KWAME NKRUMAH UNIVERSITY OF SCIENCE AND TECHNOLOGY
CHEMICAL ENGINEERING DEPARTMENT
CHE 252: CHEMICAL PROCESS CALCULATIONS II
INSTRUCTOR: Dr. (Mrs.) Mizpah A. D. Rockson

LECTURE 5: ENERGY BALANCE PROCEDURES

Learning Objectives

At the end of the lecture the student is expected to be able to do the following:

Given a description of any nonreactive process for which tabulated specific internal energies or specific enthalpies are available at all input and output states for all process species,

(a) draw and completely label a flowchart, including Q and *W* (or Q and *Ws* for an open system)
(c) write the necessary equations (including the appropriately simplified energy balance) to determine all requested variables.

5.1 Completely labeled flow sheet

A properly drawn and labeled flowchart is essential for the efficient solution of energy balance problems. When labeling the flowchart, be sure to include all of the information you will need to determine the specific enthalpy of each stream component including known temperatures and pressures. In addition, show states of aggregation of process materials when they are not obvious: do not simply write H_2O, for example, but rather $H_2O(s)$, $H_2O(l)$, or $H_2O(v)$, according to whether water is present as a solid, a liquid, or a vapor.

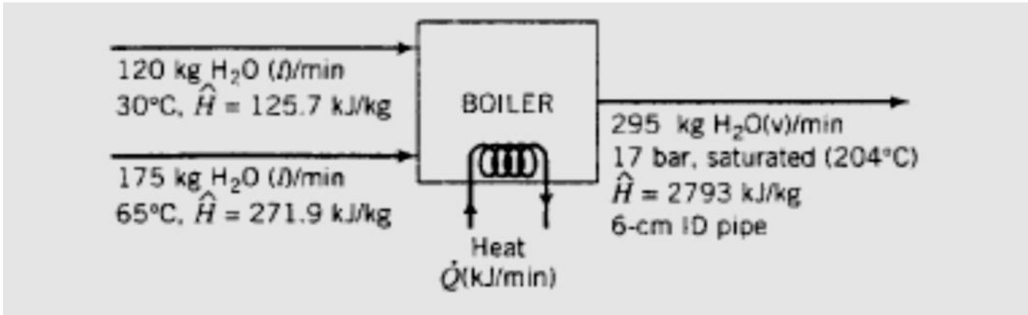
5.2 Energy Balance on a One-Component Process

Two streams of water are mixed to form the feed to a boiler. Process data are as follows:

Feed stream 1	120 kg/min @ 30^{o}C
Feed stream 2	175 kg/min @ 65^{o}C
Boiler pressure	17 bar (absolute)

The exiting steam emerges from the boiler through a 6-cm ID pipe. Calculate the required heat input to the boiler in kilojoules per minute if the emerging steam is saturated at the boiler pressure. Neglect the kinetic energies of the liquid inlet streams.

Solution



1. A first step in solving problems of this sort is to determine (if possible) the flow rates of all stream components using material balances. In this case, it is a trivial matter to write and solve a mass balance on water to determine that the flow rate of the emerging steam is 295 kg/min.

2. Next, determine the specific enthalpies of each stream component. Steam tables were used to determine H for liquid water at 30°C and 65°C and for saturated steam at 17 bar. The latter entry in the table also furnished the temperature of the saturated steam corresponding to this pressure (204°C). Note that the entries for liquid water correspond to pressures that may or may not equal the actual pressures of the inlet streams (which we do not know); we assume, however, that the enthalpy of liquid water is approximately independent of pressure and use the tabulated values.

3. The final step is to write the appropriate form of the energy balance and solve it for the desired quantity. For this open process system,

$$\dot{Q} - \dot{W}_s = \Delta\dot{H} + \Delta\dot{E}_k + \Delta\dot{E}_p$$

$\dot{W}_s = 0$ (no moving parts)

$\Delta\dot{E}_p = 0$ (generally assumed unless displacements through large heights are involved)

$$\dot{Q} = \Delta\dot{H} + \Delta\dot{E}_k$$

Evaluate ΔH

$$\Delta\dot{H} = \sum_{outlet} \dot{m}_i \hat{H}_i - \sum_{inlet} \dot{m}_i \hat{H}_i$$

$$= \frac{295\ \text{kg}}{\text{min}}\left|\frac{2793\ \text{kJ}}{\text{kg}}\right. - \frac{120\ \text{kg}}{\text{min}}\left|\frac{125.7\ \text{kJ}}{\text{kg}}\right. - \frac{175\ \text{kg}}{\text{min}}\left|\frac{271.9\ \text{kJ}}{\text{kg}}\right.$$

$$= 7.61 \times 10^5\ \text{kJ/min}$$

Evaluate ΔE_k

From steam tables, the specific volume of saturated steam at 17 bar is 0.1166 m^3/kg, and the cross-sectional area of the 6-cm ID pipe is

$$A = \pi R^2 = \frac{3.1416 \;\big|\; (3.00)^2\ cm^2 \;\big|\; 1\ m^2}{\;\big|\; \;\big|\; 10^4\ cm^2} = 2.83 \times 10^{-3}\ m^2$$

The steam velocity is

$$u(m/s) = \dot{V}(m^3/s)/A(m^2)$$

$$= \frac{295\ kg \;\big|\; 1\ min \;\big|\; 0.1166\ m^3 \;\big|\;}{min \;\big|\; 60\ s \;\big|\; kg \;\big|\; 2.83 \times 10^{-3}\ m^2}$$

$$= 202\ m/s$$

Then, since the kinetic energies of the inlet streams are assumed negligible,

$$\Delta\dot{E}_k = (\dot{E}_k)_{\text{outlet stream}} = \dot{m}u^2/2$$

$$\frac{295\ kg/min \;\big|\; (202)^2\ m^2 \;\big|\; 1\ N \;\big|\; 1\ kJ}{2 \;\big|\; s^2 \;\big|\; 1\ kg.m/s^2 \;\big|\; 10^3\ N.m} = 6.02 \times 10^3\ kJ/min$$

$$\dot{Q} = \Delta\dot{H} + \Delta\dot{E}_k$$

$$\dot{Q} = [7.61 \times 10^5 + 6.02 \times 10^3]\ kJ/min = 7.67 \times 10^5\ kJ/min$$

Note: Observe that the kinetic energy change is only a small fraction-roughly 0.8%-of the total energy requirement for the process. This is a typical result, and it is not uncommon to neglect kinetic and potential energy changes (at least as a first approximation) relative to enthalpy changes for processes that involve phase changes, chemical reactions, or large temperature changes.

5.3 Energy Balance on a Multi-Component Process

When process streams contain several components, the specific enthalpies of each component must be determined separately and substituted in the energy balance equation when $\Delta\dot{H}$ is evaluated. *For mixtures of near-ideal gases or of liquids with similar molecular structures* (e.g., mixtures of paraffins), *you may assume that* $\hat{H}$ *for a mixture component* is *the same as* $\hat{H}$ *for the pure substance at the same temperature and pressure.*

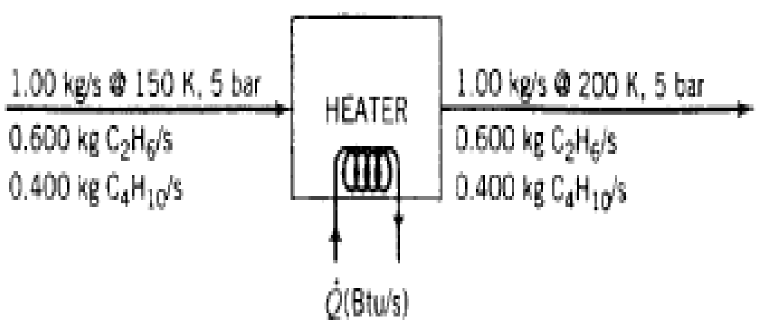
5.3.1 Energy Balance on a Two-Component Process

A liquid stream containing 60.0 wt% ethane and 40.0% n-butane is to be heated from 150 K to 200 K at a pressure of 5 bar. Calculate the required heat input per kilogram of the mixture, neglecting potential and kinetic energy changes, using tabulated enthalpy data for C_2H_6 and C_4H_{10} and assuming that mixture component enthalpies are those of the pure species at the same temperature.

Solution

Basis: 1 kg/s Mixture

The enthalpies of n-butane at 150 K and 5 bar and at 200 K and 5 bar are given on p. 2-223 of *Perry's Chemical Engineers' Handbook*, and those of ethane at the same conditions are given on p. 2-234 of the *Handbook.* The tabulated enthalpy values are shown in the energy balance.



No material balances are necessary since there is only one input stream and one output stream and no chemical reactions, so we may proceed directly to the energy balance:

$$\dot{Q} - \dot{W}_s = \Delta\dot{H} + \Delta\dot{E}_k + \Delta\dot{E}_p$$

$$\Big\Downarrow \begin{array}{l} \dot{W}_s = 0 \quad \text{(no moving parts)} \\ \Delta\dot{E}_k = 0,\ \Delta\dot{E}_p = 0 \quad \text{(by hypothesis)} \end{array}$$

$$\dot{Q} = \Delta\dot{H}$$

Since the process materials are all gases and we are assuming ideal gas behavior, we may set the enthalpies of each stream equal to the sums of the individual component enthalpies and write

$$\dot{Q} = \Delta \dot{H} = \sum_{\substack{\text{outlet} \\ \text{components}}} \dot{m}_i \hat{H}_i - \sum_{\substack{\text{inlet} \\ \text{components}}} \dot{m}_i \hat{H}_i$$

$$= \frac{0.600 \text{ kg } C_2H_6}{\text{s}} \left| \frac{434.5 \text{ kJ}}{\text{kg}} \right. + \frac{0.400 \text{ kg } C_4H_{10}}{\text{s}} \left| \frac{130.2 \text{ kJ}}{\text{kg}} \right.$$

$$- [(0.600)(314.3) + (0.400)(30.0)] \text{ kJ/s} = 112 \text{ kJ/s} \Longrightarrow \frac{112 \text{ kJ/s}}{1.00 \text{ kg/s}} = \boxed{112 \frac{\text{kJ}}{\text{kg}}}$$

5.4 Simultaneous Material and Energy Balances

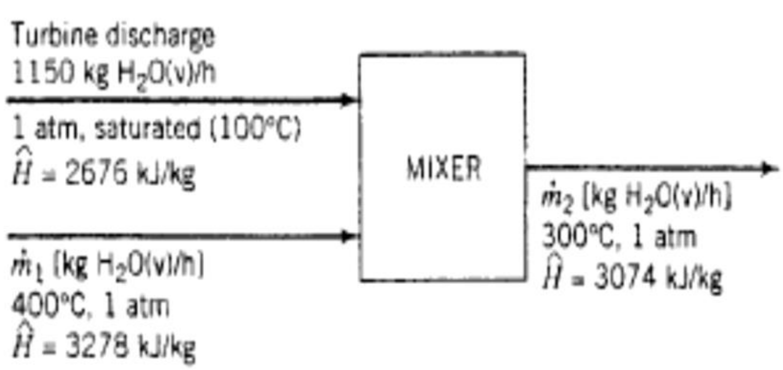
In the two previous examples, it was possible to complete all material balance calculations before undertaking the energy balance. In another class of problems one more stream amount or flow rate is unknown than can be determined by material balances alone. To solve problems of this type, you must write and solve material and energy balances simultaneously.

Example

Saturated steam at 1 atm is discharged from a turbine at a rate of 1150 kg/h. Superheated steam at 300°C and 1 atm is needed as a feed to a heat exchanger; to produce it, the turbine discharge stream is mixed with superheated steam available from a second source at 400°C and 1 atm. The mixing unit operates adiabatically. Calculate the amount of superheated steam at 300°C produced and the required volumetric flow rate of the 400°C steam.

Solution

Specific enthalpies of the two feed streams and the product stream are obtained from the steam tables and are shown below on the flowchart.



There are two unknown quantities in this process-m_1 and m_2-and only one permissible material balance. The material and energy balances must therefore be solved simultaneously to determine the two flow rates.

Mass Balance on Water
$$1150\ \text{kg/h} + \dot{m}_1 = \dot{m}_2 \qquad \textbf{(1)}$$

Energy Balance
$$\dot{Q} - \dot{W}_s = \Delta\dot{H} + \Delta\dot{E}_k + \Delta\dot{E}_p$$

$$\Bigg\Downarrow \begin{array}{l} \dot{Q} = 0 \quad \text{(process is adiabatic)} \\ \dot{W}_s = 0 \quad \text{(no moving parts)} \\ \Delta\dot{E}_k \approx 0,\ \Delta\dot{E}_p \approx 0 \quad \text{(assumption)} \end{array}$$

$$\Delta\dot{H} = \sum_{\text{outlet}} \dot{m}_i\hat{H}_i - \sum_{\text{inlet}} \dot{m}_i\hat{H}_i = 0$$

$$\frac{1150\ \text{kg}}{\text{h}}\left|\frac{2676\ \text{kJ}}{\text{kg}}\right. + \dot{m}_1(3278\ \text{kJ/kg}) = \dot{m}_2(3074\ \text{kJ/kg}) \qquad \textbf{(2)}$$

Solving Equations 1 and 2 simultaneously yields

$$\dot{m}_1 = 2240\ \text{kg/h}$$

$$\boxed{\dot{m}_2 = 3390\ \text{kg/h}} \quad \text{(product flow rate)}$$

From Table B.7, the specific volume of steam at 400°C and 1 atm ($\approx$1 bar) is 3.11 m^3/kg. The volumetric flow rate of this stream is therefore

$$\frac{2240\ \text{kg}}{\text{h}}\left|\frac{3.11\ \text{m}^3}{\text{kg}}\right. = \boxed{6980\ \text{m}^3/\text{h}}$$

If specific-volume data were not available, the ideal gas equation of state could be used as an approximation for the last calculation.