CAE 208 Thermal-Fluids Engineering I
MMAE 320: Thermodynamics

Fall 2022

November 17, 2022

Entropy (ii)

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Illinois Institute of Technology
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ANNOUNCEMENTS

Announcements

BUROHAPPOLD ENGINEERING

ASHRAE® Illinois Institute of Technology Student Branch

Energy Engineering and Commissioning in Buildings

SPEAKER

Energy Engineer, LEED AP

Aaron Kachler

WHEN

November 17th, 2022
12:40 pm – 1:40 pm

WHERE

John T. Rettaliata Engineering Center, RE 242

TALK ABOUT

- ✔ Work Experiences
- ✔ Energy Modeling
- ✔ Careers in Energy Engineering and Commissioning
- ✔ Tips for P.E. exam

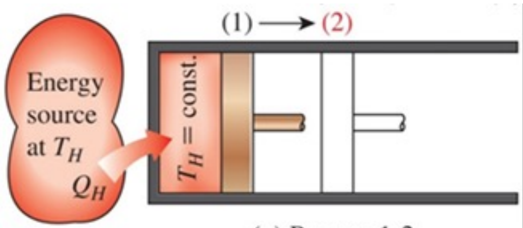
For more information, feel free to contact ASHRAE official email ashrae_iit@iit.edu

Interested in Joining

RECAP

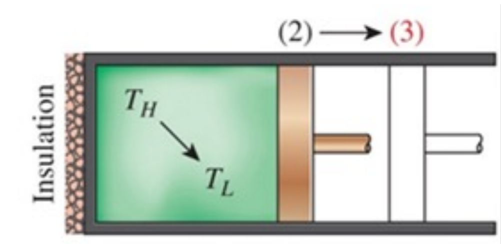
Recap

- Execution of the Carnot cycle in a closed system:



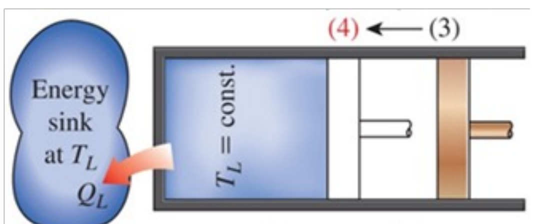
(a) Process 1-2

Reversible Isothermal Expansion (process 1-2, T_H = constant)



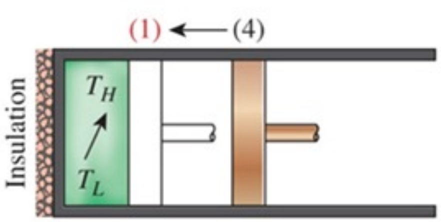
(b) Process 2-3

Reversible Adiabatic Expansion (process 2-3, temperature drops from T_H to T_L)



(c) Process 3-4

Reversible Isothermal Compression (process 3-4, T_L = constant)

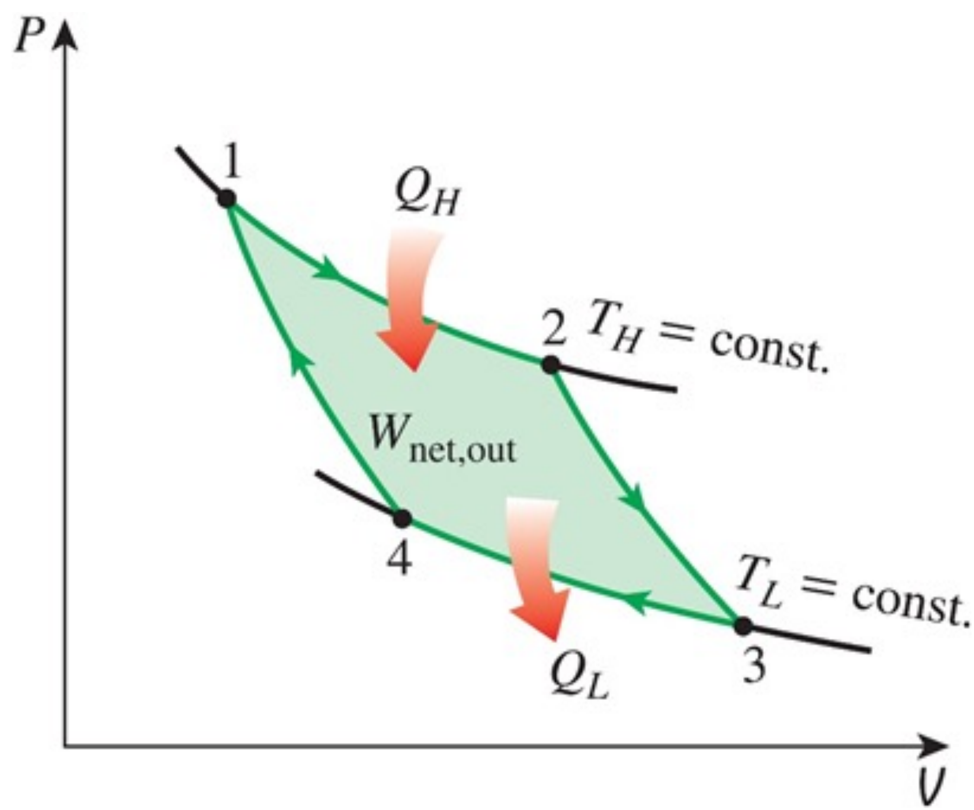


(d) Process 4-1

Reversible Adiabatic Compression (process 4-1, temperature rises from T_L to T_H)

Recap

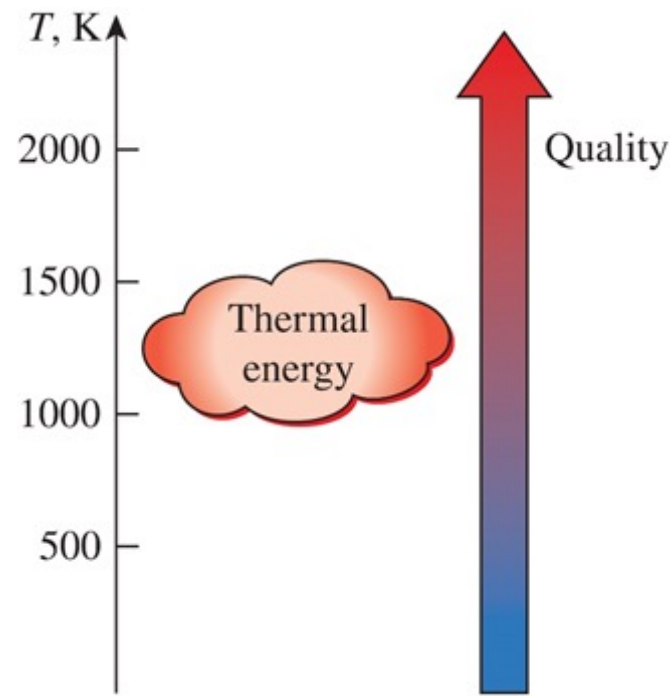
- The Reversed Carnot Cycle
  - ❑ The Carnot heat-engine cycle is a totally reversible cycle



P-V diagram of the Carnot cycle

Recap

- The higher the temperature of the thermal energy, the higher its quality



Recap

- While the first law of thermodynamics deals with the property “energy” and “the conservation of it”, the second law leads to the definition of a new property called “entropy”

- Entropy is somewhat an abstract property, and it is difficult to give a physical description of it without considering the microscopic state of the system

- Entropy is best understood and appreciated by studying its uses in commonly encountered engineering processes, and this is what we intend to do

Recap

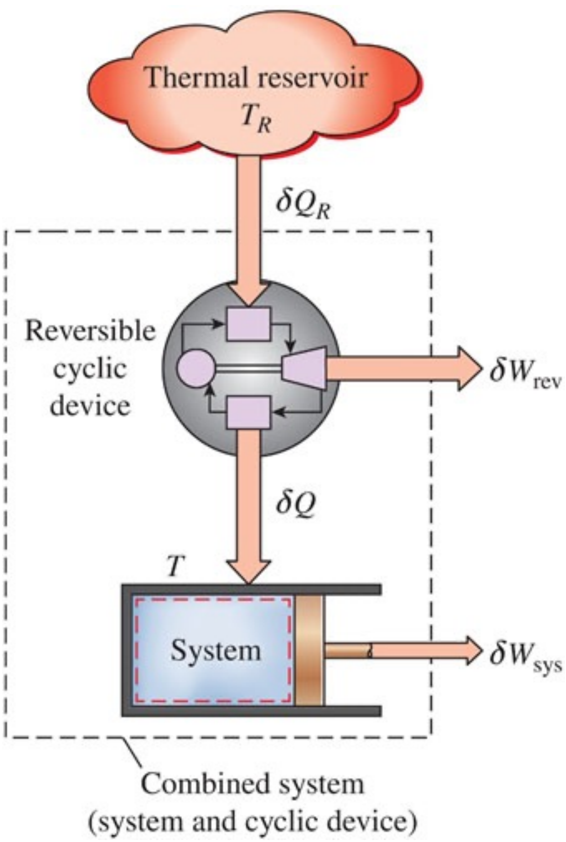
- The equality in the Clausius inequality holds for totally or just internally reversible cycles and the inequality for the irreversible ones

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

ENTROPY

Entropy

- To demonstrate the validity of the Clausius inequality:



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

$$\delta W_C = \delta W_{rev} + \delta W_{sys}$$

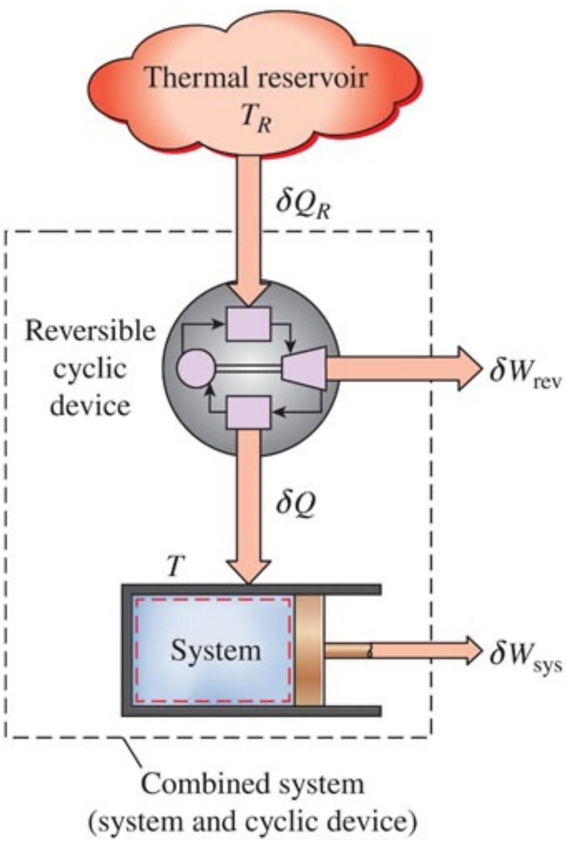
$$\frac{\delta Q_R}{T_R} = \frac{\delta Q}{T}$$

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

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

Entropy

- To demonstrate the validity of the Clausius inequality:



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

It is impossible for any device that operates on a cycle to receive heat from a single reservoir and produce a net amount of work

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

Clausius inequality

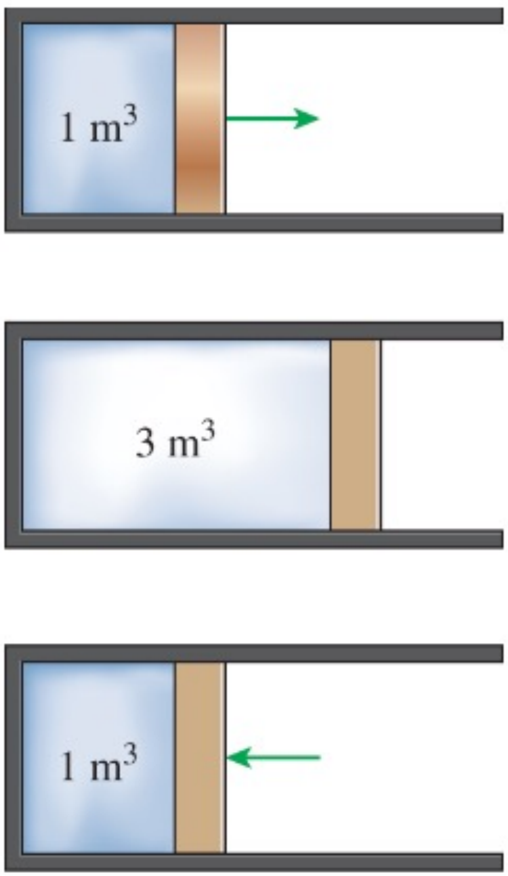
Entropy

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

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

Entropy

- Let's try to find out more about entropy with looking at work in a cycle:



$$\oint dV = ?$$

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

$How\ about\ \delta W?$

Entropy

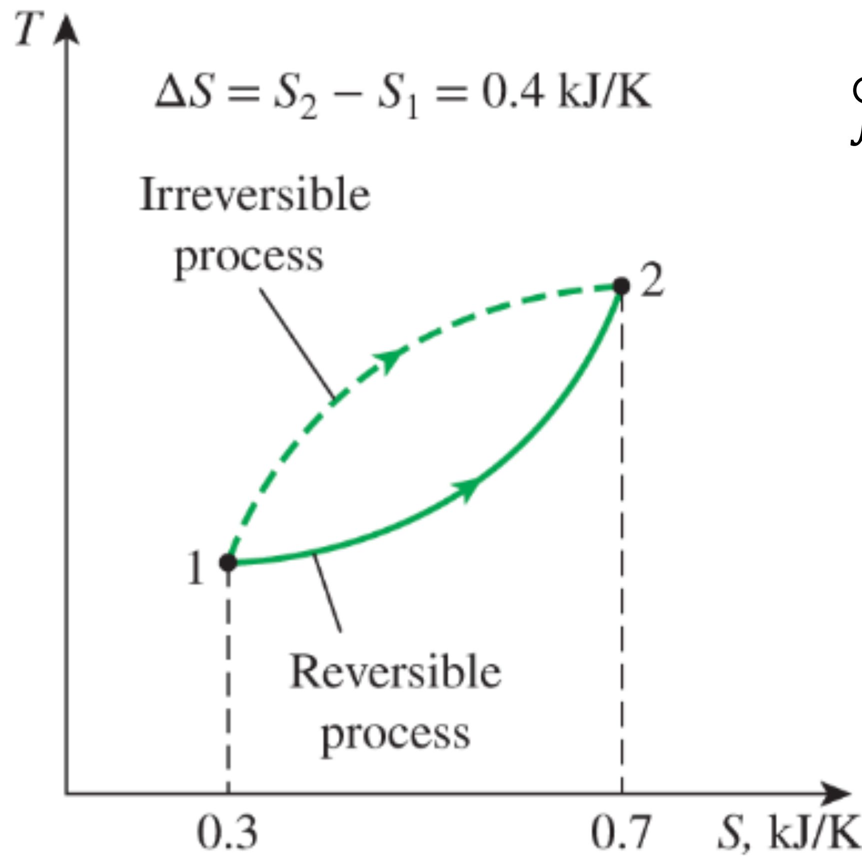
- Let's try to find out more about entropy with looking into a cycle:

$$dS = \oint \frac{\delta Q}{T} \qquad (\frac{kJ}{K})$$

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

Entropy

- Pay attention to reversible and irreversible integration:



$$\oint \frac{\delta Q}{T} = if\ internally\ reversible = S$$

Entropy

- A special case: *Internally reversible isothermal* heat transfer processes:

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

$$\Delta S_{isothermal} = \frac{Q}{T_0} \qquad \left(\frac{kJ}{K}\right)$$

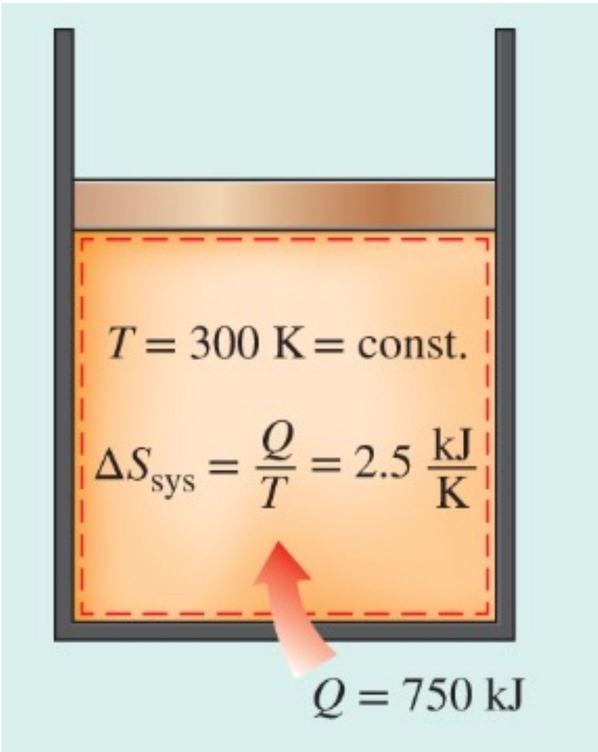
(A reservoir can absorb or supply heat indefinitely at a constant temperature)

Class Activity

- 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 of the liquid in the cylinder vaporizes. Determine the entropy change of water during this process.

Class Activity

- Solution:



$$\Delta S_{isothermal} = \frac{Q}{T_0} \qquad \left(\frac{kJ}{K}\right)$$

$$\Delta S = \frac{750\ kJ}{300\ K} = 2.5\,\frac{kJ}{K}$$

THE INCREASE OF ENTROPY PRINCIPLE

The Increase of Entropy Principle

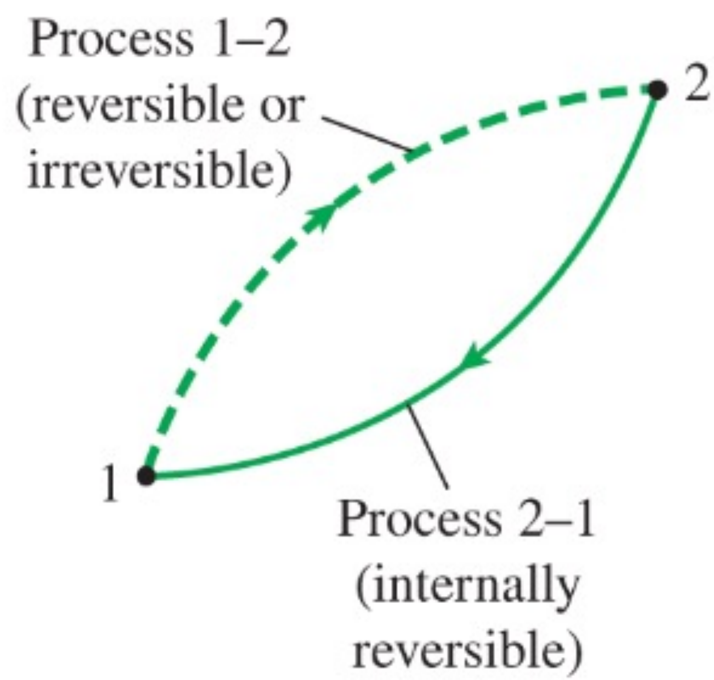
- For processes we can write:

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

$$\oint_1^2 \frac{\delta Q}{T} + \left(\oint_1^2 \frac{\delta Q}{T}\right)_{int,rev} \leq 0$$

$$\oint_1^2 \frac{\delta Q}{T} \leq S_2 - S_1$$

$$\oint_1^2 \frac{\delta Q}{T} \leq dS$$



The Increase of Entropy Principle

- For entropy, we can say

$$\oint_{1}^{2} \frac{\delta Q}{T} \leq \Delta S$$

$$\Delta S_{sys} = S_2 - S_1 = \oint_{1}^{2} \frac{\delta Q}{T} + S_{gen}$$

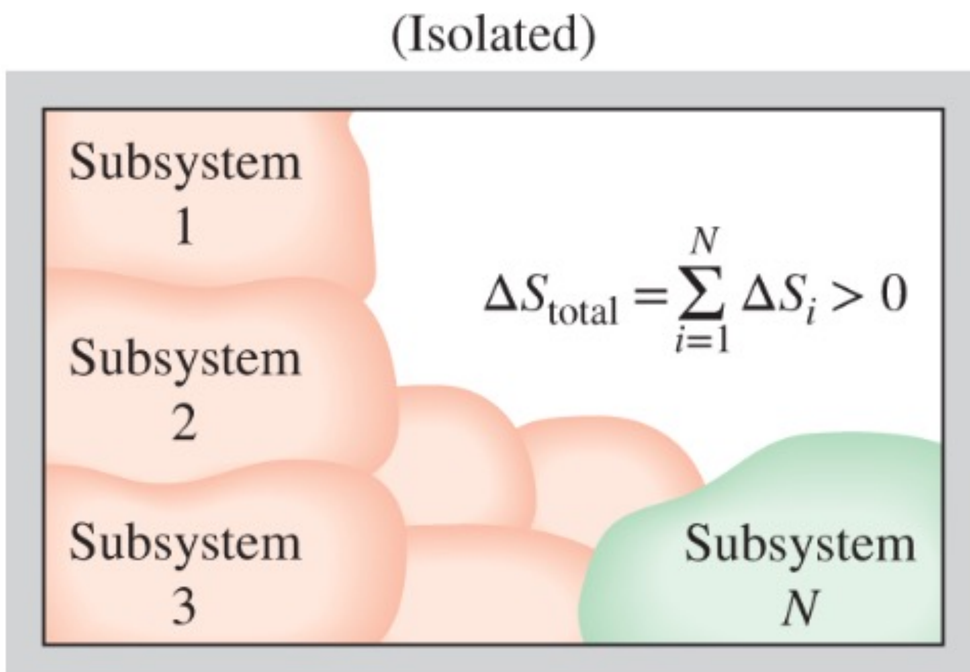
The Increase of Entropy Principle

- Increase of entropy principle:

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

The Increase of Entropy Principle

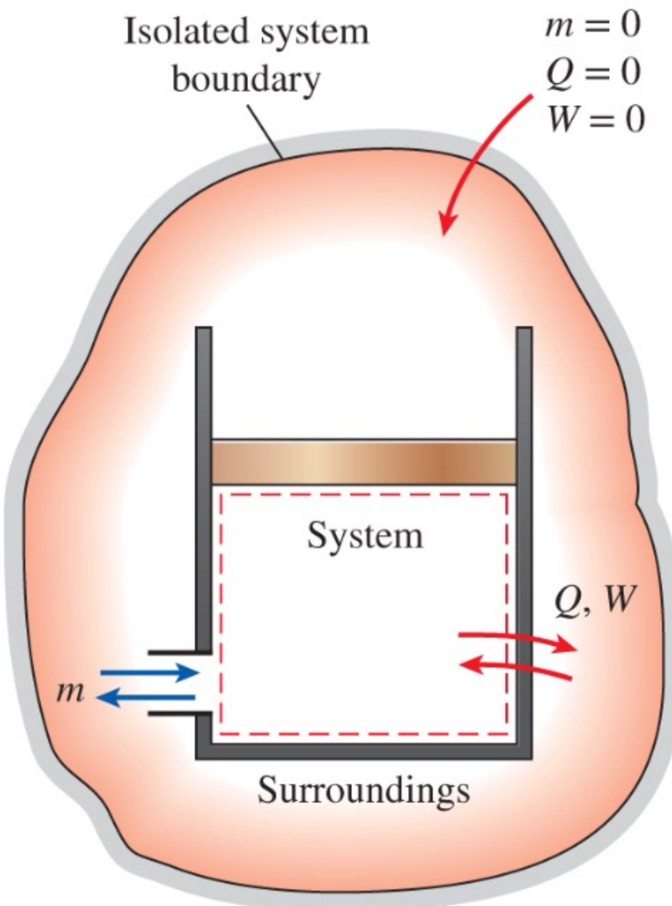
- Entropy is an extensive property (not entropy per unit mass), so the total entropy of a system is equal to the sum of the entropies of the parts of the system (i.e., an isolated system may consist of any number of subsystem



The Increase of Entropy Principle

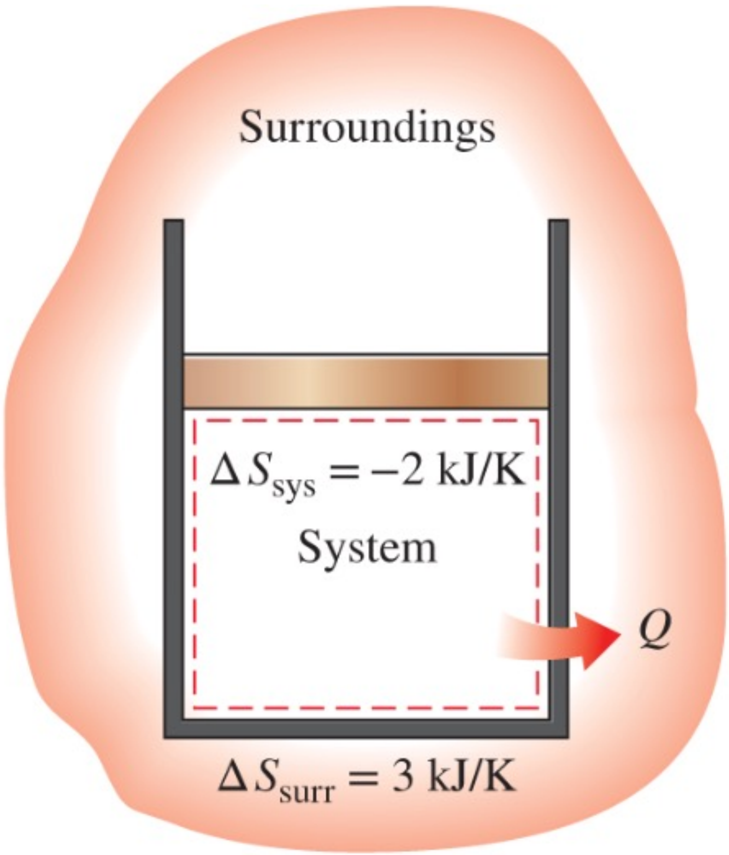
- For an isolated system:

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



The Increase of Entropy Principle

- For an isolated system:



The Increase of Entropy Principle

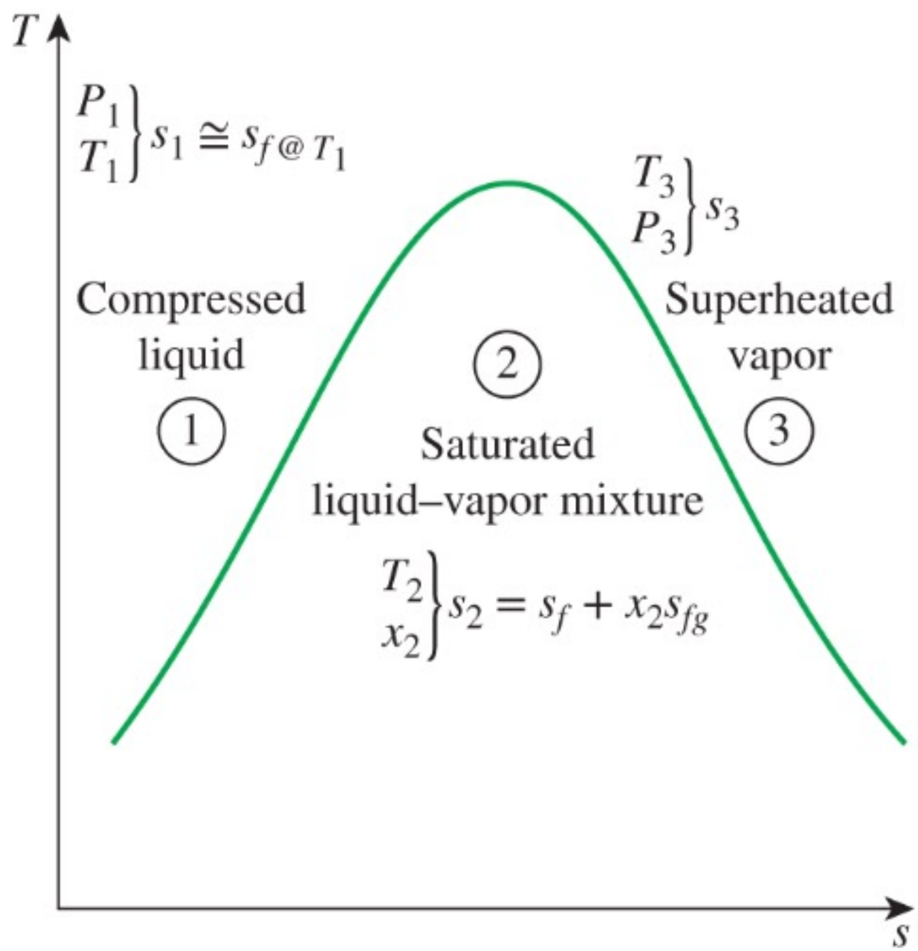
- The increase of entropy principle can be summarized as:

$$S_{gen} = \begin{cases} > 0. & irreversible\ process \\ = 0 & reversible\ process \\ < 0. & impossible\ process \end{cases}$$

ENTROPY CHANGE OF PURE SUBSTANCES

Entropy Change of Pure Substances

- Entropy is a property:



$$\Delta S = m\Delta s = m(s_2 - s_1)$$

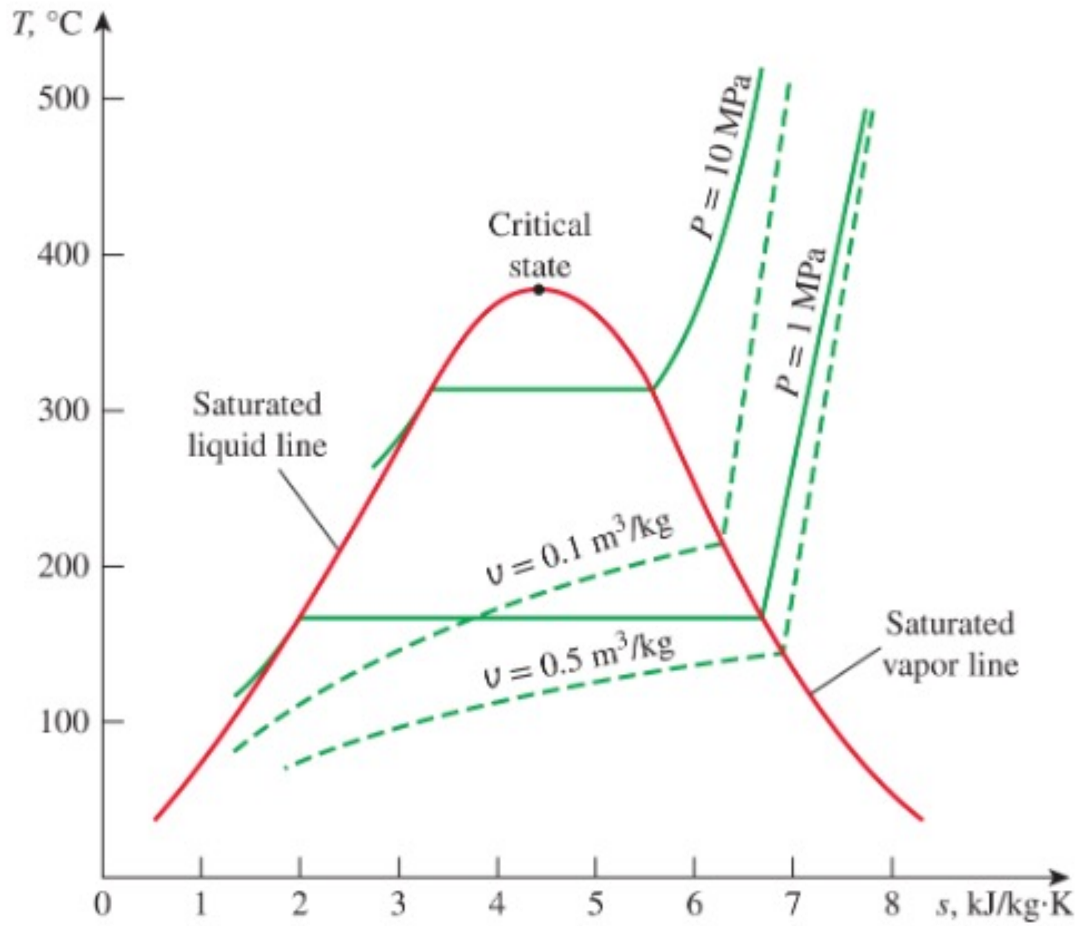
Entropy Change of Pure Substances

- For a closed system (m = constant), during a process we have:

$$\Delta S = m\Delta s = m(s_2 - s_1)$$

Entropy Change of Pure Substances

- We can draw T-s diagram now:



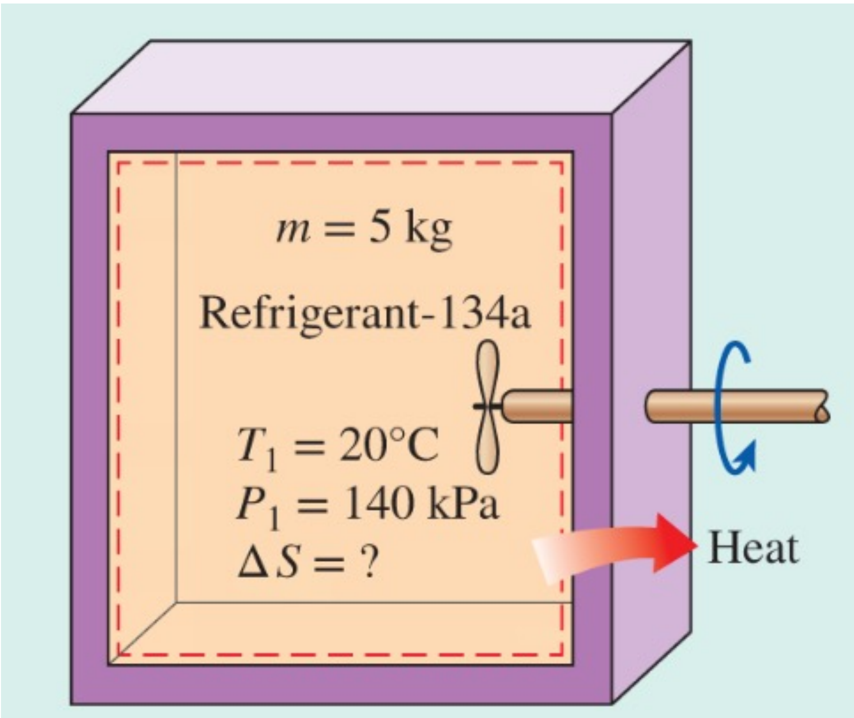
CLASS ACTIVITY

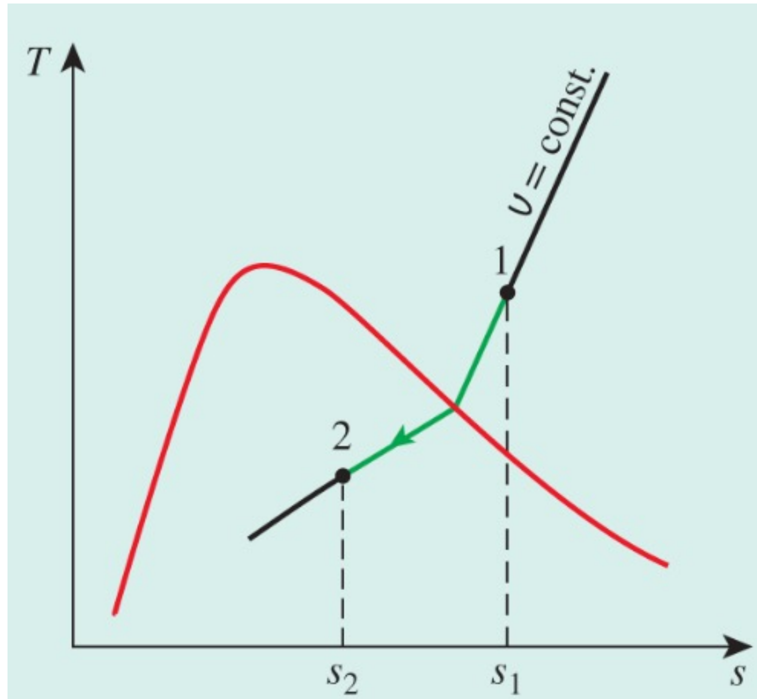
Class Activity

- A rigid tank contains 5-kg of refrigerant 134-a 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.

Class Activity

- Solutions (assumptions):
  - ❑ Closed system (m = constant)





Class Activity

- Solutions (Calculations):

$$\begin{cases} P_1 = 140\ kPa \\ T_1 = 20\ °C \end{cases} \rightarrow \quad \begin{matrix} s_1 = 1.0625\ \dfrac{kJ}{kg-K} \\ v_1 = 0.16544\ \dfrac{m^3}{kg} \end{matrix}$$

$$\begin{cases} P_2 = 100\ kPa \\ v_2 = v_1 \end{cases} \rightarrow \quad \begin{matrix} v_f = 0.0007258\ \dfrac{m^3}{kg} \\ v_g = 0.19255\ \dfrac{m^3}{kg} \end{matrix} \qquad (v_f < v_2 < v_g)$$

Class Activity

- Solutions (Calculations):

$$x_2 = \frac{v_2 - v_f}{v_{fg}} = \frac{0.16544 - 0.0007258}{0.19255 - 0.0007258} = 0.859$$

$$s_2 = s_f + x_2 s_{fg} = (0.07182) + (0.859)(0.88008) = 0.8278\,\frac{kJ}{kg-K}$$

$$\Delta S = m(s_2 - s_1) = (5\ kg)(0.8278 - 1.0625\,\frac{kJ}{kg-K}) = -1.173\ kJ/K$$

Class Activity

- Solutions (assumptions):
  - ❑ Closed system (m = constant)

$$\begin{cases} P_1 = 140\ kPa \\ T_1 = 20\ °C \end{cases} \rightarrow \quad s_1 = 1.0625\ \frac{kJ}{kg-K} \qquad v_1 = 0.16544\ \frac{m^3}{kg}$$

$$\begin{cases} P_2 = 100\ kPa \\ v_2 = v_1 \end{cases} \rightarrow \quad v_f = 0.0007258\ \frac{m^3}{kg} \qquad v_g = 0.19255\ \frac{m^3}{kg}$$

$$(v_f < v_2 < v_g)$$

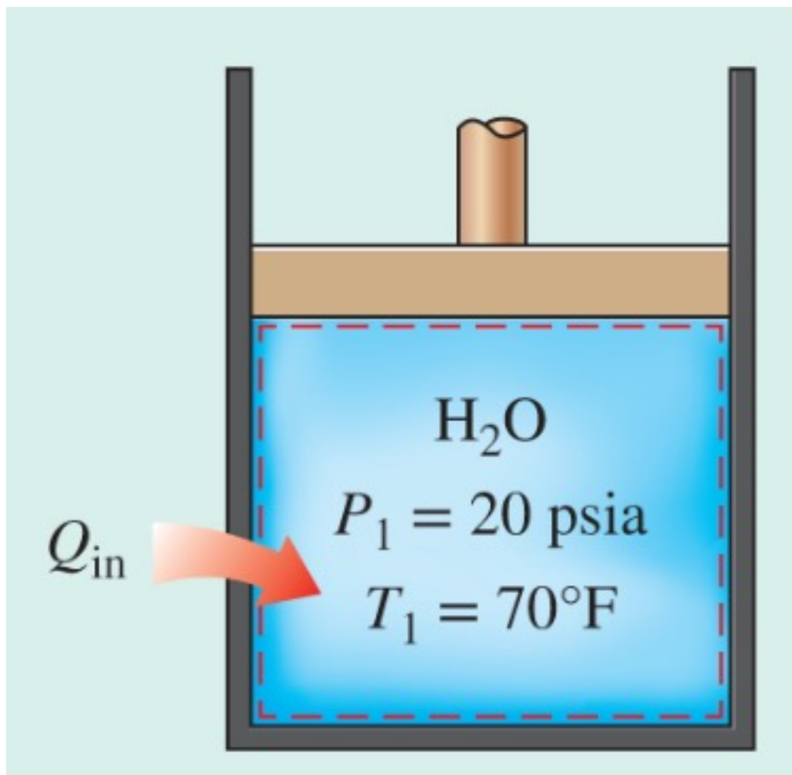
CLASS ACTIVITY

Class Activity

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

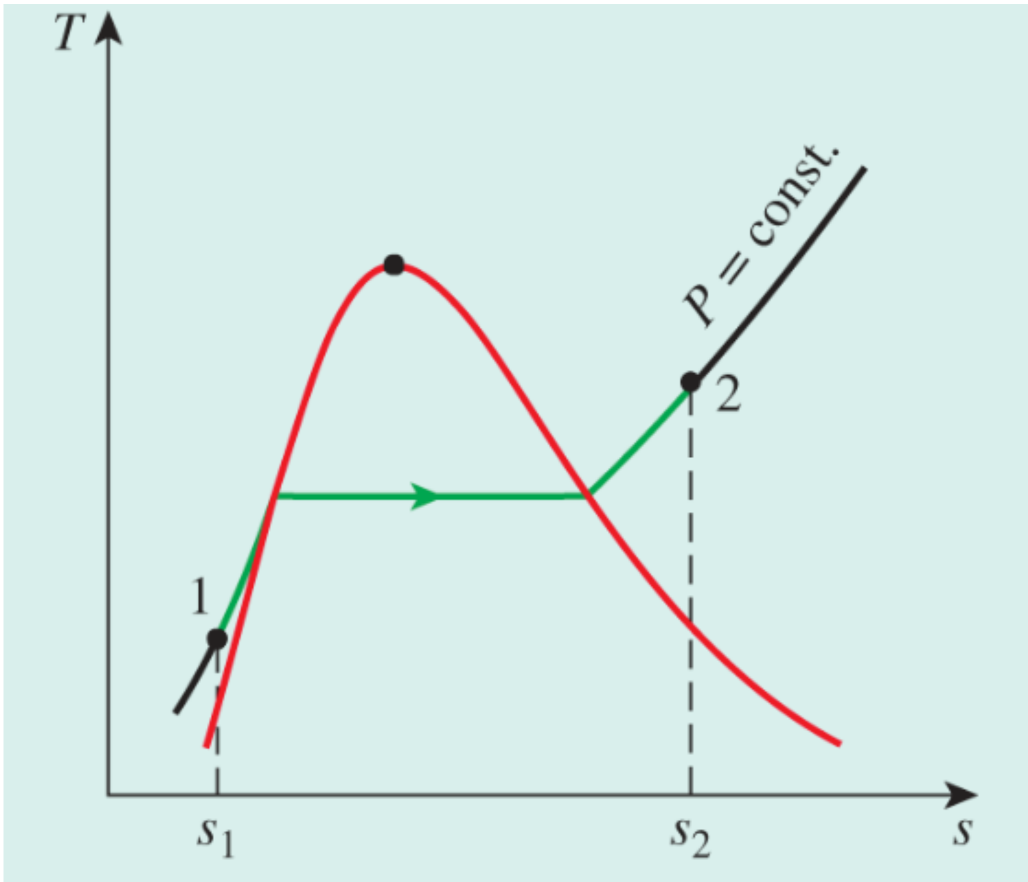
Class Activity

- Solutions (assumptions):
  - ❑ The tank is stationary and thus the kinetic and potential energy changes are zero ($\Delta KE = \Delta PE = 0$)
  - ❑ The process is quasi-equilibrium
  - ❑ The pressure remains constant during this process ($P_1 = P_2$)



Class Activity

- Solutions (processes):



$$at\ 70°F\ \rightarrow P_{sat} = 0.3632\ psia$$

Class Activity

- Solutions (Calculation):

$$\begin{matrix} P_1 = 20\ psia \\ T_1 = 70\ °F \end{matrix} \quad \rightarrow \quad \begin{matrix} s_1 \cong s_{f\ @\ 70°F} = 0.07459\ \dfrac{Btu}{lbm-R} \\ h_1 \cong h_{f\ @\ 70°F} = 38.08\ \dfrac{Btu}{lbm} \end{matrix}$$

$$\begin{matrix} P_1 = 20\ psia \\ Another\ property\ (????) \end{matrix} \quad \rightarrow$$

Class Activity

- Solutions (Calculation):

$$E_{in} - E_{out} = \Delta E_{system}$$

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

$$Q_{in} = \Delta \mathrm{H} = \mathrm{m}(\mathrm{h}_2 - \mathrm{h}_1)$$

$$3450\ Btu = (3\ lbm)(h_2 - 38.08\ \frac{Btu}{lbm})$$

$$h_2 = 1188.1\ \frac{Btu}{lbm}$$

Class Activity

- Solutions (Calculation):

$$P_1 = 20\ psia$$
$$h_2 = 1188.1\ \frac{Btu}{lbm} \quad \rightarrow \quad s_2 = 1.7761\ \frac{Btu}{lbm-R}$$
$$(From\ Table\ A-6A\ -interpolation)$$

$$\Delta S = m(s_2 - s_1) = (3\ lbm)\left(1.7761 - 0.07459\ \frac{Btu}{lbm-R}\right) = 5.105\ \frac{Btu}{R}$$

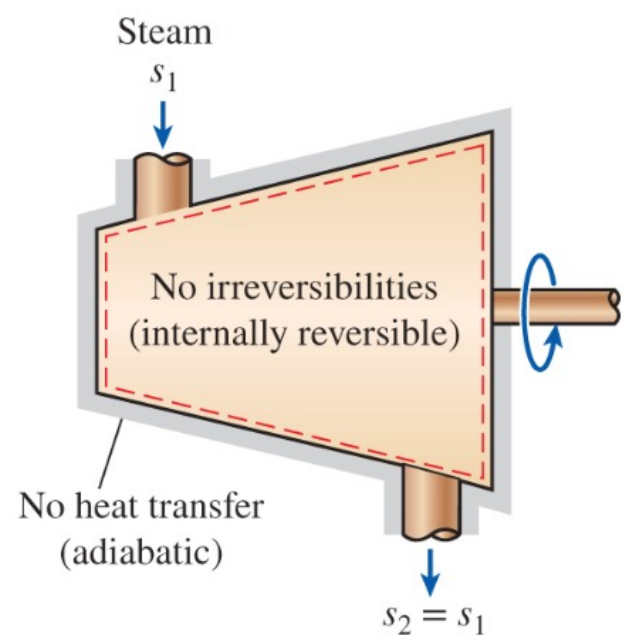
ISENTROPIC PROCESSES

Isentropic Processes

- The entropy of a fixed mass can be changed by:
  - ❑ Heat Transfer
  - ❑ Irreversibilities

- Entropy of a fixed mass does not change during a process that is internally reversible and adiabatic. During this process entropy remains constant and we call it *isentropic* process

$$\Delta s = 0 \quad or \quad s_2 = s_1 \quad \left(\frac{kJ}{kg - K}\right)$$



Isentropic Processes

- A substance will have the same entropy value at the end of the process as it does the beginning if the process is carried out in an isentropic manner

- Many engineering systems or devices such as pumps, turbines, nozzles, and diffusers are essentially adiabatic in their operation, and they perform best when the irreversibilities are minimized (idealized conditions)

Isentropic Processes

- A reversible adiabatic process is necessarily isentropic ($s_1 = s_2$), but an isentropic process is not necessarily a reversible adiabatic process (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, for example)

- The term isentropic process is customarily used in thermodynamics to imply an internally reversible, adiabatic process

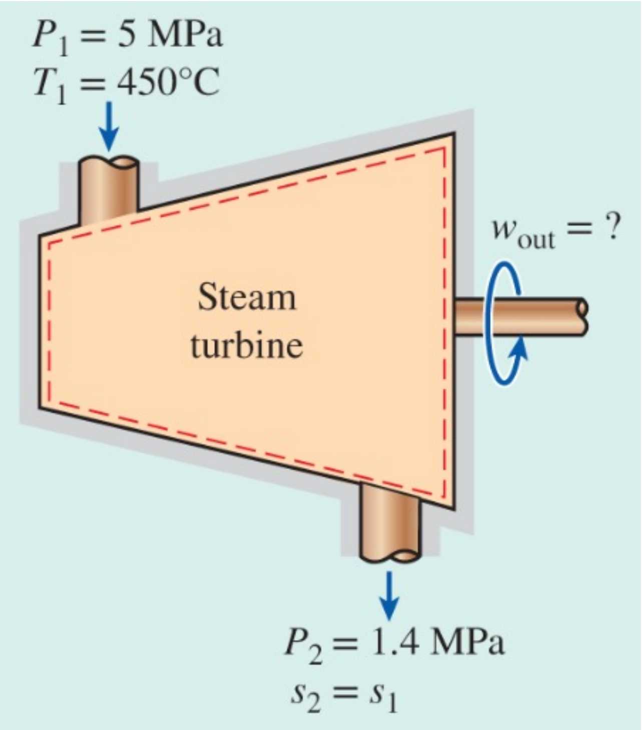
CLASS ACTIVITY

Class Activity

- 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.

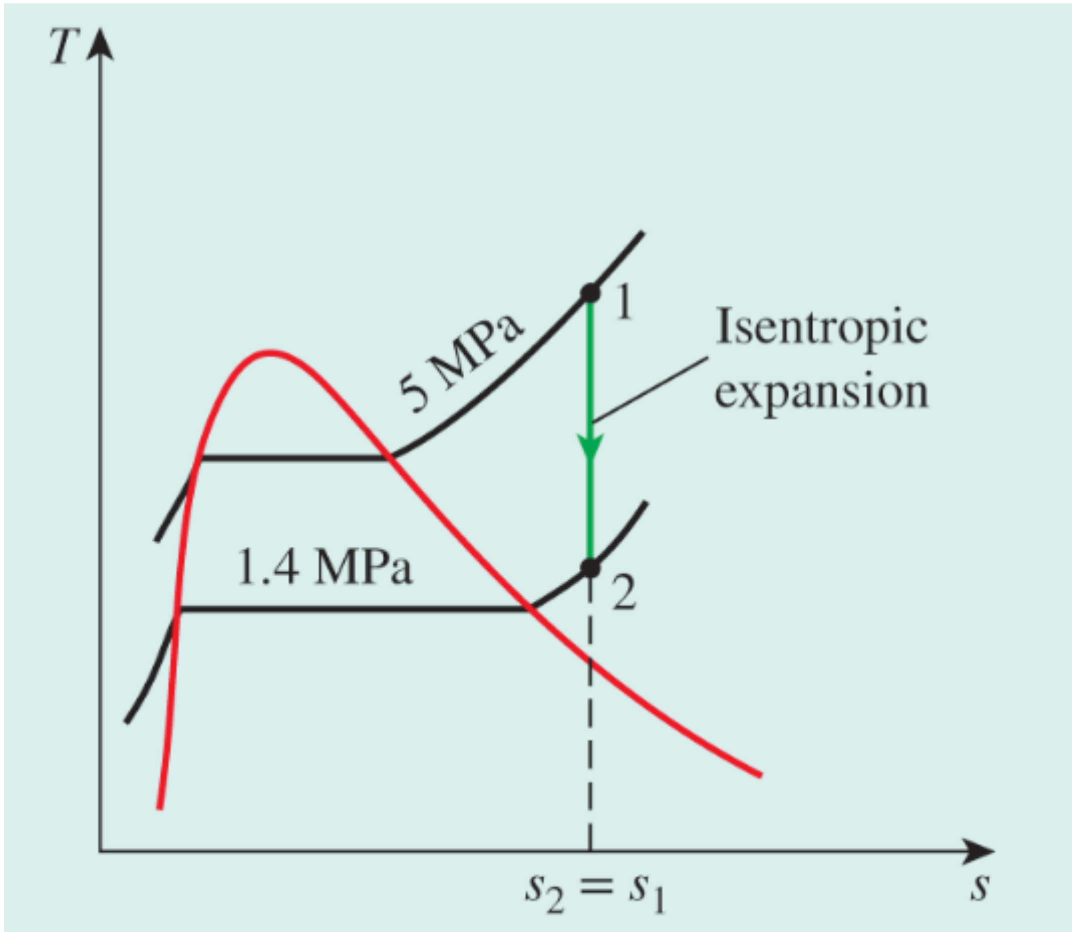
Class Activity

- Solutions (assumptions):
  - ❑ This is a steady flow process (no change with respect to time), meaning $\Delta m_{CV} = 0, \Delta E_{CV} = 0, \Delta S_{CV} = 0)$
  - ❑ The kinetic and potential energy changes are negligible $(\Delta KE = \Delta PE = 0)$
  - ❑ The process is adiabatic and thus there is no heat transfer
  - ❑ The process is reversible



Class Activity

- Solutions (processes):



Class Activity

- Solutions (calculations):

$$\dot{m} = \dot{m}_1 = \dot{m}_2$$

$$\dot{E}_{in} - \dot{E}_{out} = \frac{dE_{system}}{dt} = 0$$

$$\dot{E}_{in} = \dot{E}_{out}$$

$$\dot{m}h_1 = \dot{W}_{out} + \dot{m}h_2 \qquad (since\ \dot{Q} = 0\ , ke\ \cong 0, pe \cong 0)$$

$$\dot{W}_{out} = \dot{m}(h_1 - h_2)$$

Class Activity

- Solutions (calculations):

$$\begin{cases} P_1 = 5\ MPa \\ T_1 = 450\ °C \end{cases} \rightarrow \quad \begin{matrix} h_1 = 3317.2\ \dfrac{kJ}{kg} \\ s_1 = 6.8210\ \dfrac{kJ}{kg-K} \end{matrix}$$

$$\begin{cases} P_2 = 1.4\ MPa \\ s_2 = s_1 \end{cases} \rightarrow \quad h_2 = 2967.4\ \frac{kJ}{kg}$$

$$\dot{W}_{out} = h_1 - h_2 = 3317.2 - 2967.4 = 349.8\ \frac{kJ}{kg}$$

PROPERTY DIAGRAMS INVOLVING ENTROPY

Property Diagrams Involving Entropy

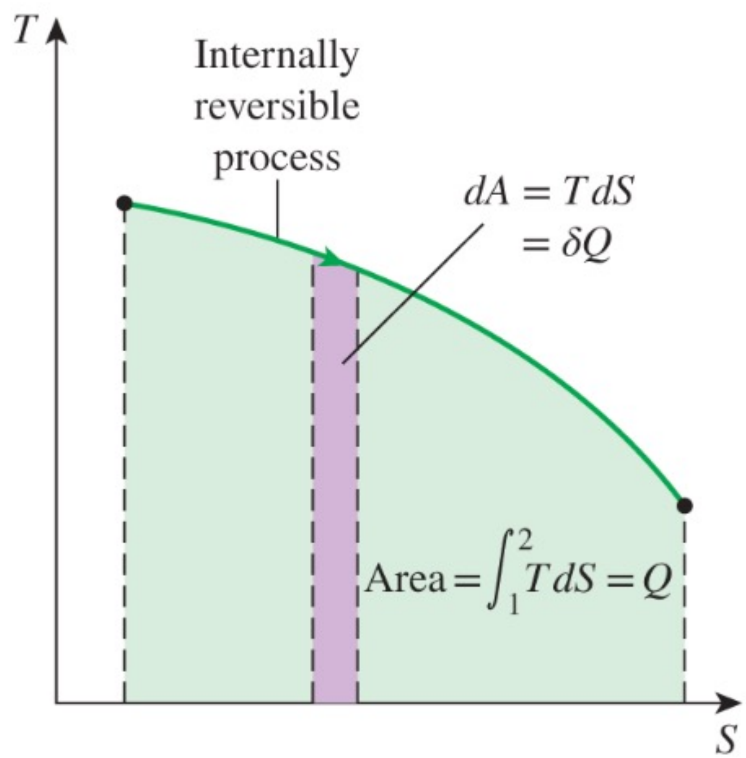
- Property diagrams serve as great visual aids in the thermodynamic analysis of processes

- Based on the 2nd law, we can plot new diagrams that involve entropy:
  - ❑ Temperature-entropy
  - ❑ Enthalpy-entropy

Property Diagrams Involving Entropy

- We can rearrange our entropy equation:

$$\delta Q_{int,rev} = T\,dS \qquad\qquad Q_{int,rev} = \int_1^2 T\,dS \quad (kJ)$$

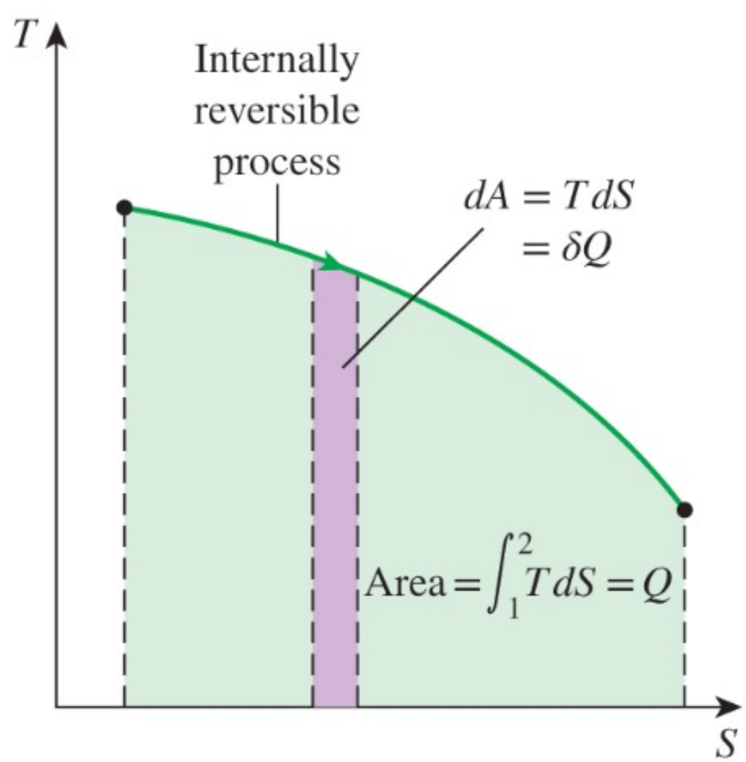


(The area under the process curve on a T-S diagram represents heat transfer during an internally reversible process)

Property Diagrams Involving Entropy

- We can use the per-unit mass equation:

$$\delta q_{int,rev} = T\,ds \qquad\qquad q_{int,rev} = \int_1^2 T\,ds \quad (kJ)$$



(The area under the process curve on a T-S diagram represents heat transfer during an internally reversible process)

Property Diagrams Involving Entropy

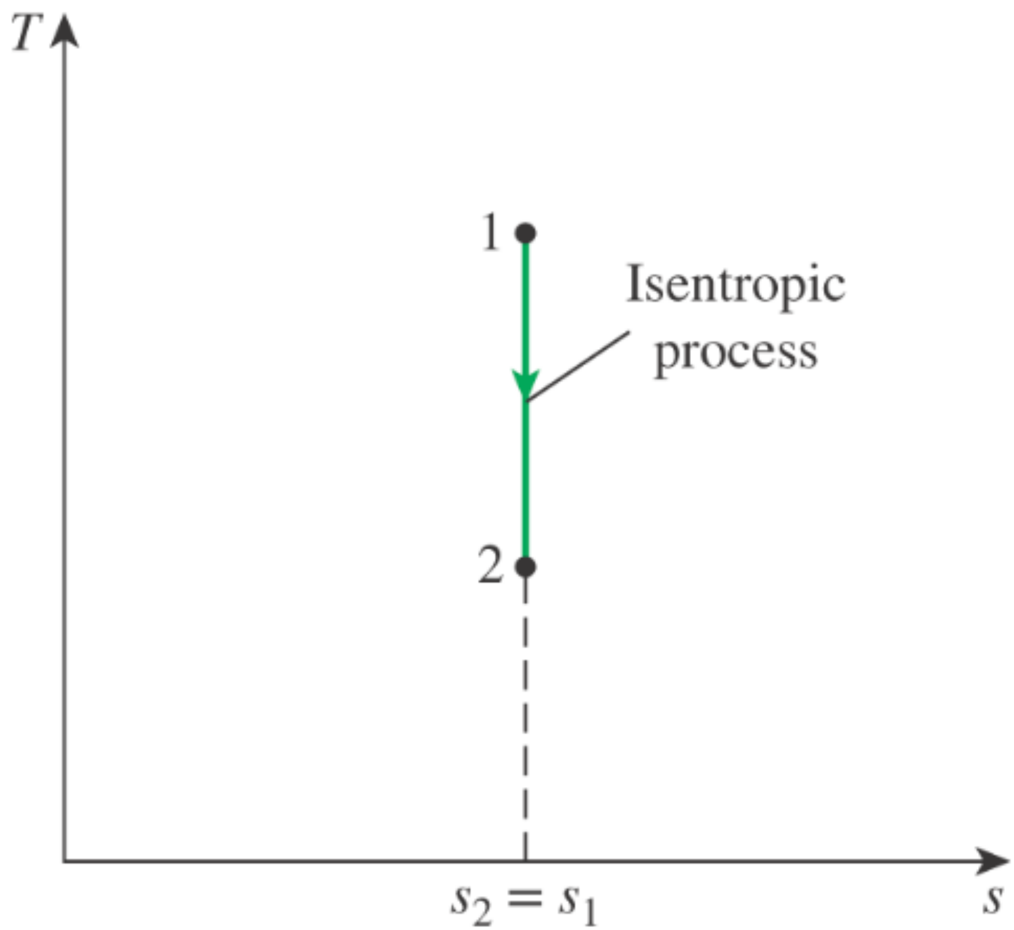
- One special case (internally reversible isothermal process):

$$Q_{int,rev} = T_0 \Delta S$$

$$q_{int,rev} = T_0 \Delta s$$

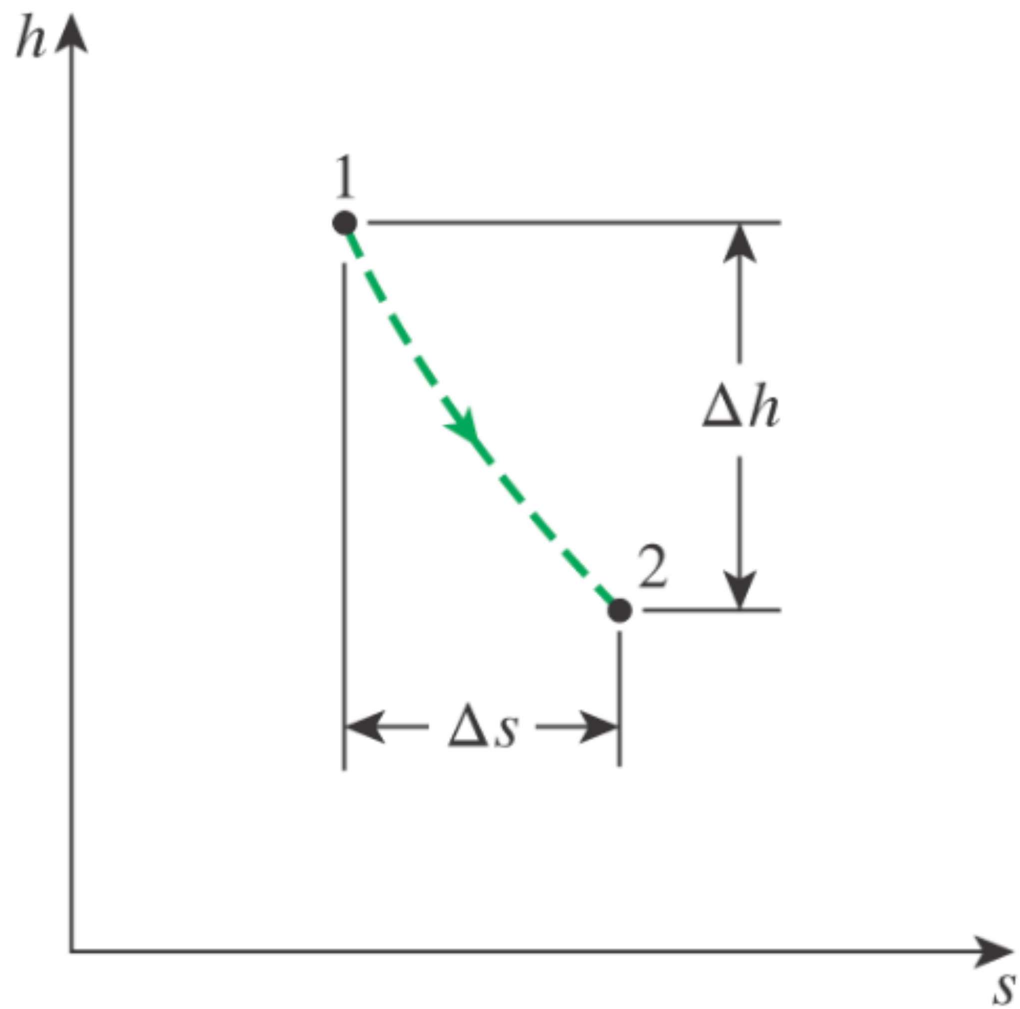
Property Diagrams Involving Entropy

- T-s diagram for an isentropic process:



Property Diagrams Involving Entropy

- h-s diagram (could be helpful for steady flow of devices such as nozzles, compressors, turbines):



Property Diagrams Involving Entropy

- T-s diagram of water is given in the appendix:

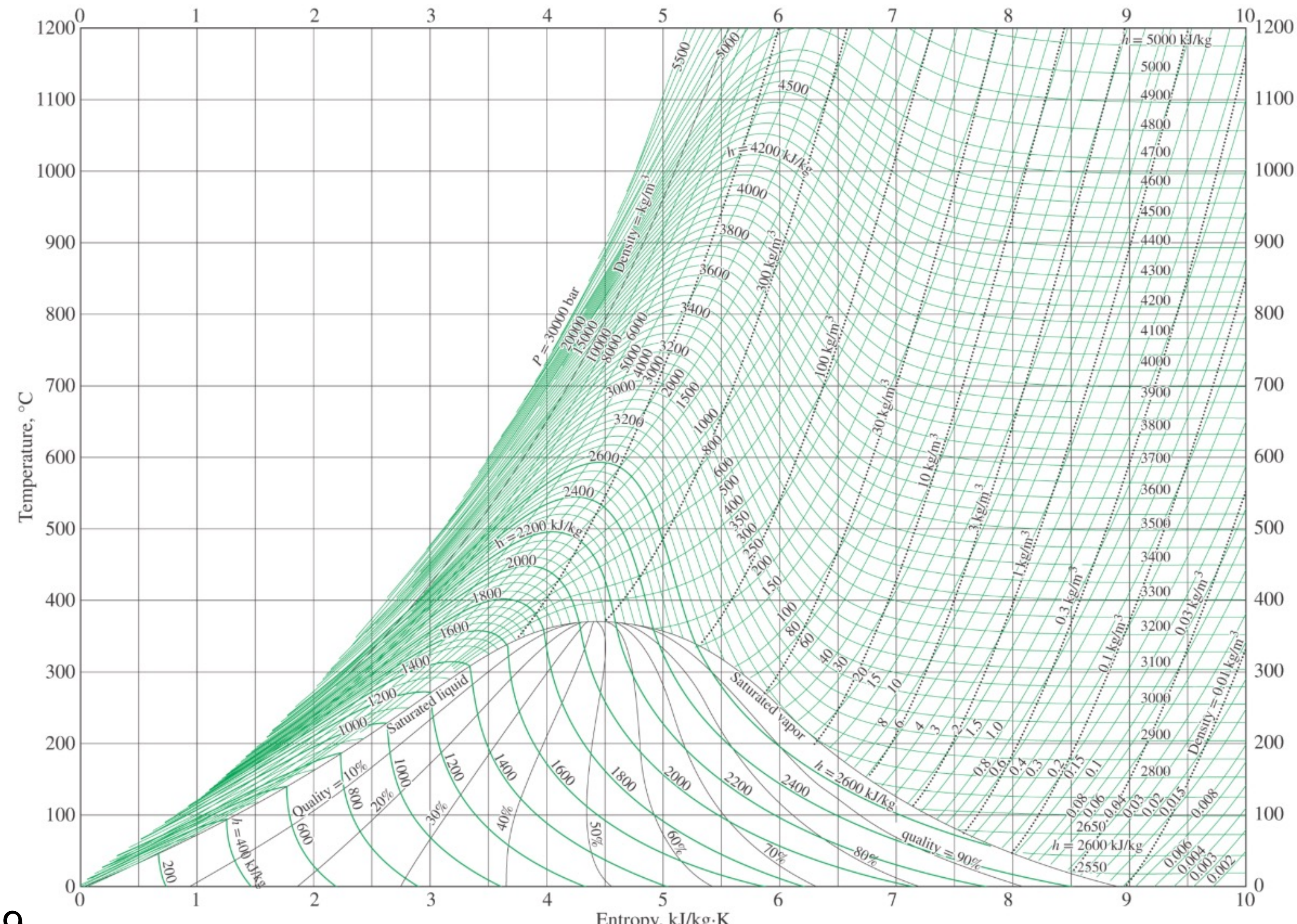


Figure A-9

Property Diagrams Involving Entropy

- h-s diagram of steam is given in the appendix:

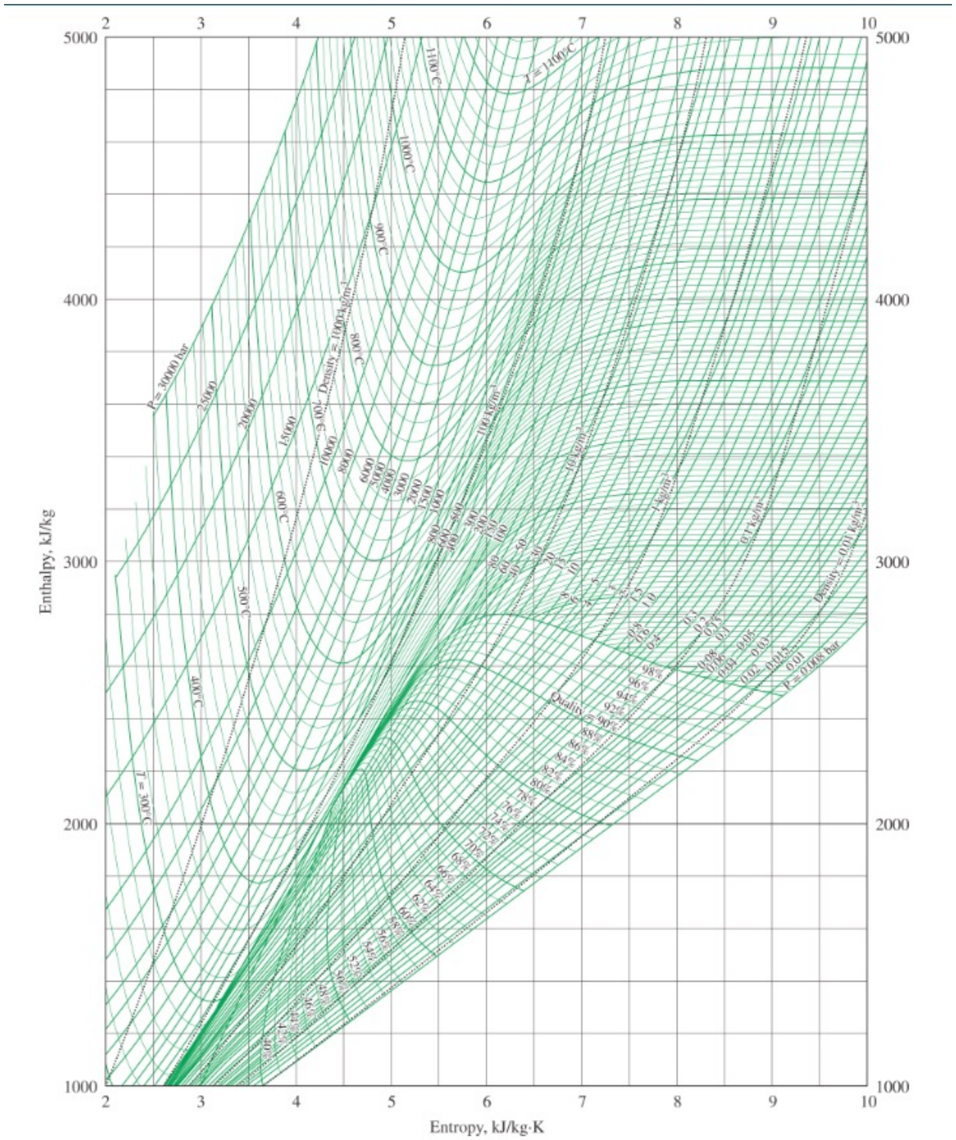


Figure A-10

CLASS ACTIVITY

Class Activity

- Show the Carnot cycle on a T-S diagram and indicate the areas that represent the heat supplied and rejected and the network in the diagram.

Class Activity

- Solution: