Republic of Iraq

Ministry of Higher Education

and Scientific Research

Al-Mustaqbal University College

Chemical Engineering and Petroleum Industries Department

Subject: Energy and Energy Balances

2nd Class

Lecture Five

1.4.1 Energy Balance for Open Systems with Multiple Inputs and Multiple Outputs

The general energy balance for an open system is

$$Q - \dot{W}_s = \Delta\dot{H} + \Delta KE + \Delta PE \qquad \text{..........(1.24)}$$

The change in the rate of enthalpy for multiple streams is

$$\Delta\dot{H} = \sum \dot{H}_{out} - \sum \dot{H}_{in} \qquad \text{...............(1.25)}$$

Setting enthalpy transport rate (*H*) *in terms of specific enthalpy h*

$$\Delta\dot{H} = \sum \dot{m}_{out}h_{out} - \sum \dot{m}_{in}h_{in} \qquad \text{................(1.26)}$$

Example 1.19 Enthalpy Change of Mixtures and Phase Change

Thousand kilomoles per hour of a liquid mixture of 70 mol% acetone and 30 mol% benzene is heated from 10°C to 50°C in a shell-and-tube heat exchanger using steam as the heating medium. The steam enters the heat exchanger in the shell as a saturated vapor at 16 bar of 90% quality, and exits as saturated liquid water at 16 bar. Calculate the mass flow rate of the inlet steam required for this purpose.

Solution

Known quantities: Inlet mixture flow rate and composition, inlet and exit temperature, steam inlet and outlet conditions.

Find: The mass flow rate of inlet steam.

Assumptions: The boiler is adiabatic, no shaft work, no change in inetic and potential energy, inlet and exit pipe is at the same diameter and level.

Analysis: Use energy balance for an open system around the heat

$$\Delta\dot{H} + \Delta KE + \Delta PE = \dot{Q} - \dot{W}_s$$

exchanger. Energy balance for an open system is given by

After including the assumptions, the equation is reduced to $\Delta\dot{H} = 0$

Since the system is of multiple inputs and multiple outputs, the change in enthalpy around the heat exchanger is $\Delta\dot{H} = 0 = \sum \dot{H}_{out} - \sum \dot{H}_{in}$

Setting the enthalpy transport rate (*H*) in terms of specific enthalpy *h*,

$$\Delta \dot{H} = 0 = \sum \dot{m}_{out} h_{out} - \sum \dot{m}_{in} h_{in}$$ In more detail,

$$\Delta \dot{H} = 0 = \left\{ \dot{m}_{s,out} h_{s,out} + \dot{m}_{a,out} h_{a,out} + \dot{m}_{b,out} h_{b,out} \right\}$$
$$- \left\{ \dot{m}_{s,in} h_{s,in} + \dot{m}_{a,in} h_{a,in} + \dot{m}_{b,in} h_{b,in} \right\}$$

where

$m_{s,in}$, $m_{s,out}$ are the inlet and exit mass flow rates of steam which are equal
$\dot{m}_{a,in}$, $\dot{m}_{a,out}$ are the inlet and exit mass flow rates of acetone
$\dot{m}_{b,in}$, $\dot{m}_{b,out}$ are the inlet and exit mass flow rates of benzene

Rearranging the earlier equation,

$$\Delta \dot{H} = 0 = \dot{m}_s \left(h_{s,out} - h_{s,in} \right) + \dot{m}_a \left(h_{a,out} - h_{a,in} \right) + \dot{m}_b \left(h_{b,out} - h_{b,in} \right)$$

where

$\dot{m}_a = \dot{m}_{a,in} = \dot{m}_{a,out}$ is the mass flow rate of acetone
$\dot{m}_b = \dot{m}_{b,in} = \dot{m}_{b,out}$ is the mass flow rate of benzene

Rearranging,

$$\Delta \dot{H} = 0 = \dot{m}_s \Delta h_s + \dot{m}_a \Delta h_a + \dot{m}_b \Delta h_b$$

where

Δh_s is the change in the specific enthalpy of steam
Δh_a is the change in the specific enthalpy of acetone
Δh_b is the change in the specific enthalpy of benzene

Since the mixture contains 70% acetone and 30% benzene, the mixture mass flow rate and change of mixture enthalpy can be written as

$$m_{mix} = 0.7 \dot{m}_a + 0.3 \dot{m}_b$$

The change in mixture specific enthalpy is given by

$$\Delta h_{mix} = 0.7 \Delta h_a + 0.3 \Delta h_b$$

The change in the specific enthalpy of steam, Δhs, is given by $\Delta h_s = h_{s,2} - h_{s,1}$

The inlet steam specific enthalpy ($hs,1$) of saturated vapor at 16 bar and 90% quality is

$$h_{s,1}\big|_{16\text{ bar}, x=0.9} = h_f + x h_{fg} = 858.6 + 0.9 \times 1933.2 = 2598.5 \text{ kJ/kg}$$

The exit steam specific enthalpy at 16 bar, saturated water is

$$h_{s,2}\big|_{16\text{ bar, sat'd water}} = 858.6 \text{ kJ/kg}$$

Substituting the values of the specific enthalpies of steam,

$$\Delta h_s = h_{s,2} - h_{s,1} = 858.6 - 2598.5 = -1740 \text{ kJ/kg}$$

The change in specific enthalpy of acetone and benzene mixture, Δhmix, is given by

$$\Delta h_{\text{mix}} = 0.7\Delta h_a + 0.3\Delta h_b = \int_{10°C}^{50°C} C_{P,\text{mix}}\, dT$$

The specific heat capacity of the mixture is given by

$$C_{P,\text{mix}} = \sum y_i C_{Pi} = 0.7 C_{P,\text{acetone}} + 0.3 C_{P,\text{benzene}}$$

The heat capacity at constant pressure as a function of temperature:

$$\text{Acetone (liquid): } C_{Pa}\left(\frac{\text{J}}{\text{mol °C}}\right) = 123 + 0.186T$$

$$\text{Benzene (liquid): } C_{Pb}\left(\frac{\text{J}}{\text{mol °C}}\right) = 126.5 + 0.234T$$

Substitute the heat capacities of acetone and benzene:

$$C_{P,\text{mix}} = \{0.7(123) + 0.3(126.5)\} + \{0.7(0.186) + 0.3(0.234)\}T$$

Rearranging,

$$C_{P,\text{mix}} = 124 + 0.20T$$

Substituting the mixture heat capacity,

$$\Delta h_{\text{mix}} = \int_{10°C}^{50°C} C_{P,\text{mix}}\, dT = \int_{10°C}^{50°C} (124 + 0.20T)\, dT$$

Integrating,

$$\Delta h_{\text{mix}} = \int_{10^\circ\text{C}}^{50^\circ\text{C}} (124 + 0.20T)\,dT = \left(124T + 0.20T^2\right)\Big|_{10}^{50}$$

The change in enthalpy of the acetone–benzene mixture, Δhmix, is given by

$$\Delta h_{\text{mix}} = 124(50-10) + \frac{0.20}{2}\left(50^2 - 10^2\right) = 5200\ \text{J/mol}$$

Substituting the values of change in steam enthalpy and mixture enthalpy,

$$0 = \dot{m}_s \Delta h_s + \dot{m}_{\text{mix}} \Delta h_{\text{mix}}$$

$$= \dot{m}_s \left(-1740\ \frac{\text{kJ}}{\text{kg}}\right) + 1000\ \frac{\text{kmol}}{\text{h}}\left(\frac{1000\ \text{mol}}{\text{kmol}}\right)\left(5200\ \frac{\text{J}}{\text{mol}}\left|\frac{\text{kJ}}{1000\ \text{J}}\right.\right)$$

Solving for $\dot{m}_s$, $\dot{m}_s\left(1740\ \frac{\text{kJ}}{\text{kg}}\right) = \left(5.20 \times 10^6\ \text{kJ/h}\right)$.

The rounded value of the steam mass flow rate is $ms = 2990$ kg/h. The amount of steam required for heating the acetone–benzene mixture is 2990 kg/h.

1.4.2 Enthalpy Change because of Mixing

The thermodynamic property of an ideal mixture is the sum of the contributions from the individual compounds. The following example illustrates the thermodynamic property of an ideal mixing.

Example 1.20 Mixing

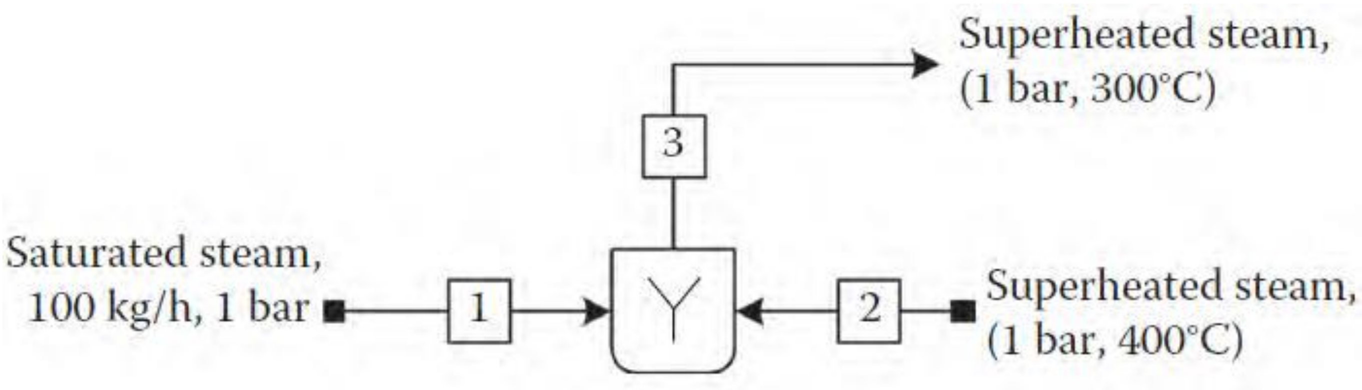
Hundred kilograms per hour of a saturated steam at 1 bar is mixed with superheated steam available at 400°C and 1 bar to produce superheated steam at 300°C and 1 bar. Calculate the amount of superheated steam produced at 300°C, and the required mass flow rate of the 400°C steam.

Solution

Known quantities: Stream 1: mass flow rate, saturated steam, 1 bar. Stream 2: 400°C and 1 atm. Stream 3: superheated steam produced at 300°C, 1 bar.

Find: Volumetric flow rate of stream 2.

Assumptions: No change in kinetic and potential energy, no shaft work.



EXAMPLE FIGURE 1.20.1 Mixing of saturated and superheated steam.

Analysis: Use open system energy balance with multiple inputs, single output. The process flow sheet is shown in Example Figure 1.20.1. The general energy balance for an open system after applying the assumptions is reduced to

$$\Delta H = 0$$

For two inputs, single output,

$$\Delta \dot{H} = \dot{H}_3 - \dot{H}_1 - \dot{H}_2 = 0$$

Putting the equation in terms of mass flow rate and specific enthalpy,

$$\Delta \dot{H} = \dot{m}_3 h_3 - \dot{m}_1 h_1 - \dot{m}_2 h_2 = 0$$

Overall mass balance for the mixing system is

$$\dot{m}_1 + \dot{m}_2 = \dot{m}_3 \Rightarrow 100\ \frac{\text{kg}}{\text{h}} + \dot{m}_2 = \dot{m}_3$$

The specific enthalpy of stream 1 is

$$h_1\big|_{\text{1 bar, sat'd steam}} = 2675.4\ \text{kJ/kg}$$

The specific enthalpy of stream 2 is

$$h_2\big|_{\text{1 bar, 400°C}} = 3278\ \text{kJ/kg}$$

The specific enthalpy of stream 3 is

$$h_3\big|_{\text{1 bar, 300°C}} = 3074\ \text{kJ/kg}$$

The general energy balance for the mixing process is

$$\dot{m}_1 \hat{H}_1 + \dot{m}_2 \hat{H}_2 = \dot{m}_3 \hat{H}_3$$

Substituting the values,

$$100\ \frac{kg}{h}\left(2675.4\ \frac{kJ}{kg}\right)+\dot{m}_2\left(3278\ \frac{kJ}{kg}\right)=\dot{m}_3\left(3074\ kJ/kg\right)$$

From the material balance equation,

$$\dot{m}_2=\dot{m}_3-100$$

Substitute the value of $\dot{m}_2$ in the earlier equation:

$$100\ kg/h\left(2675.4\ kJ/kg\right)+(\dot{m}_3-100)\left(3278\ kJ/kg\right)=\dot{m}_3\left(3074\ kJ/kg\right)$$

Solving for $\dot{m}_3$,

$$100\ kg/h\left(2675.4-3278\right)kJ/kg=\dot{m}_3\left(3074\ kJ/kg\right)-m_3\left(3278\ kJ/kg\right)$$

Rearranging,

$$\frac{100\times\left(2675.4-3278\right)\frac{kJ}{h}}{\left(3074-3278\right)\frac{kJ}{kg}}=\dot{m}_3$$

The rounded values of the mass flow rates of streams 3 and 2 are

$$\dot{m}_3=295\ kg/h \text{ and } \dot{m}_2=195\ kg/h$$