2. COMPRESSION PROCESSES

Just as expansion processes result in pressure reductions in a flowing fluid, so compression processes bring about pressure increases. Compressors, pumps, fans, blowers, and vacuum pumps are all devices designed for this purpose.

Compressors

The compression of gases may be accomplished in equipment with rotating blades (like a turbine operating in reverse) or in cylinders with reciprocating pistons. Rotary equipment is used for high-volume flow where the discharge pressure is not too high. For high pressures, reciprocating compressors are required

In a compression process, the isentropic work, as given by Eq. (7.15), is the minimum shaft work required for compression of a gas from a given initial state to a given discharge pressure. Thus we define compressor efficiency as:

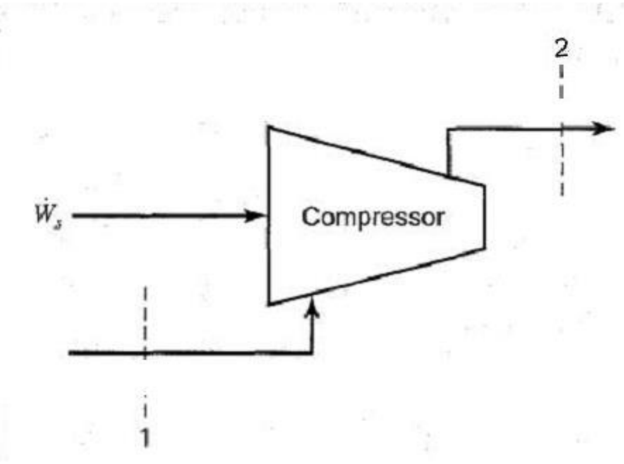

Figure ***7.5*** Steady-state compression process

$$\eta \equiv \frac{W_s(\text{isentropic})}{W_s}$$

In view of Eqs. (7.14) and (7.15), this is also given by:

$$\eta \equiv \frac{(\Delta H)_S}{\Delta H} \qquad (7.17)$$

Compressor efficiencies are usually in the range of 0.7 to 0.8

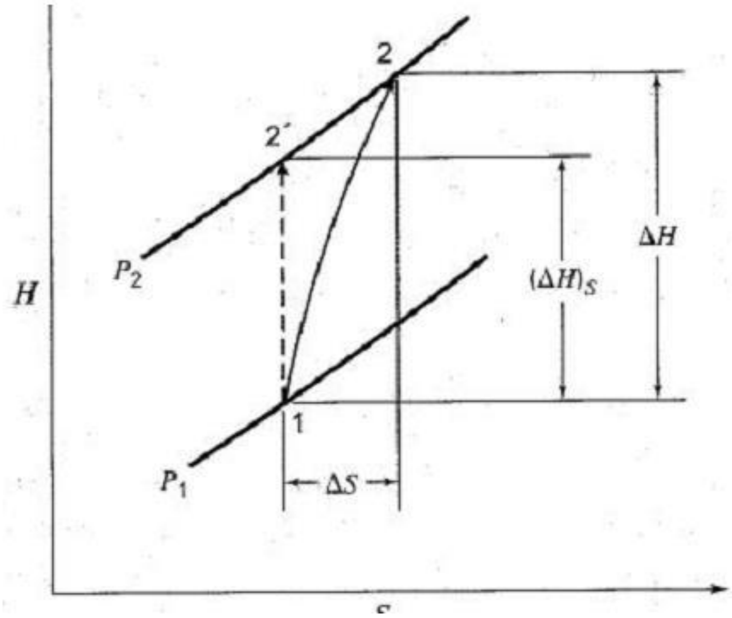

Figure 7.6 Adiabatic compression process

The compression process is shown on an HS diagram in Fig. 7.6. The vertical path rising from point 1 to point 2' represents the isentropic compression process from P_1 to P_2. The actual compression process follows a path from point 1 upward and to the right in the direction of increasing entropy, terminating at point 2 on the isobar for P_2.

Example 7.8

Saturated-vapor steam at 100 kPa (t^{sat} = 99.63°C) is compressed adiabatically to 300 kPa. If the compressor efficiency is 0.75, what is the work required and what are the properties of the discharge stream?

Solution 7.8

For saturated steam at 100 kPa,

$$S_1 = 7.3598 \text{ kJ}\cdot\text{kg}^{-1}\cdot\text{K}^{-1} \qquad H_1 = 2675.4 \text{ kJ}\cdot\text{kg}^{-1}$$

For isentropic compression to 300 kPa, $S_2' = S_1 = 7.3598$ kJ·kg^{-1}·K^{-1}. Interpolation in the tables for superheated steam at 300 kPa shows that steam with this entropy has the enthalpy: $H_2' = 2888.8$ kJ·kg^{-1}.

Thus, $$(\Delta H)_S = 2888.8 - 2675.4 = 213.4 \text{ kJ}\cdot\text{kg}^{-1}$$

By Eq. (7.17), $$(\Delta H) = \frac{(\Delta H)_S}{\eta} = \frac{213.4}{0.75} = 284.5 \text{ kJ}\cdot\text{kg}^{-1}$$

and $$H_2 = H_1 + \Delta H = 2675.4 + 284.5 = 2959.9 \text{ kJ}\cdot\text{kg}^{-1}$$

For superheated steam with this enthalpy, interpolation yields:

$$T_2 = 246.1°\text{C} \qquad S_2 = 7.5019 \text{ kJ}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$$

Moreover, by Eq. (7.14), the work required is:

$$W_s = \Delta H = 284.5 \text{ kJ}\cdot\text{kg}^{-1}$$

3. Pumps

Liquids are usually moved by pumps, generally rotating equipment. The same equations apply to adiabatic pumps as to adiabatic compressors. Thus, Eqs. (7.13) through (7.15) and Eq. (7.16) are valid. However, application of Eq. (7.14) for the calculation of W, = ΔH requires values of the enthalpy of compressed (subcooled) liquids, and these are seldom available. The fundamental property relation, Eq. (6.8), provides an alternative. For an isentropic process,

$$dH = V\,dP \qquad (\text{const } S)$$

Combining this with Eq. (7.15) yields:

$$W_s(\text{isentropic}) = (\Delta H)_S = \int_{P_1}^{P_2} V\,dP$$

The usual assumption for liquids (at conditions well removed from the critical point) is that V is independent of P. Integration then gives:

$$W_s(\text{isentropic}) = (\Delta H)_S = V(P_2 - P_1) \qquad (7.24)$$

Also useful are the following equations from Chap. 6:

$$dH = C_P\,dT + V(1 - \beta T)\,dP \qquad (6.28)$$

$$dS = C_P \frac{dT}{T} - \beta V\,dP \qquad (6.29)$$

where the volume expansivity β is defined by Eq. (3.2). Since temperature changes in the pumped fluid are very small and since the properties of liquids are insensitive to pressure (again at conditions not close to the critical point), these equations are usually integrated on the assumption that C_p, V, and β are constant, usually at initial values. Thus, to a good approximation.

$$\Delta S = C_P \ln \frac{T_2}{T_1} - \beta V\,\Delta P \qquad (7.26)$$

- ***Volume expansivity:*** $$\beta \equiv \frac{1}{V}\left(\frac{\partial V}{\partial T}\right)_P \qquad (3.2)$$

Example 7.10

Water at 45°C and 10 kPa enters an adiabatic pump and is discharged at a pressure of 8600 kPa. Assume the pump efficiency to be 0.75. Calculate the work of the pump, the temperature change of the water, and the entropy change of the water.

Solution 7.10

The following are properties for saturated liquid water at 45°C (318.15 K):

$$V = 1010\ \text{cm}^3\cdot\text{kg}^{-1} \qquad \beta = 425 \times 10^{-6}\ \text{K}^{-1} \qquad C_P = 4.178\ \text{kJ}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$$

By Eq. (7.24),

$$W_s(\text{isentropic}) = (\Delta H)_S = (1010)(8600 - 10) = 8.676 \times 10^6\ \text{kPa}\cdot\text{cm}^3\cdot\text{kg}^{-1}$$

Because $1\ \text{kJ} = 10^6\ \text{kPa}\cdot\text{cm}^3$,

$$W_s(\text{isentropic}) = (\Delta H)_S = 8.676\ \text{kJ}\cdot\text{kg}^{-1}$$

By Eq. (7.17),

$$\Delta H = \frac{(\Delta H)_S}{\eta} = \frac{8.676}{0.75} = 11.57\ \text{kJ}\cdot\text{kg}^{-1}$$

and

$$W_s = \Delta H = 11.57\ \text{kJ}\cdot\text{kg}^{-1}$$

The temperature change of the water during pumping, from Eq. (7.25):

$$11.57 = 4.178\ \Delta T + 1010\left[1 - (425 \times 10^{-6})(318.15)\right]\frac{8590}{10^6}$$

Solution for ΔT gives:

$$\Delta T = 0.97\ \text{K} \qquad \text{or} \qquad 0.97°\text{C}$$

The entropy change of the water is given by Eq. (7.26):

$$\Delta S = 4.178 \ln\frac{319.12}{318.15} - (425 \times 10^{-6})(1010)\frac{8590}{10^6} = 0.0090\ \text{kJ}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$$