ESO 201A: Thermodynamics

2016-2017-I semester

Entropy: part 4

Dr. Jayant K. Singh
Department of Chemical Engineering
Faculty Building 469,
Telephone: 512-259-6141
E-Mail: jayantks@iitk.ac.in
home.iitk.ac.in/~jayantks/ESO201/index.html

Next lecture

- 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.

Reversible steady flow work

$$\delta q_{\text{rev}} - \delta w_{\text{rev}} = dh + d\text{ke} + d\text{pe}$$

$$\left.\begin{aligned} \delta q_{\text{rev}} &= T\,ds && \text{(Eq. 7–16)} \\ T\,ds &= dh - v\,dP && \text{(Eq. 7–24)} \end{aligned}\right\} \quad \delta q_{\text{rev}} = dh - v\,dP$$

$$-\delta w_{\text{rev}} = v\,dP + d\text{ke} + d\text{pe}$$

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

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

When kinetic and potential energies are negligible

$$w_{\text{rev,in}} = \int_1^2 v\,dP + \Delta\text{ke} + \Delta\text{pe}$$

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

For the steady flow of a liquid through a device that involves no work interactions
(such as a pipe section), the work term is zero (Bernoulli equation):

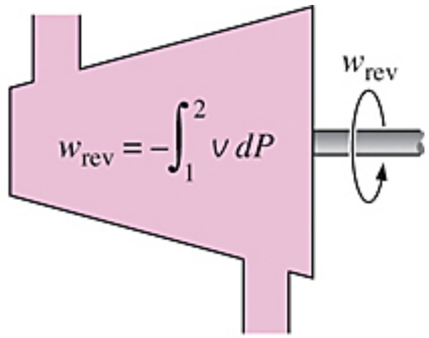
$$v(P_2 - P_1) + \frac{V_2^2 - V_1^1}{2} + g(z_2 - z_1) = 0$$

$$w = -\int_1^2 v\,dP$$

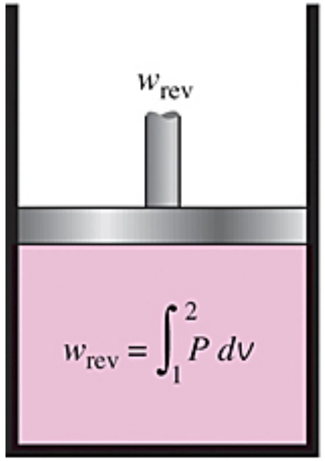
$$w = -\int_1^2 V\,dP$$

$$W = -\int_1^2 V\,dP$$

The larger the specific volume, the greater the work produced (or consumed) by a steady-flow device.



(a) Steady-flow system



(b) Closed system

Proof that Steady-Flow Devices Deliver the Most and Consume the Least Work when the Process Is Reversible

Taking heat input and work output positive:

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

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

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

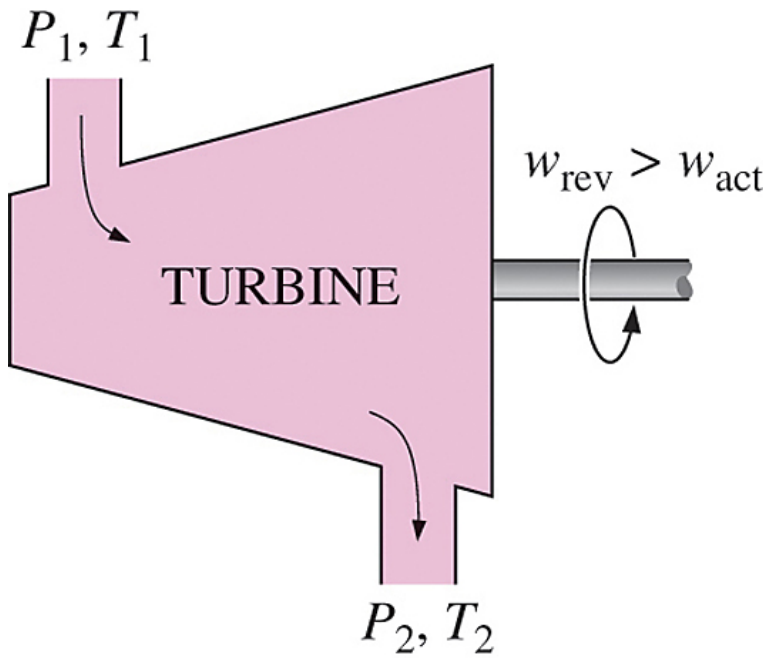
$$\delta w_{rev} - \delta w_{act} = \delta q_{rev} - \delta q_{act}$$

$$\delta q_{rev} = T\,ds \qquad ds \geq \frac{\delta q_{act}}{T}$$

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

$$\partial w_{rev} \geq \partial w_{act}$$

$$w_{rev} \geq w_{act}$$



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

Work-producing devices such as turbines deliver more work, and work-consuming devices such as pumps and compressors require less work when they operate reversibly.

MINIMIZING THE COMPRESSOR WORK

$$w_{\text{rev,in}} = \int_1^2 v\, dP$$ When kinetic and potential energies are negligible

Isentropic (Pv^k = constant):

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

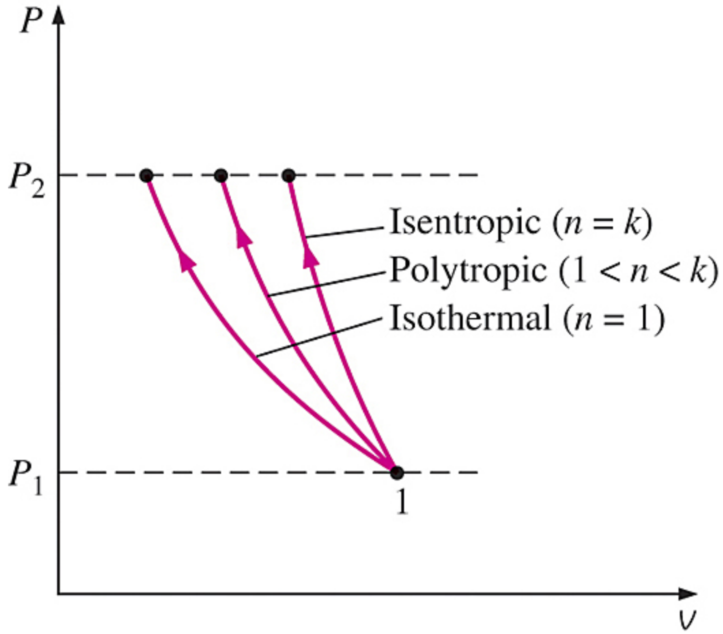
Polytropic (Pv^n = constant):

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

Isothermal (Pv = constant):

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

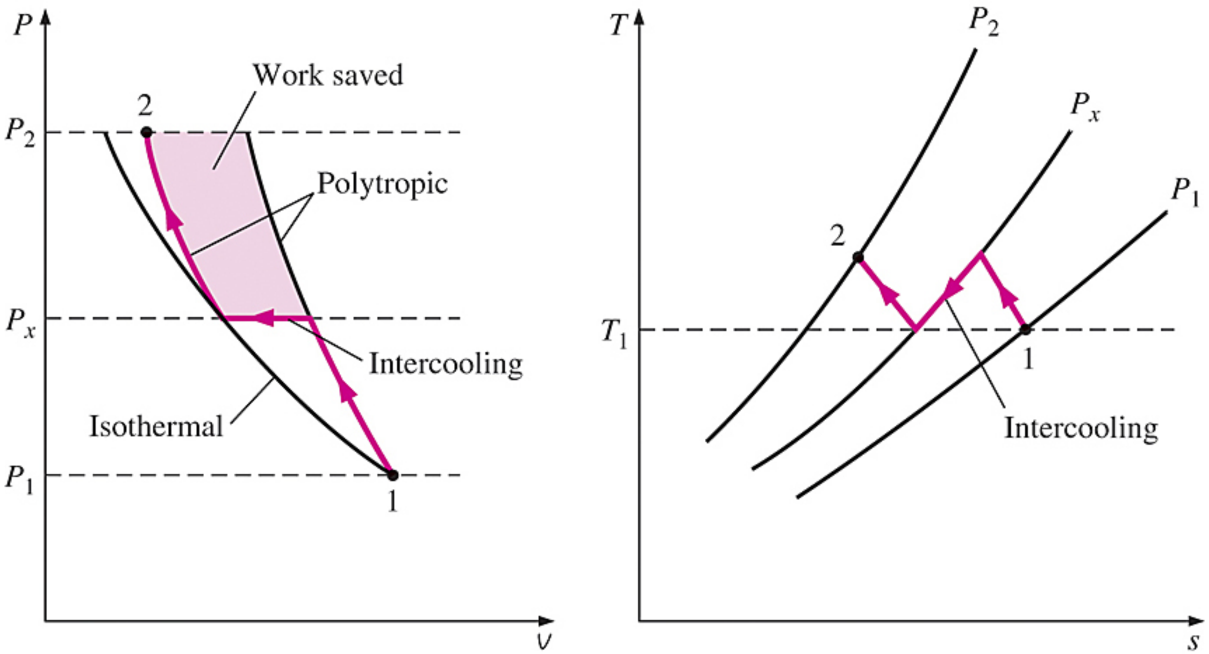
The adiabatic compression (Pv^k = constant) requires the maximum work and the isothermal compression (T = constant) requires the minimum. **Why?**



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*.



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

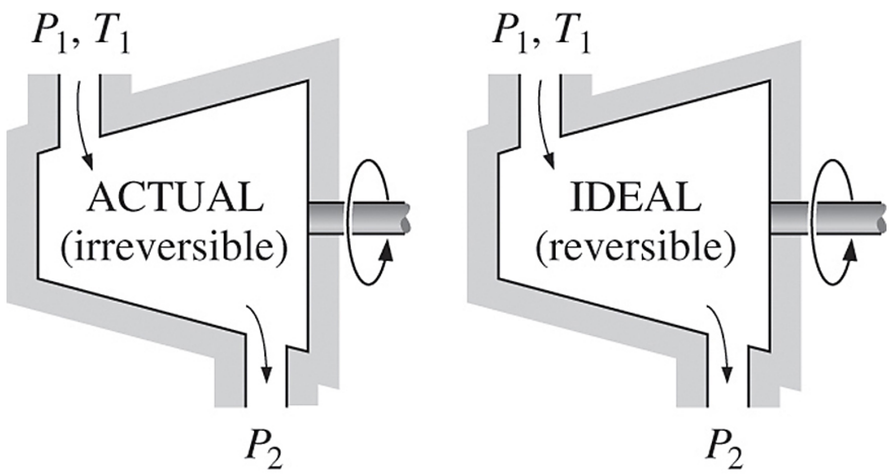
$$w_{\text{comp,in}} = w_{\text{comp I,in}} + w_{\text{comp II,in}}$$

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

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

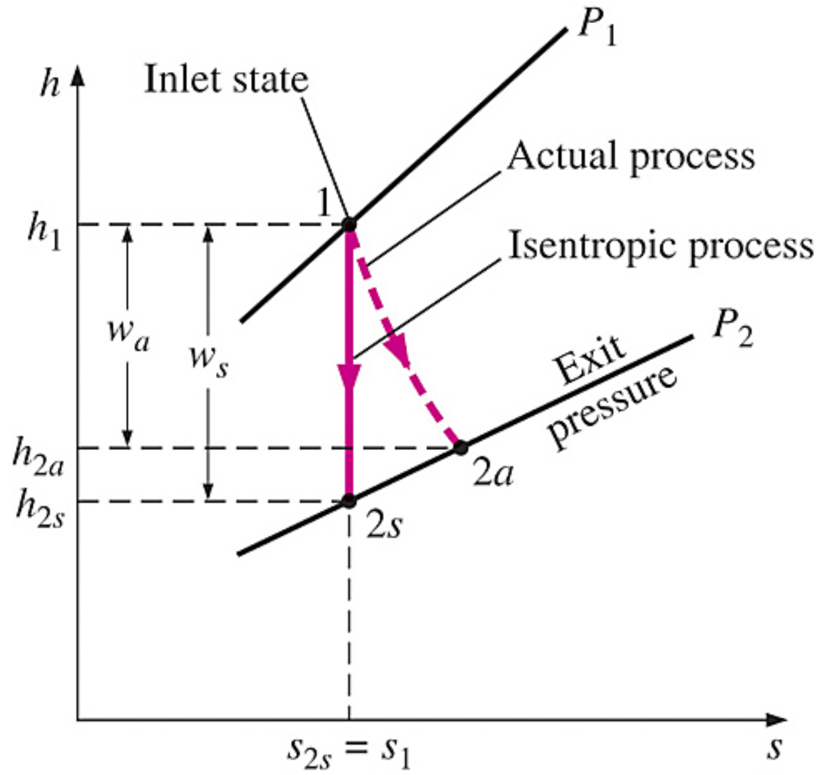
To minimize compression work during two-stage compression, the pressure ratio across each stage of the compressor must be the same.

ISENTROPIC EFFICIENCIES OF STEADY-FLOW DEVICES



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

Isentropic Efficiency of Turbines



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

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

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

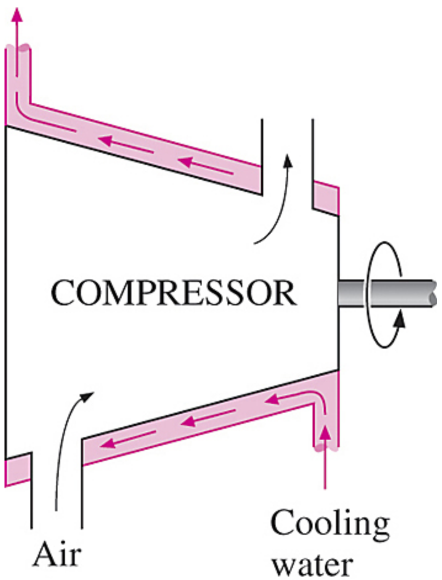
Isentropic Efficiencies of Compressors and Pumps

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

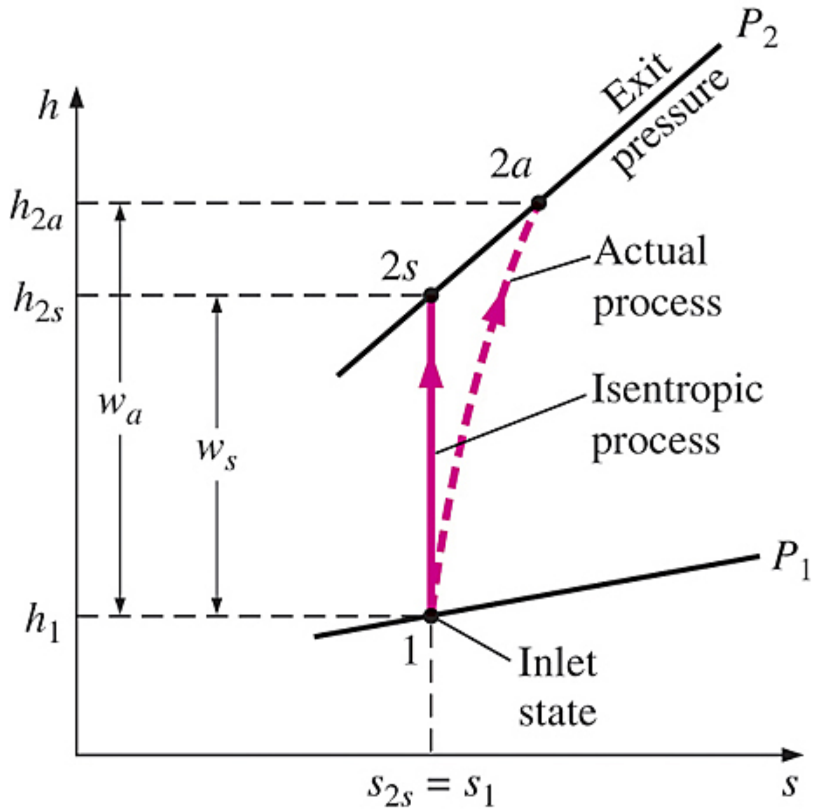
$$\eta_C \cong \frac{h_{2s} - h_1}{h_{2a} - h_1}$$ When kinetic and potential energies are negligible

$$\eta_P = \frac{w_s}{w_a} = \frac{v(P_2 - P_1)}{h_{2a} - h_1}$$ For a pump

$$\eta_C = \frac{w_t}{w_a}$$ Isothermal efficiency



Compressors are sometimes intentionally cooled to minimize the work input.



Can you use isentropic efficiency for a non-adiabatic compressor?

Can you use isothermal efficiency for an adiabatic compressor?

Isentropic Efficiency of Nozzles

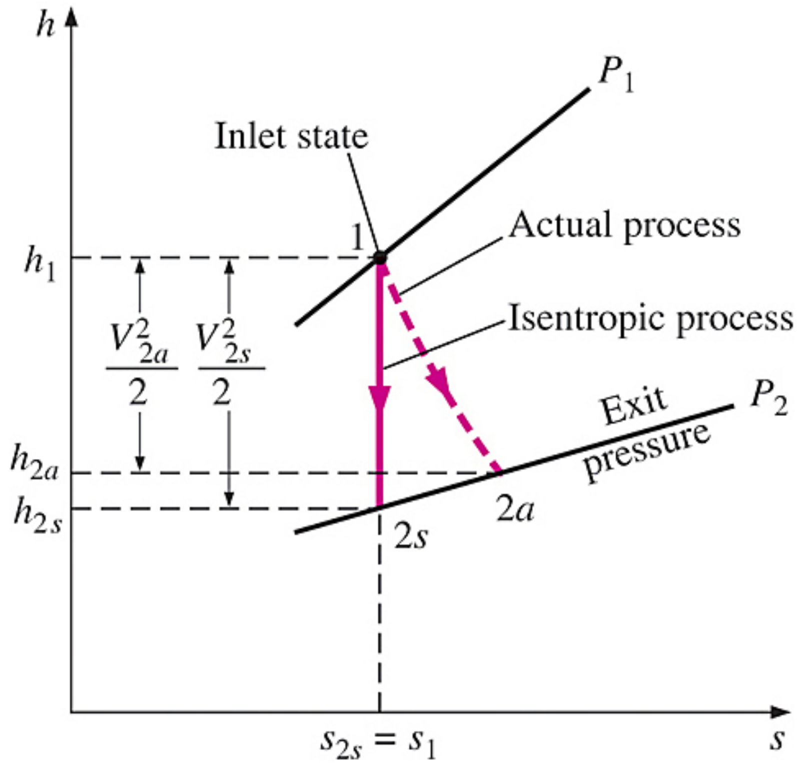
$$\eta_N = \frac{\text{Actual KE at nozzle exit}}{\text{Isentropic KE at nozzle exit}} = \frac{V_{2a}^2}{V_{2s}^2}$$

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

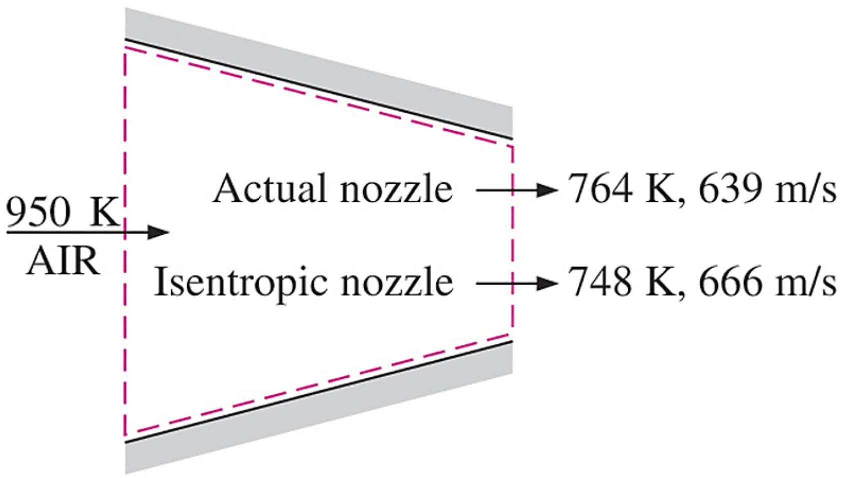
$$h_1 = h_{2a} + \frac{V_{2a}^2}{2}$$

Then,

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



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



Next lecture

- 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.