CEN 202 THERMODYNAMICS

CHAPTER 7: APPLICATIONS OF THERMODYNAMICS TO FLOW PROCESSES

TEXT BOOK: : J. M. SMITH, H. C. VAN NESS, M. M. ABBOTT, M. T. SWIHART. "INTRODUCTION TO CHEMICAL ENGINEERING THERMODYNAMICS", EIGHTH EDITION. 2018

Applications of Thermodynamics to Flow Processes

The thermodynamics of flow is based on the mass, energy, and entropy balances

The application of these balances to specific processes is the subject of this chapter.

- Treat **throttling processes**, i.e., flow through restrictions
- Calculate the work produced by **turbines** and **expanders**
- Examine compression processes as produced by **compressors**, **pumps**, blowers, fans, and vacuum pumps

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Throttling Process

When a fluid flows through a restriction, such as an **orifice**, a partly closed **valve**, or **a porous plug,** without any appreciable change in kinetic or potential energy, the primary result of the process is a pressure drop in the fluid. Such a throttling process produces no shaft work, and in the absence of heat transfer, Eq. $\Delta H + \frac{1}{2}\Delta u^2 + g\Delta z = Q + W_s$ reduces to

$\Delta H = 0$ or $H_2 = H_1$

The process therefore occurs at constant enthalpy. Because enthalpy in the ideal-gas state depends on temperature only, **a throttling process does not change the temperature in this state**. For most real gases at moderate conditions of temperature and pressure, a reduction in pressure at constant enthalpy results in a decrease in temperature.

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7.2 TURBINES (EXPANDERS)

The expansion of a gas in a nozzle to produce a high-velocity stream is a process that converts internal energy into kinetic energy, which in turn is converted into shaft work when the stream impinges on blades attached to a rotating shaft.

Thus a turbine (or expander) consists of alternate sets of nozzles and rotating blades through which vapour or gas flows in a steady-state expansion process.

The overall result is the conversion of the internal energy of a high-pressure stream into shaft work.

When steam provides the motive force as in most power plants, the device is called a turbine; when it is a high-pressure gas, such as ammonia or ethylene in a chemical plant, the device is usually called an expander.

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7.2 TURBINES (EXPANDERS)

Negligible: heat transfer, kinetic and potential energies

In turbine (expanders), heat transfer, kinetic and potential energies are negligible. So energy balance equation is reduced:

$$\dot{W}_s = \dot{m}\Delta H = \dot{m}(H_2 - H_1)$$
$$W_s = \Delta H = H_2 - H_1$$

Usually, the inlet conditions T_1 and P_1 and the discharge pressure P_2 are fixed. Thus in equation only H_1 is known; both H_2 and W_s are unknown, and the energy balance equation alone does not allow their calculation. However, if the fluid in the turbine expands reversibly and adiabatically, the process is isentropic, and $S_2 = S_1$. This second equation fixes the final state of the fluid and determines H_2.

W_s (isentropic) = $(\Delta H)_S$

The shaft work W_s (isentropic) is the maximum that can be obtained from an adiabatic turbine with given inlet conditions and given discharge pressure. Actual turbines produce less work, because the actual expansion process is irreversible; we define a turbine efficiency as:

$$\eta \equiv \frac{W_s}{W_s(isentropic)} = \frac{\Delta H}{(\Delta H)_S}$$

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7.3 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.

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

$$\eta \equiv \frac{W_s(isentropic)}{W_s} = \frac{(\Delta \boldsymbol{H})_S}{\Delta \boldsymbol{H}}$$

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7.3 COMPRESSION PROCES

Compressors:

The assumption of the ideal-gas state leads to relatively simple equations. To calculate entropy change:

$$\Delta S = \langle C_P^{ig} \rangle_S ln\frac{T_2}{T_1} - Rln\frac{P_2}{P_1} \rightarrow \Delta S = \langle C_P \rangle_S ln\frac{T_2}{T_1} - Rln\frac{P_2}{P_1}$$

where for simplicity the superscript ig has been omitted from the mean heat capacity. If the compression is isentropic, ΔS = 0, and this equation becomes:

(if ΔS = 0, T→T_2' and $\langle C_P \rangle_S \rightarrow \langle C_P' \rangle_S$)

$$T_2' = T_1 \left(\frac{P_2}{P_1}\right)^{R/\langle C_P' \rangle_S}$$

with T_2' the temperature that results when compression from T_1 and P_1 to P_2 is isentropic and where $\langle C_P' \rangle_S$ is the mean heat capacity for the temperature range from T_1 to T_2' .

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7.3 COMPRESSION PROCES

Compressors:

Applied to isentropic compression, Eq. (4.10) here becomes:

$$(\Delta \boldsymbol{H})_{\boldsymbol{S}} = \langle \boldsymbol{C}'_{\boldsymbol{P}} \rangle_{\boldsymbol{H}} (\boldsymbol{T}'_{\boldsymbol{2}} - \boldsymbol{T}_{\boldsymbol{1}})$$

Or $$W_s(isentropic) = \langle C'_P \rangle_H (T'_2 - T_1)$$

This result may be combined with the compressor efficiency to give:

$$W_s = \frac{W_s(isentropic)}{\eta}$$

The actual discharge temperature T_2 resulting from compression is also found from Chapter 4, rewritten as:

$$\Delta H = \langle C_P \rangle_H (T_2 - T_1)$$

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7.3 COMPRESSION PROCES

Compressors:

Whence, $$T_2 = T_1 + \frac{\Delta H}{\langle C_P \rangle_H} \qquad (7.21)$$

For the special case of the ideal-gas state and constant heat capacities,

$$\langle C_P' \rangle_H = \langle C_P \rangle_H = \langle C_P' \rangle_S = C_P$$

Equations above therefore become:

$$T_2' = T_1 \left(\frac{P_2}{P_1}\right)^{R/C_P} \quad \textbf{and} \quad W_s(isentropic) = C_P(T_2' - T_1)$$

Combining these equations gives:

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7.3 COMPRESSION PROCES

Compressors:

$$W_s(isentropic) = C_P T_1 \left[\left(\frac{P_2}{P_1}\right)^{R/C_P} - 1\right]$$

For monatomic gases, such as argon and helium, $R/C_P = 2/5 = 0.4$. For such diatomic gases as oxygen, nitrogen, and air at moderate temperatures, $R/C_P \approx 2/7 = 0.2857$. For gases of greater molecular complexity the ideal-gas heat capacity depends more strongly on temperature. One can easily show that the assumption of constant heat capacities also leads to the result:

$$T_2 = T_1 + \frac{(T_2' - T_1)}{\eta}$$

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Pumps

Liquids are usually moved by pumps, which are generally rotating equipment. The same equations apply to adiabatic pumps as to adiabatic compressors.

For an isentropic process, dH = V dP (const S)

For isentropic work: $\boldsymbol{W_s(isentropic) = (\Delta H)_S = \int_{P_1}^{P_2} V\,dP}$

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

$$W_s(isentropic) = (\Delta H)_S = V(P_2 - P_1)$$

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