ESO 201A: Thermodynamics

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Entropy: part 2

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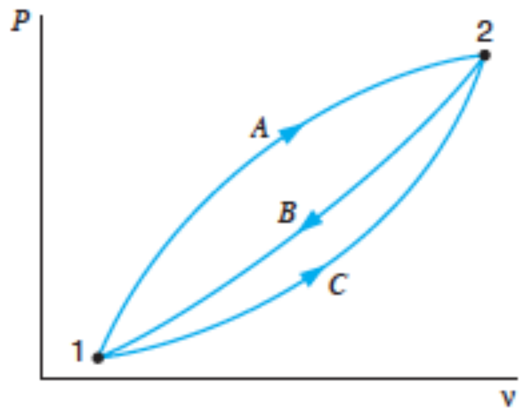
Learning objectives

- 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*.
- Examine a special class of idealized processes, called *isentropic processes*, and develop the property relations for these processes.
- 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.

Entropy



For a reversible cycle A-B (totally or internally reversible)

$$\oint \frac{\delta Q}{T} = 0 = \int_1^2 \left(\frac{\delta Q}{T}\right)_A + \int_2^1 \left(\frac{\delta Q}{T}\right)_B$$

For another cycle : B-C

$$\oint \frac{\delta Q}{T} = 0 = \int_1^2 \left(\frac{\delta Q}{T}\right)_C + \int_2^1 \left(\frac{\delta Q}{T}\right)_B$$

Subtracting the second equation from first

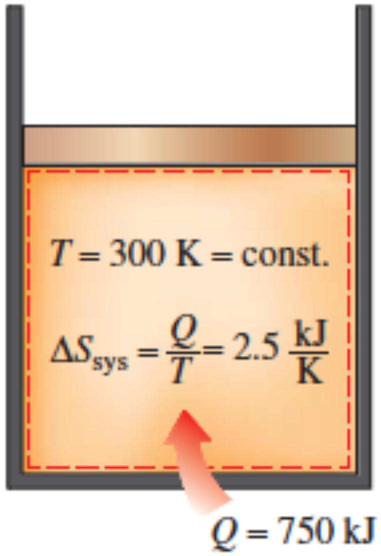
$$\int_1^2 \left(\frac{\delta Q}{T}\right)_A = \int_1^2 \left(\frac{\delta Q}{T}\right)_C$$

- Independent of path for all reversible paths between 1 and 2
- Depends on the end states
- Thus it is property, called entropy, S

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

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

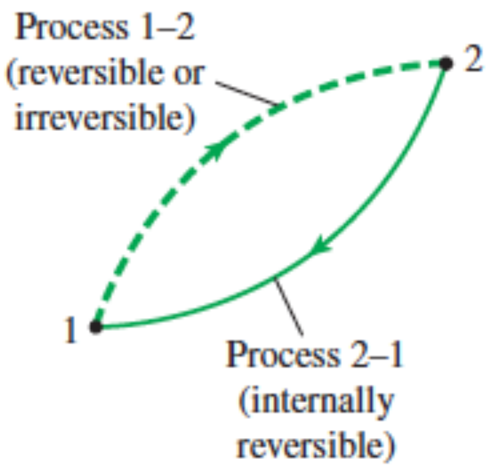
Entropy



Isothermal process

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

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



A cycle composed of a reversible and an irreversible process

Clausius inequality

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

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

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

Increase of entropy

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

In differential form

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

where the equality holds for an internally reversible process and the inequality for an irreversible process

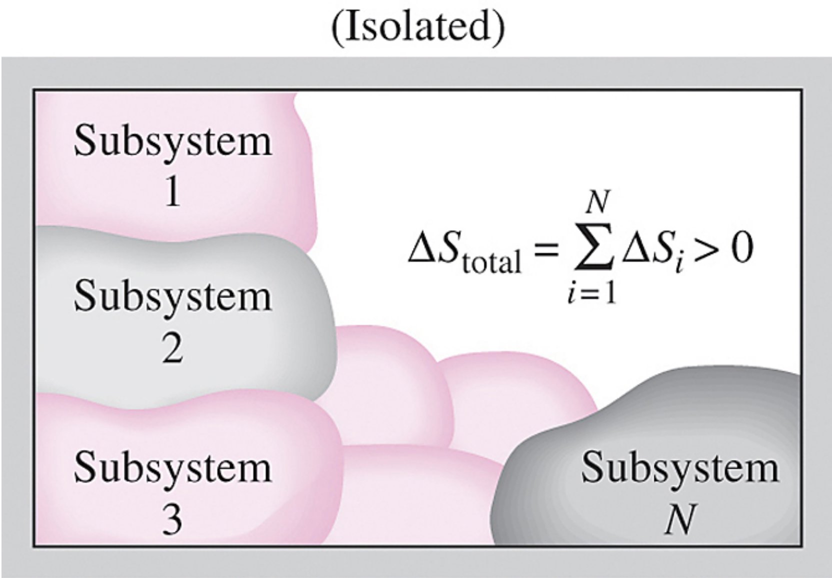
$$\Delta S_{sys} = S_2 - S_1 = \int_1^2 \frac{\delta Q}{T} + S_{gen}$$

- Entropy change of a closed system, during irreversible process, is always greater than the entropy transfer due to heat transfer between the system and surrounding.
- Some entropy is *generated* or *created* during an irreversible process, and this generation is due entirely to the presence of irreversibilities
- S_{gen} , entropy generation, is always a positive quantity or zero (for reversible process), depends on the process.
- Entropy for an isolated system during a process $\Delta S_{isolated} \geq 0$

  always increases or is constant for a reversible process i.e., it never decreases

  increase of entropy principle

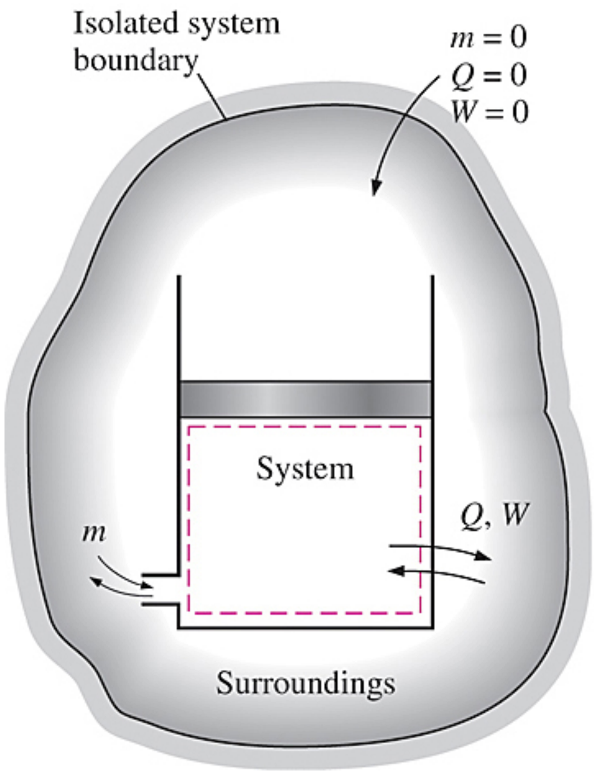
Entropy : an extensive property



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

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

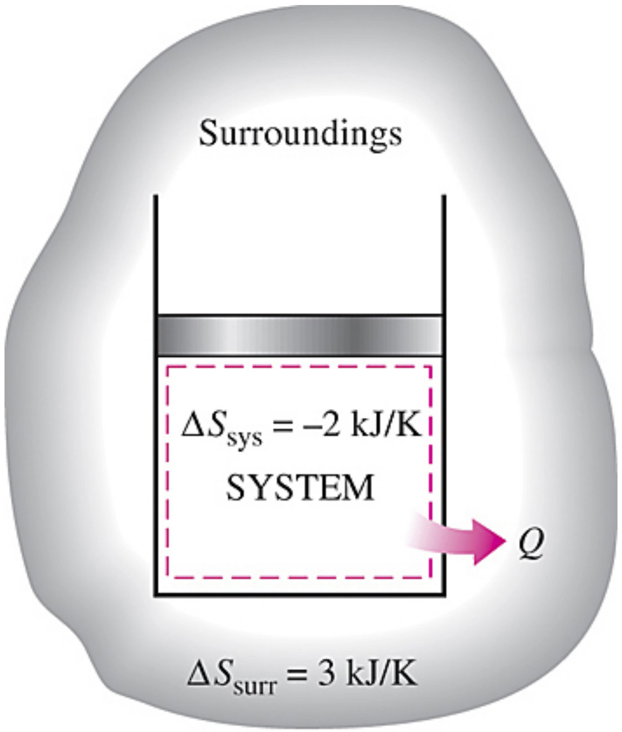
$$S_{gen} \begin{cases} > 0 & \text{Irreversible process} \\ = 0 & \text{Reversible process} \\ < 0 & \text{Impossible process} \end{cases}$$



A system and its surroundings form an isolated system.

Can the entropy of a system during a process decrease?

Some remarks about Entropy



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

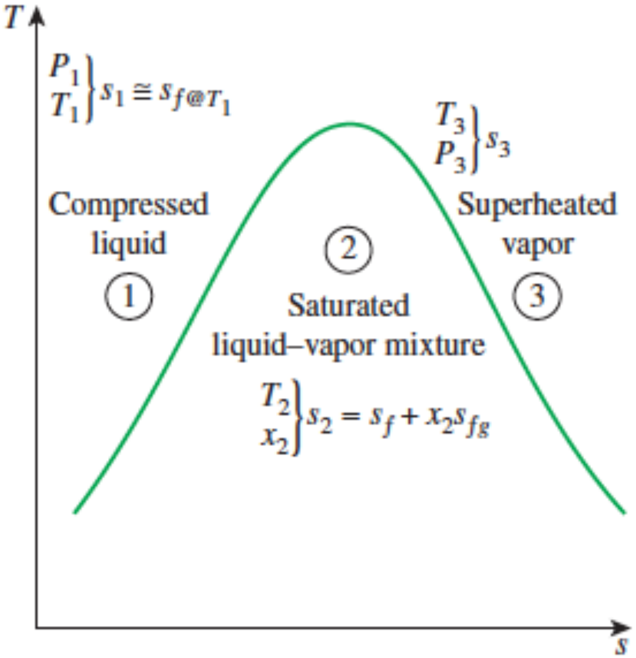
The entropy change of a system can be negative, but the entropy generation cannot.

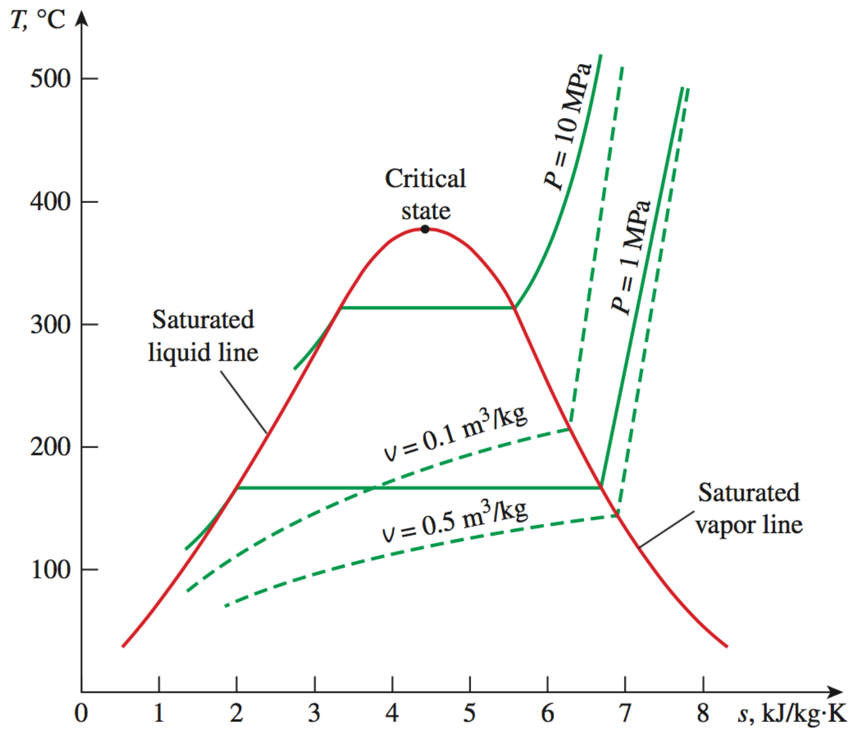
1. Processes can occur in a *certain* direction only, not in *any* direction. A process must proceed in the direction that complies with the increase of entropy principle, that is, $S_{gen} \geq 0$. A process that violates this principle is impossible.
2. Entropy is a *nonconserved property*, and there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

Entropy change of pure substance

Entropy

- A property, fixed for a state, specified by two intensive variable (for simple compressible system)





Compressible liquid without much data can be approximated to its saturation value

The entropy change of a specified mass m (a closed system) during a process is simply

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

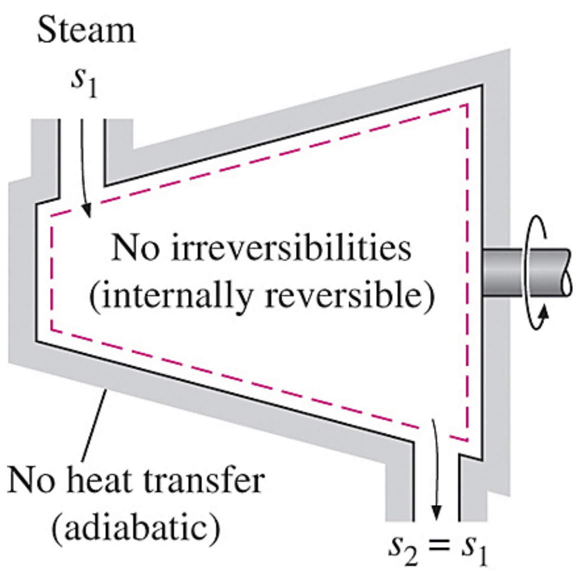
Insentropic process

The entropy of a fixed mass can be changed by

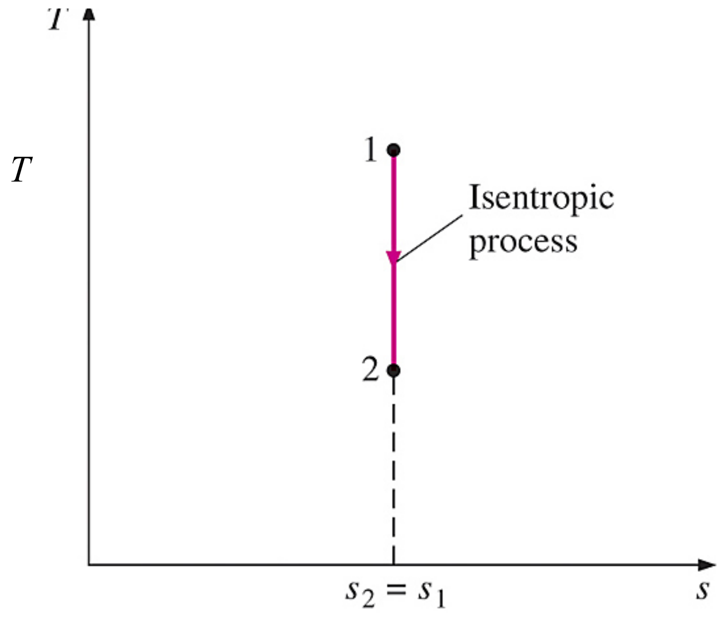
- heat transfer
- irreversibility

The entropy remains constant for internally reversible and adiabatic process: **isentropic process**.

Isentropic process: $\Delta s = 0$ or $s_2 = s_1$ (kJ/kg·K)

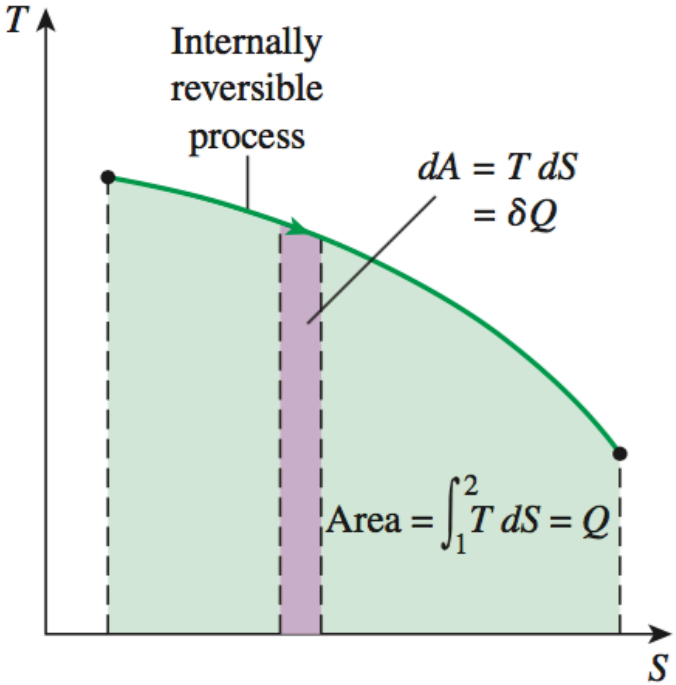


During an internally reversible, adiabatic (isentropic) process, the entropy remains constant.



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

Property diagram involving Entropy



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

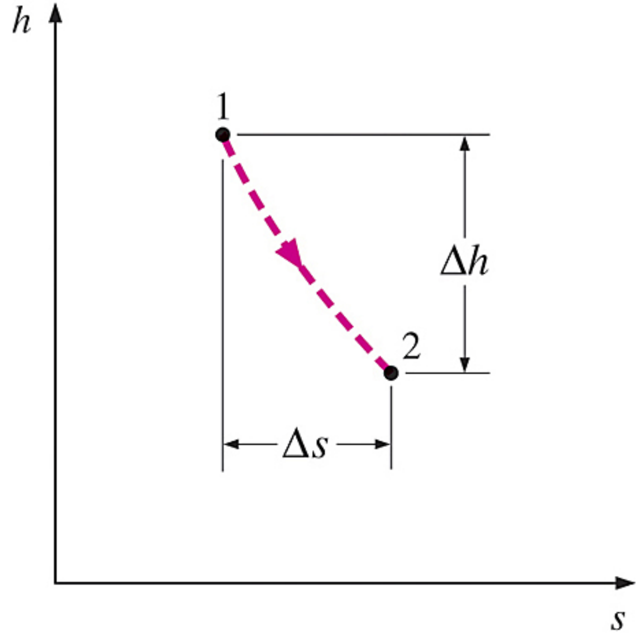
$$\delta Q_{\text{int rev}} = T\,dS \qquad Q_{\text{int rev}} = \int_1^2 T\,dS$$

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

Internally reversible Isothermal process

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

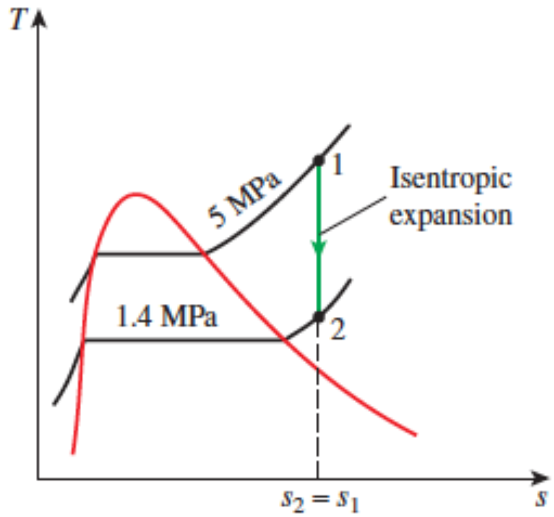
Mollier diagram: The *h-s* diagram



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.

Insentropic 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.



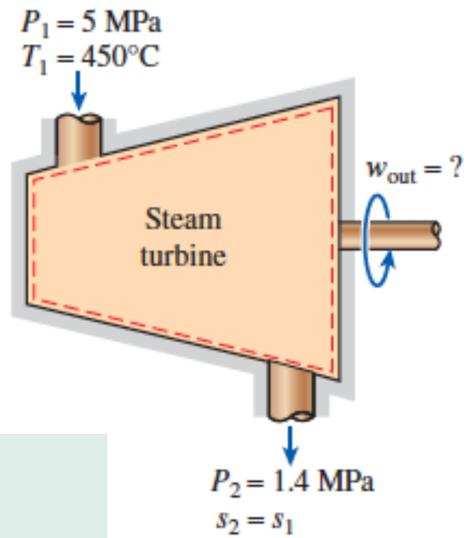
Steady-flow process, reversible process,

$$\underbrace{\dot{E}_{in} - \dot{E}_{out}}_{\text{Rate of net energy transfer by heat, work, and mass}} = \underbrace{dE_{system}/dt}_{\text{Rate of change in internal, kinetic, potential, etc., energies}}^{\nearrow 0 \text{ (steady)}} = 0$$

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

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

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



Reversible and adiabatic => isentropic

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

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

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

Next lecture

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