Rate of entropy} \\ \text{generation}}} = \underbrace{\frac{dS_{\text{system}}}{dt}}_{\substack{\text{Rate of change} \\ \text{in entropy}}}^0 \text{ (steady)}$$
$$\dot{m}s_1 - \dot{m}s_2 + \dot{S}_{\text{gen}} = 0$$
$$\dot{S}_{\text{gen}} = \dot{m}(s_2 - s_1)$$

$$s_{\text{gen}} = s_2 - s_1 = 7.0046 - 6.6353 = 0.3693 \text{ kJ/kg}\cdot\text{K}$$

Entropy is generated due to unrestrained expansion

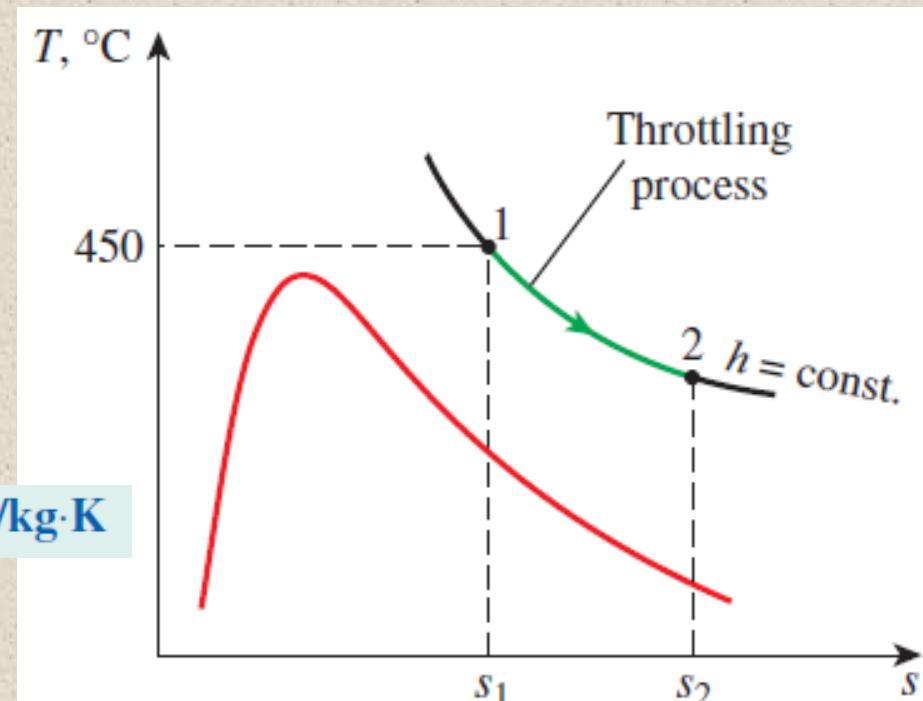


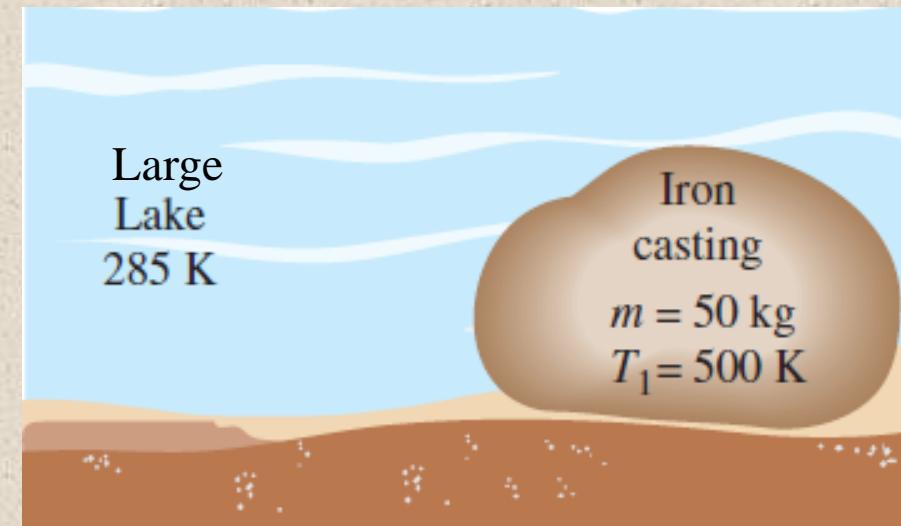
TABLE A-6Superheated water (*Continued*)

<i>T</i> °C	<i>v</i> m ³ /kg	<i>u</i> kJ/kg	<i>h</i> kJ/kg	<i>s</i> kJ/kg·K
<i>P</i> = 7.0 MPa (285.83°C)				
Sat.	0.027378	2581.0	2772.6	5.8148
300	0.029492	2633.5	2839.9	5.9337
350	0.035262	2770.1	3016.9	6.2305
400	0.039958	2879.5	3159.2	6.4502
450	0.044187	2979.0	3288.3	6.6353
500	0.048157	3074.3	3411.4	6.8000
550	0.051966	3167.9	3531.6	6.9507
600	0.055665	3261.0	3650.6	7.0910
700	0.062850	3448.3	3888.3	7.3487
800	0.069856	3639.5	4128.5	7.5836
900	0.076750	3835.7	4373.0	7.8014
1000	0.083571	4037.5	4622.5	8.0055
1100	0.090341	4245.0	4877.4	8.1982
1200	0.097075	4457.9	5137.4	8.3810
1300	0.103781	4676.1	5402.6	8.5551

<i>T</i> °C	<i>v</i> m ³ /kg	<i>u</i> kJ/kg	<i>h</i> kJ/kg	<i>s</i> kJ/kg·K
<i>P</i> = 3.00 MPa (233.85°C)				
Sat.	0.06667	2603.2	2803.2	6.1856
225				
250	0.07063	2644.7	2856.5	6.2893
300	0.08118	2750.8	2994.3	6.5412
350	0.09056	2844.4	3116.1	6.7450
400	0.09938	2933.6	3231.7	6.9235
450	0.10789	3021.2	3344.9	7.0856
500	0.11620	3108.6	3457.2	7.2359
600	0.13245	3285.5	3682.8	7.5103
700	0.14841	3467.0	3912.2	7.7590
800	0.16420	3654.3	4146.9	7.9885
900	0.17988	3847.9	4387.5	8.2028
1000	0.19549	4047.7	4634.2	8.4045
1100	0.21105	4253.6	4886.7	8.5955
1200	0.22658	4465.3	5145.1	8.7771
1300	0.24207	4682.6	5408.8	8.9502

Entropy Generated when a Hot Block is Dropped in a Lake

Determine (a) the entropy change of the iron block, (b) the entropy change of the lake water, and (c) the entropy generated during this process.

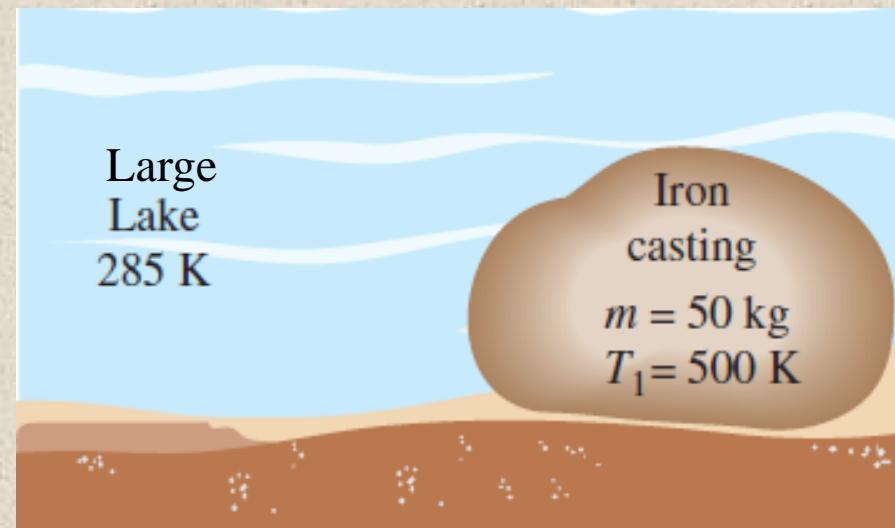


Analysis We take the *iron casting* as the system

Properties The specific heat of the iron is $0.45 \text{ kJ/kg}\cdot\text{K}$ (Table A-3)

$$\begin{aligned}\Delta S_{\text{iron}} &= m(s_2 - s_1) = mc_{\text{avg}} \ln \frac{T_2}{T_1} \\ &= (50 \text{ kg})(0.45 \text{ kJ/kg}\cdot\text{K}) \ln \frac{285 \text{ K}}{500 \text{ K}} \\ &= \mathbf{-12.65 \text{ kJ/K}}\end{aligned}$$

Entropy Generated when a Hot Block Is Dropped in a Lake



(b) The temperature of the lake water remains constant during this process at 285 K. Also, the amount of heat transfer from the iron block to the lake is determined from an energy balance on the iron block to be

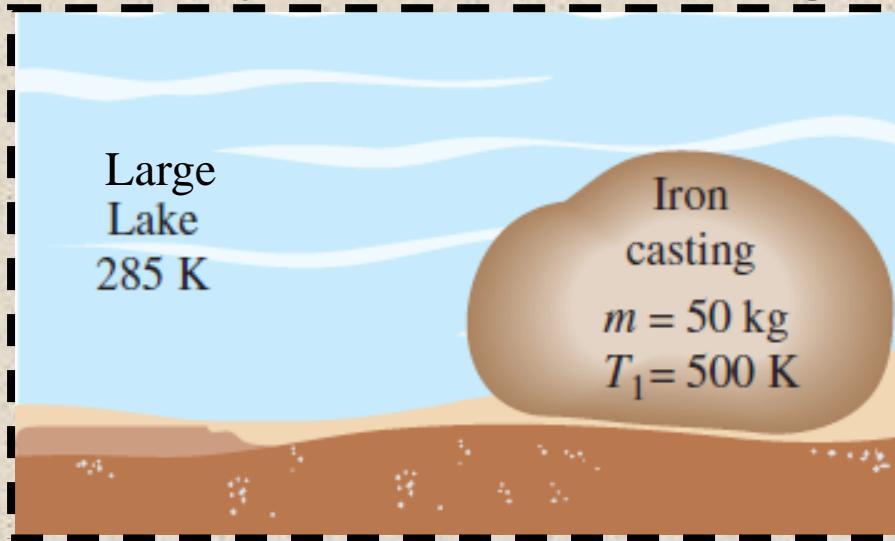
$$Q_{\text{out}} = mc_{\text{avg}}(T_1 - T_2) = (50 \text{ kg})(0.45 \text{ kJ/kg}\cdot\text{K})(500 - 285) \text{ K} = 4838 \text{ kJ}$$

Then, the entropy change of the lake becomes

$$\Delta S_{\text{lake}} = \frac{Q_{\text{lake}}}{T_{\text{lake}}} = \frac{+4838 \text{ kJ}}{285 \text{ K}} = \mathbf{16.97 \text{ kJ/K}}$$

Entropy Generated when a Hot Block Is Dropped in a Lake

Isolated system (lake + iron casting)



Discussion The entropy generated can be determined by taking the iron block and the entire lake as the system, which is an isolated system, and applying an entropy balance. An isolated system involves no heat or entropy transfer, and thus the entropy generation in this case becomes equal to the total entropy change,

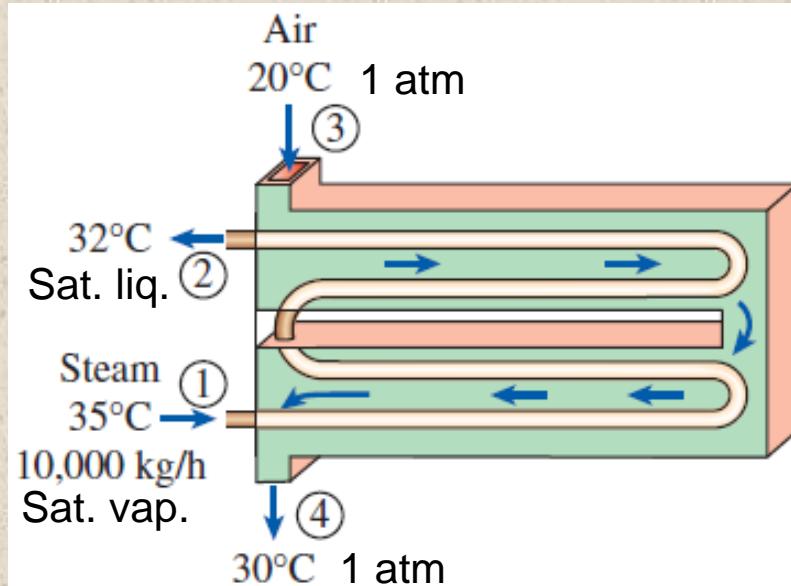
$$S_{\text{gen}} = \Delta S_{\text{total}} = \Delta S_{\text{system}} + \Delta S_{\text{lake}} = -12.65 + 16.97 = 4.32 \text{ kJ/K}$$

Entropy is generated due to heat transfer through finite temperature difference

Entropy Generation in a Heat Exchanger

Determine the rate of entropy generation associated with this process.

Analysis The rate of entropy generation within the heat exchanger is determined by applying the rate form of the entropy balance on the entire heat exchanger:



$$\underbrace{\dot{S}_{in} - \dot{S}_{out}}_{\text{Rate of net entropy transfer by heat and mass}} + \underbrace{\dot{S}_{gen}}_{\text{Rate of entropy generation}} = \underbrace{\Delta \dot{S}_{\text{system}}^0}_{\substack{\text{0 (steady)} \\ \text{Rate of change in entropy}}}$$

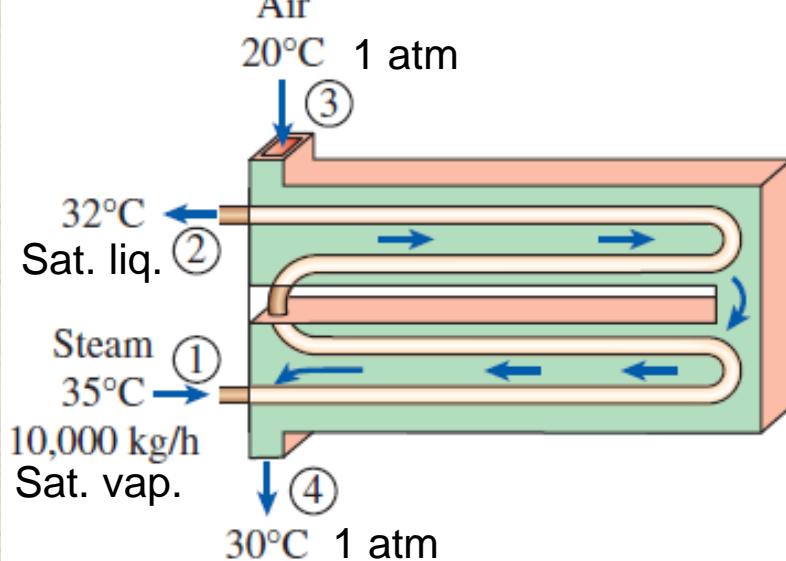
$$\dot{m}_{\text{steam}} s_1 + \dot{m}_{\text{air}} s_3 - \dot{m}_{\text{steam}} s_2 - \dot{m}_{\text{air}} s_4 + \dot{S}_{\text{gen}} = 0$$

$$\dot{S}_{\text{gen}} = \dot{m}_{\text{steam}}(s_2 - s_1) + \dot{m}_{\text{air}}(s_4 - s_3)$$

Entropy Generation in a Heat Exchanger

$$\left. \begin{array}{l} T_1 = 35^\circ\text{C} \\ x_1 = 1 \end{array} \right\} \quad \left. \begin{array}{l} h_1 = 2564.6 \text{ kJ/kg} \\ s_1 = 8.3517 \text{ kJ/kg}\cdot\text{K} \end{array} \right.$$

$$\left. \begin{array}{l} T_2 = 32^\circ\text{C} \\ x_2 = 0 \end{array} \right\} \quad \left. \begin{array}{l} h_2 = 134.10 \text{ kJ/kg} \\ s_2 = 0.4641 \text{ kJ/kg}\cdot\text{K} \end{array} \right.$$



$$\dot{Q} = \dot{m}_{\text{steam}}(h_1 - h_2) = (10,000/3600 \text{ kg/s})(2564.6 - 134.10) \text{ kJ/kg} = 6751 \text{ kW}$$

$$\dot{m}_{\text{air}} = \frac{\dot{Q}}{c_p(T_4 - T_3)} = \frac{6751 \text{ kW}}{(1.005 \text{ kJ/kg}\cdot\text{K})(30 - 20)^\circ\text{C}} = 671.7 \text{ kg/s}$$

$$\begin{aligned} \dot{S}_{\text{gen}} &= \dot{m}_{\text{steam}}(s_2 - s_1) + \dot{m}_{\text{air}}(s_4 - s_3) \\ &= \dot{m}_{\text{steam}}(s_2 - s_1) + \dot{m}_{\text{air}}c_p \ln \frac{T_4}{T_3} \\ &= (10,000/3600 \text{ kg/s})(0.4641 - 8.3517) \text{ kJ/kg}\cdot\text{K} \\ &\quad + (671.7 \text{ kg/s})(1.005 \text{ kJ/kg}\cdot\text{K}) \ln \frac{303 \text{ K}}{293 \text{ K}} \\ &= \mathbf{0.745 \text{ kW/K}} \end{aligned}$$

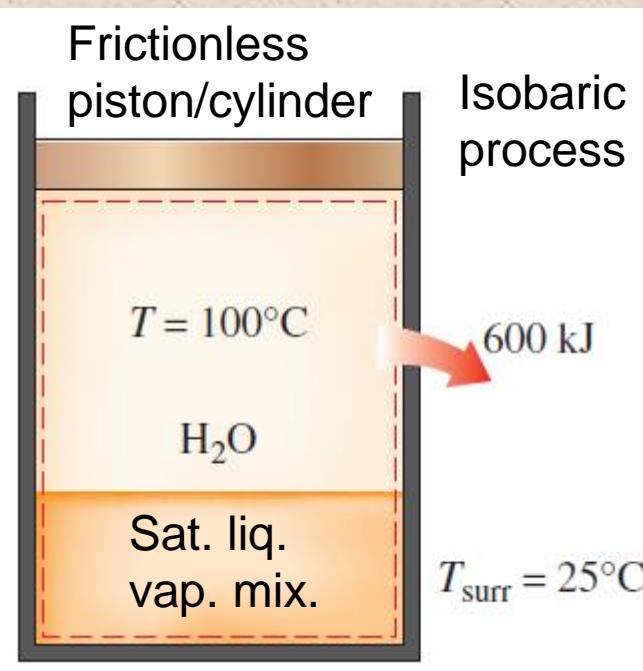
Entropy is generated due to heat transfer through finite temperature difference

TABLE A-4

Saturated water—Temperature table

Temp., <i>T</i> °C	Specific volume, m ³ /kg			Internal energy, kJ/kg			Enthalpy, kJ/kg			Entropy, kJ/kg·K		
	Sat. press., <i>P_{sat}</i> kPa	Sat. liquid, <i>v_f</i>	Sat. vapor, <i>v_g</i>	Sat. liquid, <i>u_f</i>	Evap., <i>u_{fg}</i>	Sat. vapor, <i>u_g</i>	Sat. liquid, <i>h_f</i>	Evap., <i>h_{fg}</i>	Sat. vapor, <i>h_g</i>	Sat. liquid, <i>s_f</i>	Evap., <i>s_{fg}</i>	Sat. vapor, <i>s_g</i>
0.01	0.6117	0.001000	206.00	0.000	2374.9	2374.9	0.001	2500.9	2500.9	0.0000	9.1556	9.1556
5	0.8725	0.001000	147.03	21.019	2360.8	2381.8	21.020	2489.1	2510.1	0.0763	8.9487	9.0249
10	1.2281	0.001000	106.32	42.020	2346.6	2388.7	42.022	2477.2	2519.2	0.1511	8.7488	8.8999
15	1.7057	0.001001	77.885	62.980	2332.5	2395.5	62.982	2465.4	2528.3	0.2245	8.5559	8.7803
20	2.3392	0.001002	57.762	83.913	2318.4	2402.3	83.915	2453.5	2537.4	0.2965	8.3696	8.6661
25	3.1698	0.001003	43.340	104.83	2304.3	2409.1	104.83	2441.7	2546.5	0.3672	8.1895	8.5567
30	4.2469	0.001004	32.879	125.73	2290.2	2415.9	125.74	2429.8	2555.6	0.4368	8.0152	8.4520
35	5.6291	0.001006	25.205	146.63	2276.0	2422.7	146.64	2417.9	2564.6	0.5051	7.8466	8.3517
40	7.3851	0.001008	19.515	167.53	2261.9	2429.4	167.53	2406.0	2573.5	0.5724	7.6832	8.2556
45	9.5953	0.001010	15.251	188.43	2247.7	2436.1	188.44	2394.0	2582.4	0.6386	7.5247	8.1633
50	12.352	0.001012	12.026	209.33	2233.4	2442.7	209.34	2382.0	2591.3	0.7038	7.3710	8.0748
55	15.763	0.001015	9.5639	230.24	2219.1	2449.3	230.26	2369.8	2600.1	0.7680	7.2218	7.9898
60	19.947	0.001017	7.6670	251.16	2204.7	2455.9	251.18	2357.7	2608.8	0.8313	7.0769	7.9082
65	25.043	0.001020	6.1935	272.09	2190.3	2462.4	272.12	2345.4	2617.5	0.8937	6.9360	7.8296
70	31.202	0.001023	5.0396	293.04	2175.8	2468.9	293.07	2333.0	2626.1	0.9551	6.7989	7.7540

Entropy Generation Associated with Heat Transfer



Determine (a) the entropy change of the water and (b) the total entropy generation during this heat transfer process.

Analysis We first take the *water in the cylinder* as the system

Assumptions There are no irreversibilities involved within the system boundaries, and thus the process is internally reversible.

$$\Delta S_{\text{system}} = \frac{Q}{T_{\text{system}}} = \frac{-600 \text{ kJ}}{(100 + 273 \text{ K})} = -1.61 \text{ kJ/K}$$

Entropy Generation Associated with Heat Transfer

Extended System

Frictionless
piston/cylinder

Isobaric
process

$T = 100^\circ\text{C}$

H_2O

Sat. liq.
vap. mix.

600 kJ

Thermal energy
reservoir (25°C)

To determine the total entropy generation during this process, we consider the **extended system**, which includes the water, the piston–cylinder device, and the region immediately outside the system that experiences a temperature change so that the entire boundary of the extended system is at the surrounding temperature of 25°C .

$$S_{\text{gen}} = \frac{Q_{\text{out}}}{T_b} + \Delta S_{\text{system}} = \frac{600 \text{ kJ}}{(25 + 273) \text{ K}} + (-1.61 \text{ kJ/K}) = \mathbf{0.40 \text{ kJ/K}}$$

Entropy generation associated with a heat transfer process

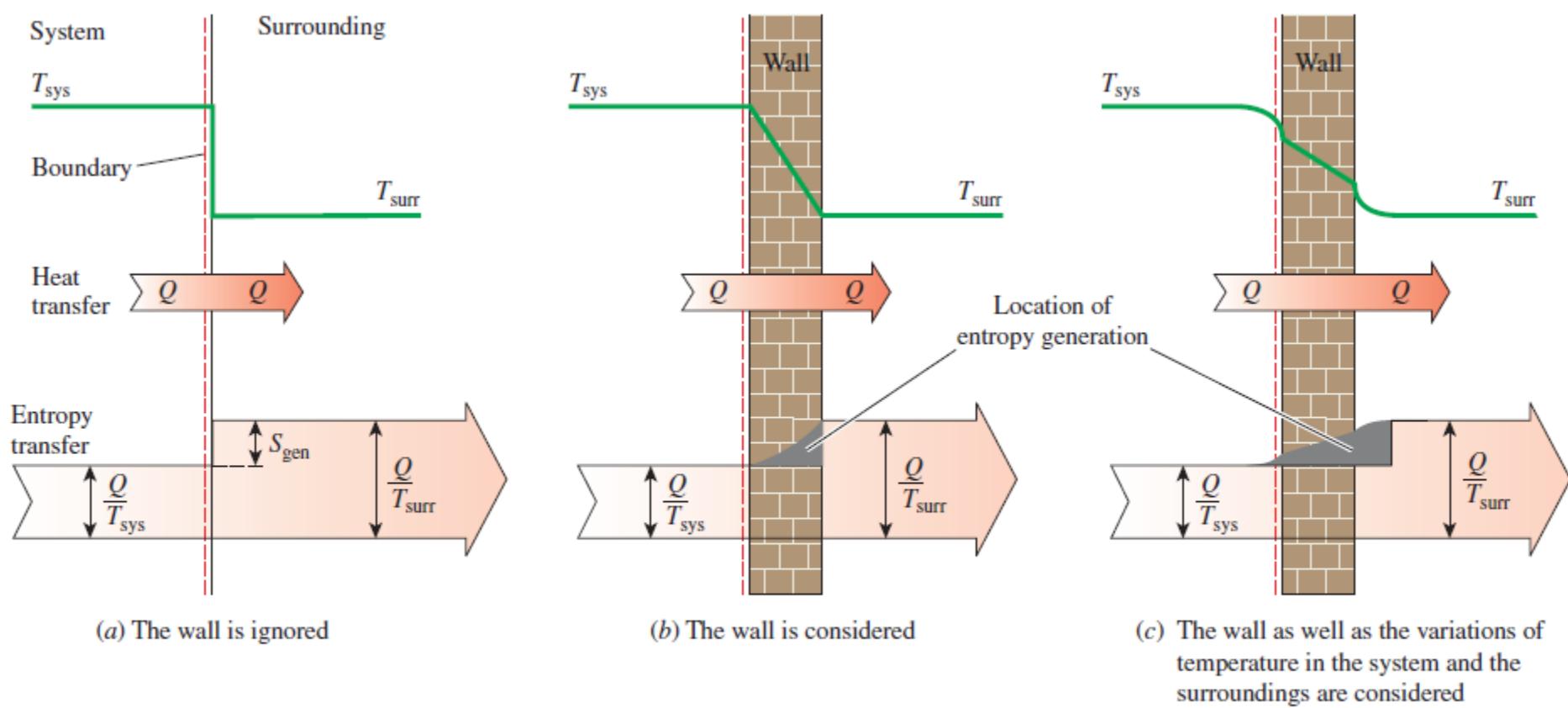


FIGURE 7–69

Graphical representation of entropy generation during a heat transfer process through a finite temperature difference.

Summary

- Entropy
- The Increase of entropy principle
- Entropy change of pure substances
- Isentropic processes
- Property diagrams involving entropy
- What is entropy?
- The $T ds$ relations
- Entropy change of liquids and solids
- The entropy change of ideal gases
- Reversible steady-flow work
- Minimizing the compressor work
- Isentropic efficiencies of steady-flow devices
- Entropy balance