Thermodynamics: An Engineering Approach
8th Edition
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Topic 15
Reversible Work

Objectives

- 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.
- Apply the second law of thermodynamics to processes.

REVERSIBLE STEADY-FLOW WORK

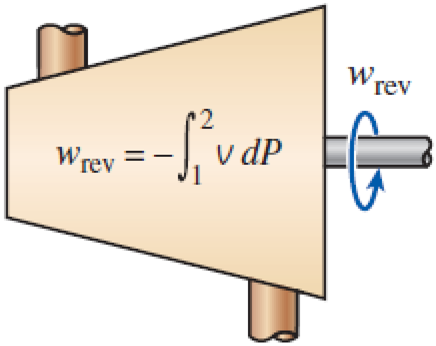
Recall the formula for boundary work:

$$W_b = \int_1^2 P dV$$

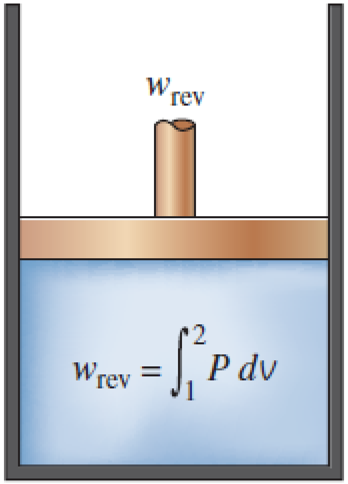
This was useful for closed systems like piston cylinders. But what about open, steady flow systems like turbines?

Total Energy Balance (differential form):

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



(*a*) Steady-flow system



(*b*) Closed system

FIGURE 7–40
Reversible work relations for steady-flow and closed systems.

Reversible Steady-flow Work

$$\delta q_{rev} = Tds = dh - \nu dP$$

$$dh - \nu dP - \delta w_{rev} = dh + dke + dpe$$

$$-\delta w_{rev} = \nu dP + dke + dpe$$

If kinetic and potential energies are ignored, then:

$$w_{rev,out} = -\int_1^2 \nu dP$$

$$w_{rev,in} = \int_1^2 \nu dP$$

Reversible Steady-flow Work

$$-\delta w_{rev} = \nu dP + dke + dpe$$

$$\dot{W}_{in} = \dot{m}\left[\nu \Delta P + \Delta ke + \Delta pe\right]$$

$$\dot{W}_{in} = \dot{m}\left[\nu\left(P_2 - P_1\right) + \frac{V_2^2 - V_1^2}{2} + g\left(z_2 - z_1\right)\right]$$

$$\dot{W}_{in} = \dot{m}\left[\frac{\left(P_2 - P_1\right)}{\rho} + \frac{V_2^2 - V_1^2}{2} + g\left(z_2 - z_1\right)\right]$$

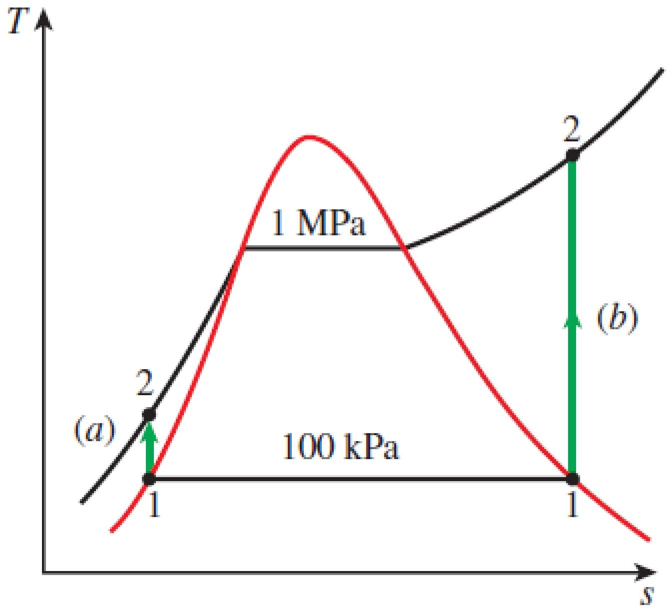
Look familiar?

What if there is no work?

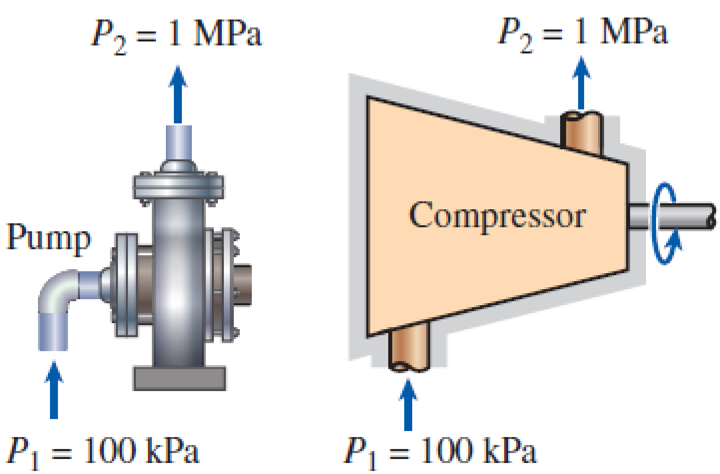
$$0 = \left[\frac{\left(P_2 - P_1\right)}{\rho} + \frac{V_2^2 - V_1^2}{2} + g\left(z_2 - z_1\right)\right]$$

Bernoulli Equation

Compressing a Liquid vs. Gas



Determine the work input required to compress steam isentropically from 100 kPa to 1 MPa, assuming that the steam exists as (a) saturated liquid and (b) as saturated vapor.



(*a*) Compressing a liquid

(*b*) Compressing a vapor

Example 1

Proof that Reversible Process is more Efficient

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

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

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

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

$$\delta q_{rev} = T ds$$

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

$$ds \geq \frac{\delta q_{act}}{T}$$

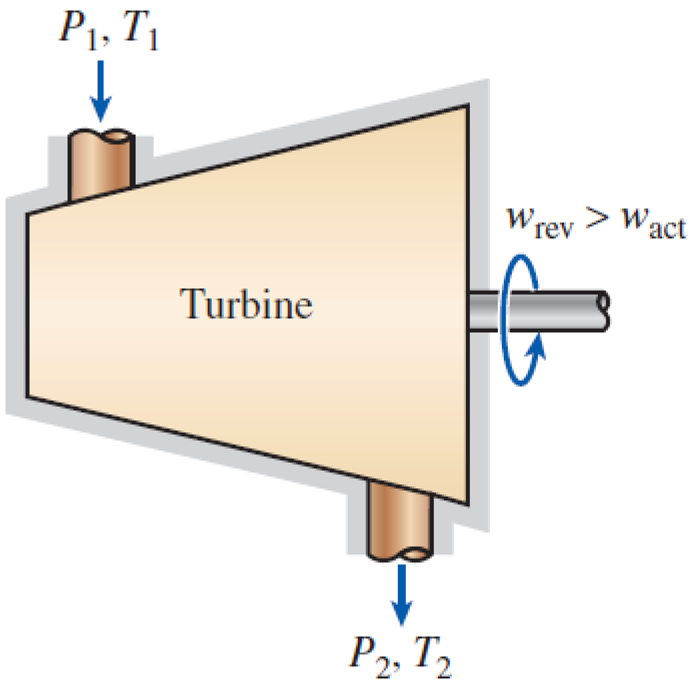


FIGURE 7–43
A reversible turbine delivers more work than an irreversible one if both operate between the same end states.

MINIMIZING THE COMPRESSOR WORK

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

When kinetic and potential energies are negligible

Isentropic (Pv^k = constant):

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

Polytropic (Pv^n = constant):

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

Isothermal (Pv = constant):

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

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

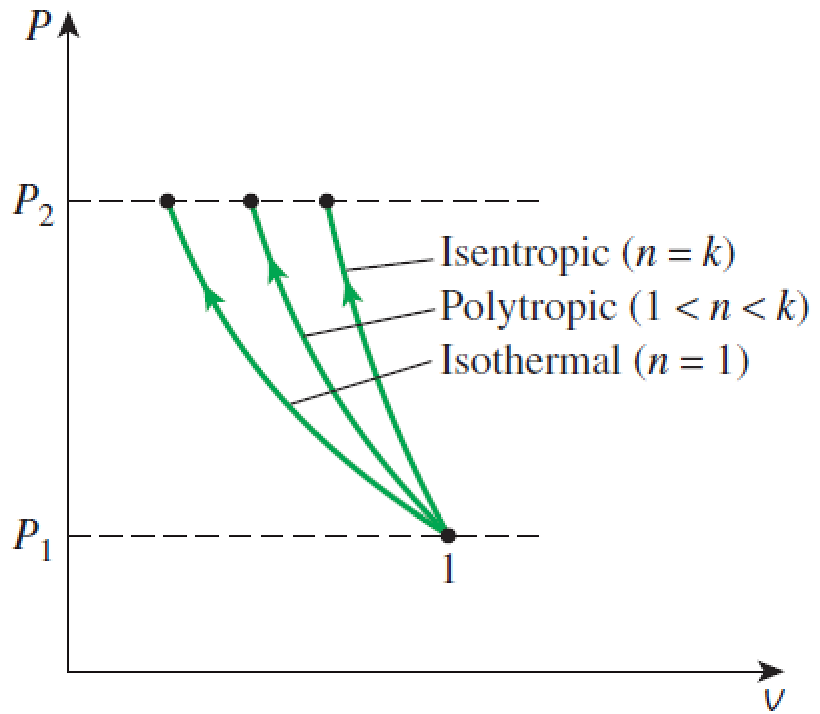


FIGURE 7–44

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*.

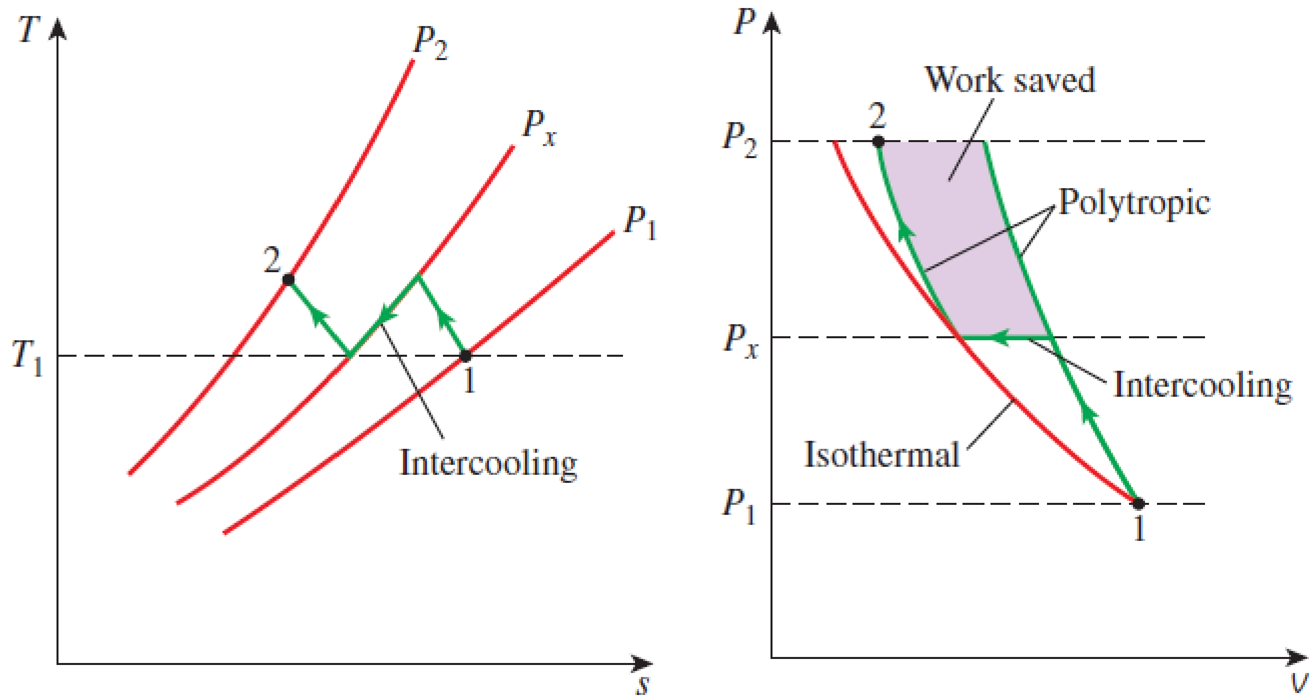


FIGURE 7–45
P-v and T-s diagrams for a two-stage steady-flow compression process.

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

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

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

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

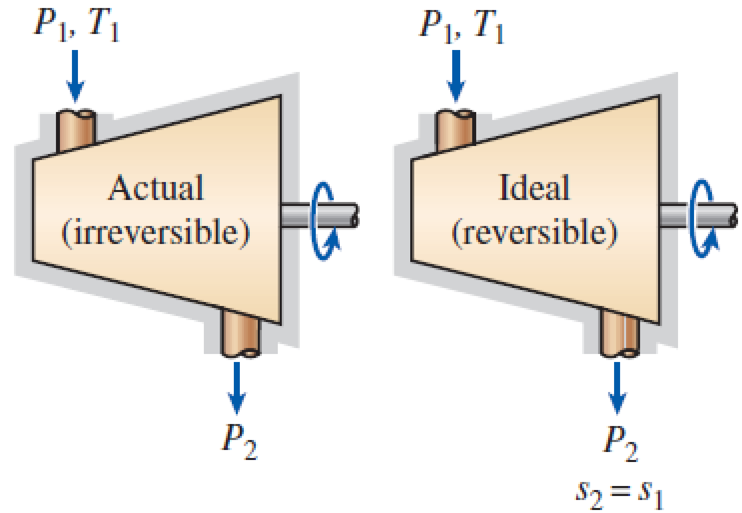


FIGURE 7–47
The isentropic process involves no irreversibilities and serves as the ideal process for adiabatic devices.

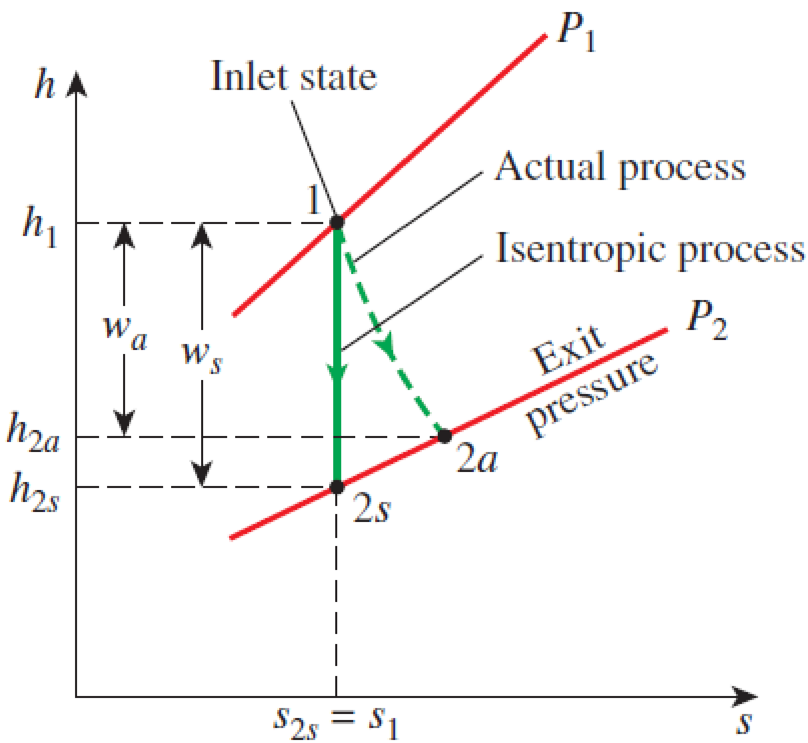


FIGURE 7–48
The *h-s* diagram for the actual and isentropic processes of an adiabatic turbine.

Isentropic Efficiency of Turbines

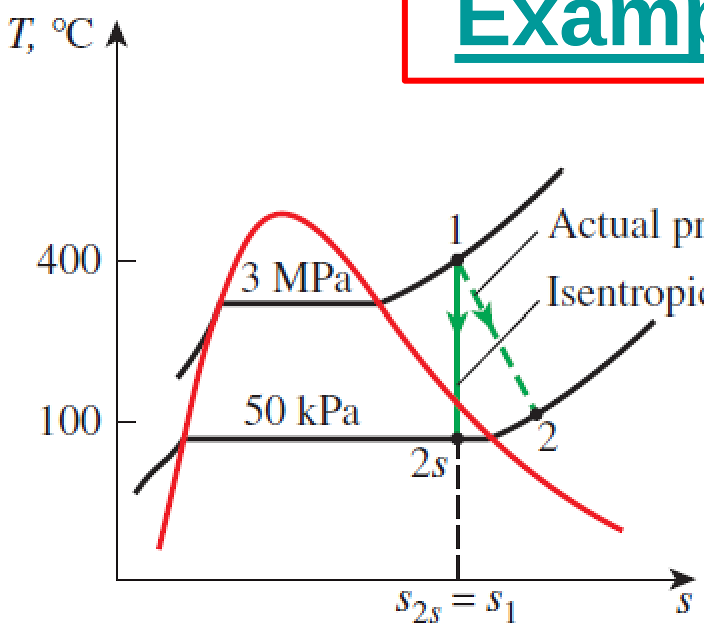
$$\eta_T = \frac{\text{Actual turbine work}}{\text{Isentropic turbine work}} = \frac{w_a}{w_s}$$

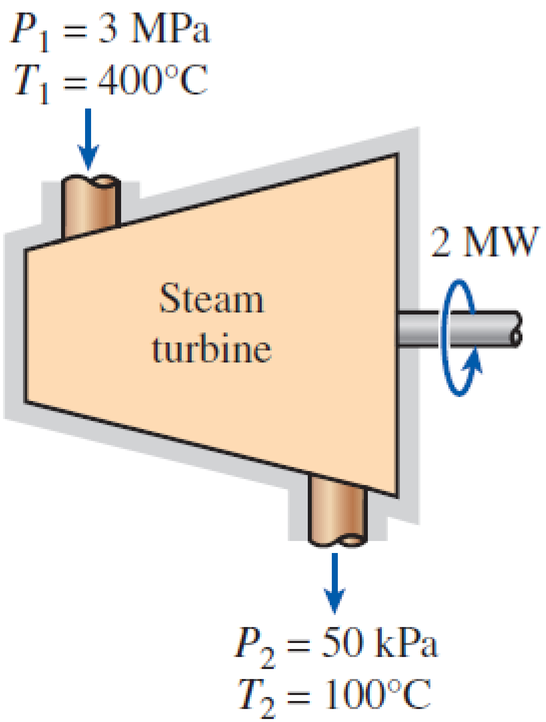
$$\eta_T \cong \frac{h_1 - h_{2a}}{h_1 - h_{2s}}$$

Isentropic Efficiency of a Turbine

Steam enters an adiabatic turbine steadily at 3 MPa and 400ºC and leaves at 50 kPa and 100ºC. If the power output of the turbine is 2 MW, determine the isentropic efficiency and the mass flow rate of the steam.

Example 2





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

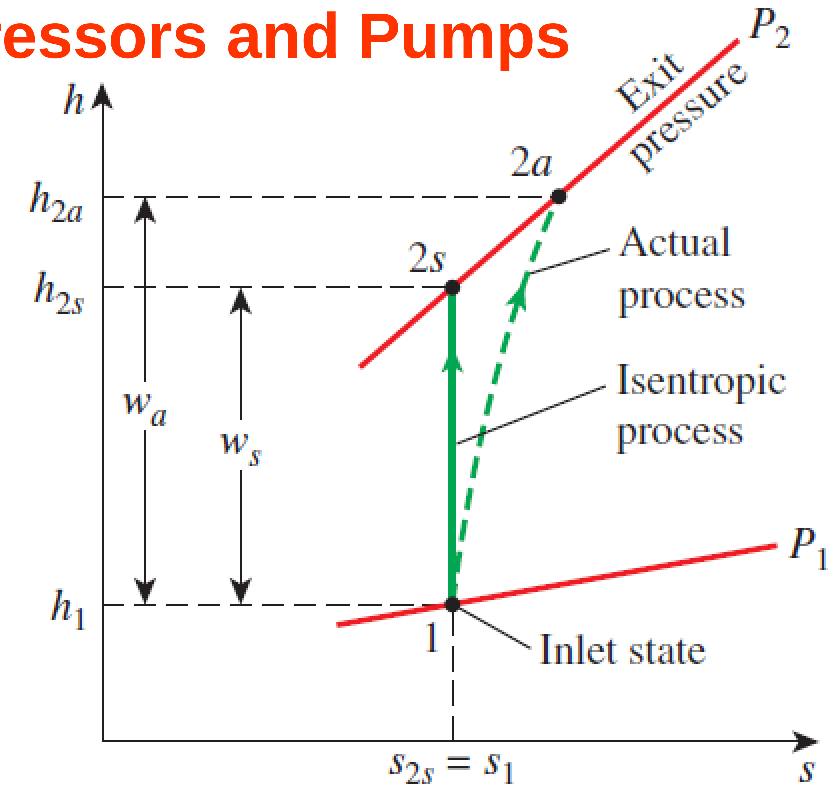
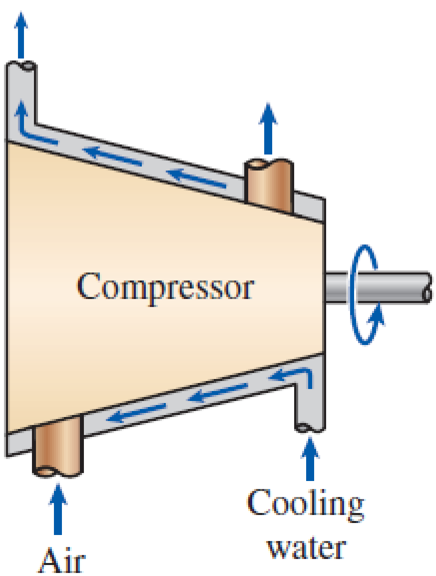


FIGURE 7–50
The *h*-*s* diagram of the actual and isentropic processes of an adiabatic compressor.



Compressors are sometimes intentionally cooled to minimize the work input.

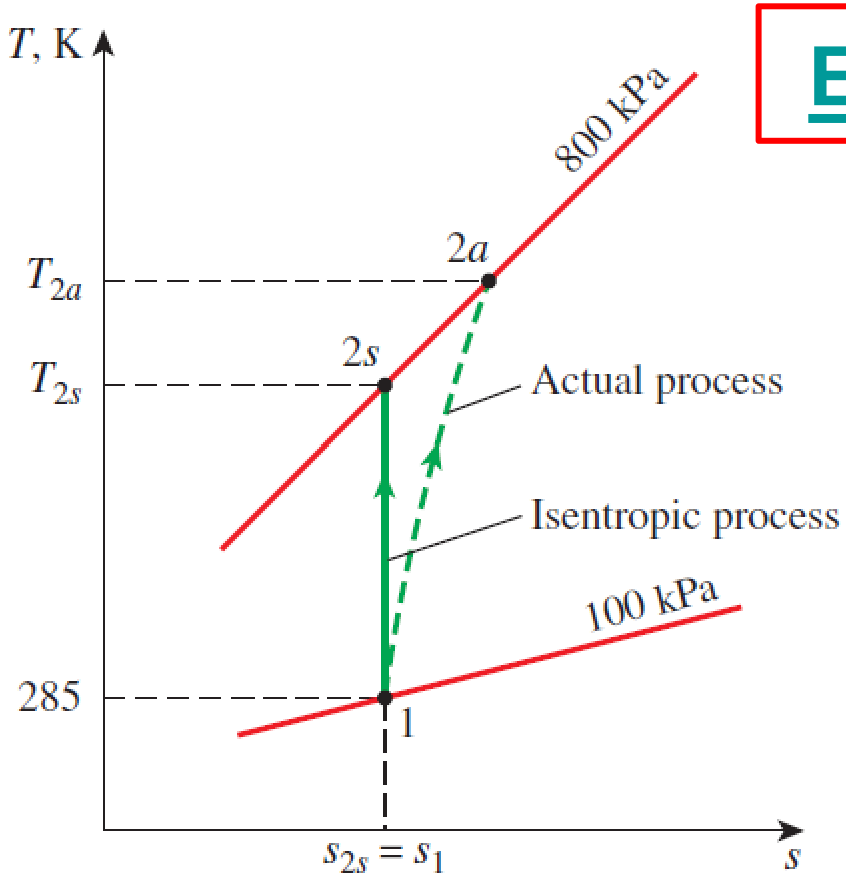
Can you use isentropic efficiency for a non-adiabatic compressor?

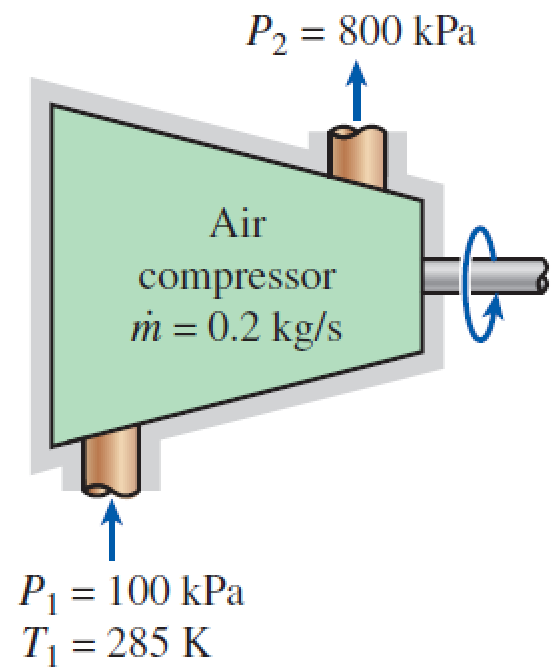
Can you use isothermal efficiency for an adiabatic compressor?

Effect of Efficiency on Compressor Power Input

Air is compressed by an adiabatic compressor from 100 kPa and 12°C to a pressure of 800 kPa at a steady rate of 0.2 kg/s. If the isentropic efficiency is 80%, determine the air temperature at the exit and the require power input for the compressor.

Example 3





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,

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

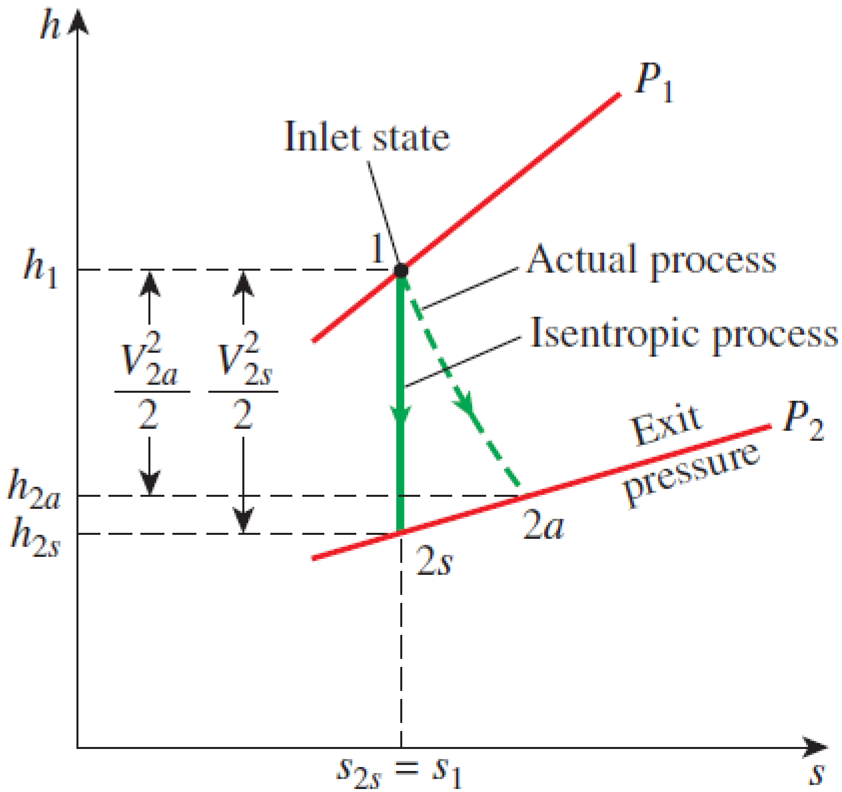
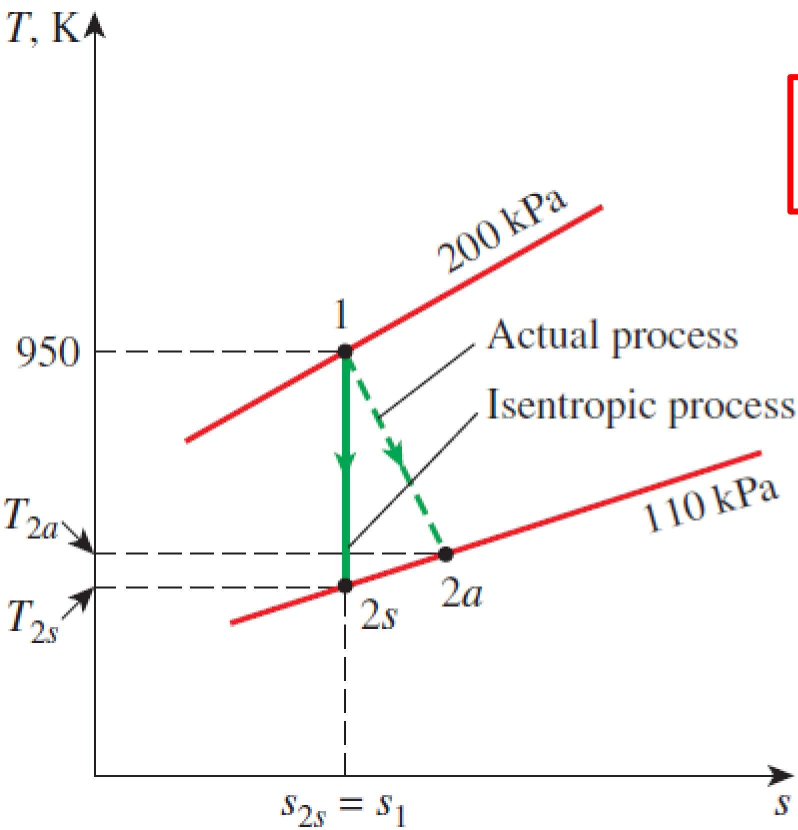


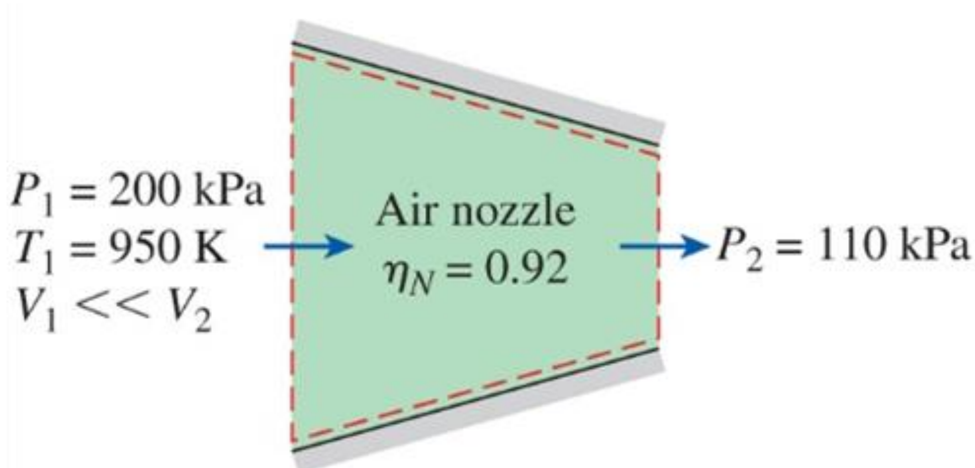
FIGURE 7–53
The h-s diagram of the actual and isentropic processes of an adiabatic nozzle.

Effect of Efficiency on Nozzle Exit Velocity

Air at 200 kPa and 950 K enters an adiabatic nozzle at low velocity and is discharged at a pressure of 110 kPa. If the isentropic efficiency of the nozzle is 92%, determine the maximum possible velocity, the exit temperature of the air, and the actual velocity of the air. Assume constant specific heat of air is 1.11 kJ/ kg K and the specific heat ratio is 1.349.



Example 4



Summary

- Reversible steady-flow work
- Minimizing the compressor work
- Isentropic efficiencies of steady-flow devices
- The increase of entropy principle