Republic of Iraq
Ministry of Higher Education
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Al-Mustaqbal University College
Chemical Engineering and Petroleum Industries Department

Subject: Energy and Energy Balances

2nd Class

Lecture two

1.1.3 Energy Balance for an Open System

In open systems, material crosses the system boundary as the process occurs (e.g., continuous process at steady state). In an open system, work must be

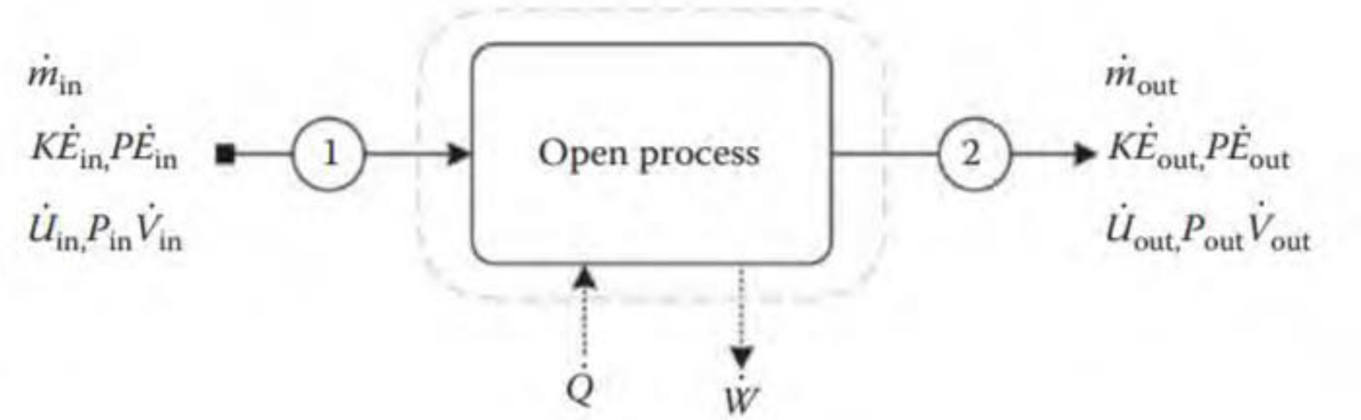


FIGURE 1.2 Energy balance for an open system.

done on the system to push input fluid streams at a pressure Pin into the system, and work is done on the surroundings to push output fluid streams at a pressure Pout out of the system, as shown in the schematic diagram in Figure 8.2 [3].

Net rate of work done by the system is

$$\dot{W}_f = \dot{W}_{out} - \dot{W}_{in} = P_{out}\dot{V}_{out} - P_{in}\dot{V}_{in} \qquad \text{……………………(1.8)}$$

For several input and output streams

$$\dot{W}_f = \sum_{output} P_j\dot{V}_j - \sum_{input} P_j\dot{V}_j \qquad \text{……………………(1.9)}$$

The total rate of work (W) done by a system on its surroundings is divided into two parts:

$$\dot{W} = \dot{W}_s + \dot{W}_f \qquad \text{…………………………(1.10)}$$

where shaft work (Ws) is the rate of work done by the fluid on a moving part within the system (e.g., piston, turbine, and rotor), and flow work (Wf) is the rate of work done by the fluid at the system outlet minus the rate of work done on the fluid at the system inlet. The general balance equation for an open continuous system (Figure 1.2) under steady state in the absence of generation/consumption term is

$$\text{Energy input} = \dot{U}_{in} + \dot{KE}_{,in} + \dot{PE}_{,in} + P_{in}\dot{V}_{in}$$ **… …….(1.11)**

$$\text{Energy output} = \dot{U}_{out} + \dot{KE}_{,out} + \dot{PE}_{,out} + P_{out}\dot{V}_{out}$$ **………(1.12)**

$$\text{Energy transferred} = \dot{Q} - \dot{W}_s$$ **………(1.13)**

Under steady state, the accumulation term is set to zero and the following equation is valid:
Energy input=Energy output

$$\dot{Q} - W_s = \Delta\dot{U} + \Delta\dot{KE} + \Delta\dot{PE} + \Delta\left(P\dot{V}\right)$$ **………………(1.14)**

Enthalpy (H) is the sum of the internal energy (U) of fluid volume added to the system plus the flow work (PV) performed on the system in order to push the fluid in/out of the system:

$$H = U + PV$$ **……………………………………….(1.15)**

The change in enthalpy transport rate is given by

$$\Delta\dot{H} = \Delta\dot{U} + \Delta\left(P\dot{V}\right)$$ **……………………………..(1.16)**

Rearranging the earlier equations leads to the first law of thermodynamics for an open system under steady state:

$$\dot{Q} - \dot{W}_s = \Delta\dot{H} + \Delta\dot{KE} + \Delta\dot{PE}$$ **………………………(1.17)**

Steam turbine is an example of an open system. Electrical generating plants operate by generating steam at elevated temperatures and pressures, then reducing the pressure in a turbine. As the pressure is reduced, the high pressure, high temperature steam expands (and cools down), driving the turbine. The shaft work produced by the turbine is transferred to a generator to produce electricity. One limitation on steam turbines is that they cannot tolerate small amounts of water in its liquid state in the gases passing through the turbine. If the liquid content of the steam is above the threshold limit (a few percentage points), the liquid droplets damage the turbine blades and lead to failure of the turbine. The steam tables in Appendix A.3 are used to determine the temperature, specific internal energy, and specific enthalpy of saturated steam and superheated steam.

Example 1.5 Energy Balance for an Open System:

The Steam Turbine

Steam flowing at a rate of 10 kg/h enters a steam turbine at a velocity of 50 m/s and leaves at a point 5 m below the inlet at a velocity of 300 m/s. The heat loss from the turbine is estimated to be 10 kW, and the turbine delivers shaft work at a rate of 70 kW. Calculate the change in enthalpy transport rate of the process.

Solution

Known quantities: Steam flow rate, inlet and exit velocity, heat loss, and work delivered.

Find: Change in enthalpy transport rate.

Analysis: Use the general energy balance equation for an open system.

System: Steam turbine as open system

The energy balance for an open system has been derived as

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

In this example, heat is lost (negative value) from the system:

$$Q = -10\ \text{kW} = -10\ \text{kJ/s}$$

The shaft work is delivered (positive value) by the system:

$$W_s = 70\ \text{kW} = 70\ \text{kJ/s}$$

The change in kinetic energy

$$\Delta KE = \frac{1}{2}\dot{m}\left(\upsilon_2^2 - \upsilon_1^2\right)$$

Substitute the values of mass flow rate (m), inlet ($\upsilon 1$), and exit ($\upsilon 2$) velocities, and use conversion factors (make sure units are consistent):

$$\Delta KE = \frac{1}{2}\left(10\,\frac{\text{kg}}{\text{h}}\,\frac{\text{h}}{3600\ \text{s}}\right)\left(300^2 - 50^2\right)$$

$$\times\left(\frac{\text{m}}{\text{s}}\right)^2\left|\frac{\text{N}}{\text{kg m/s}^2}\right|\frac{\text{J}}{\text{N}\cdot\text{m}}\left|\frac{\text{kJ}}{1000\ \text{J}}\right. = 0.12\ \text{kJ}$$

Change in potential energy

$$\Delta PE = \dot{m}g\left(z_2 - z_1\right)$$

Substitute the values of mass flow rate (m), and inlet and exit heights from the surface of the earth ($z1$,$z2$):

$$\Delta PE = 10\,\frac{\text{kg}}{\text{h}}\,\frac{\text{h}}{3600\ \text{s}} \times 9.81\,\frac{\text{m}}{\text{s}^2}$$

$$\times(\text{-5-0})\text{m}\left|\frac{\text{N}}{\text{kg m/s}^2}\right|\frac{\text{J}}{\text{N}\cdot\text{m}}\left|\frac{\text{kJ}}{1000\ \text{J}}\right. = -0.00014\ \text{kJ}$$

The change in potential energy is almost negligible compared to the magnitudes of heat and work. Substitute the values of Q, Ws, and changes in kinetic and potential energies in the energy balance equation for an open system:

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

$$\Delta \dot{H} + 0.12 \frac{\text{kJ}}{\text{s}} - 0.00014 \frac{\text{kJ}}{\text{s}} = -10 \frac{\text{kJ}}{\text{s}} - \left(70 \frac{\text{kJ}}{\text{s}}\right)$$

The change in enthalpy transport

$\Delta \dot{H} = -80.12 \text{ kJ/s}$ **rate is**

Example 1.6 Use of a Steam Table

Use steam tables in the appendix to determine the temperature, specific Internal energy and specific enthalpy of saturated steam at 3.0 bar. What is the state of the steam at 10 bar and 400°C? (i.e., is it saturated or superheated steam?)

Solution

Known quantities: *Case 1*: 3 bar, saturated steam, *Case 2*: 10 bar, 400°C.

Find: Specific enthalpy (h) and specific internal energy (u), specific volume (v). The state of steam at 10 bar and 400°C.

Analysis: Two properties are needed to be able to use saturated steam table and superheated steam table in the appendix.

Case 1: At 3 bar, steam is saturated: use saturated steam table (Appendix A.3). The temperature is 133.5°C, specific enthalpy is 2724.7 kJ/kg, and specific internal energy is 2543 kJ/kg.

Case 2: At 10 bar and 400°C: At 10 bar the saturated temperature is 179.9°C, and since the steam is at 400°C, this temperature is higher than the saturated temperature at 10 bar. Therefore, the state of water is superheated steam, and hence, the superheated steam table (Table A.5) is used. Specific enthalpy is 3264 kJ/kg, specific internal energy is 2958 kJ/kg, and specific volume is 0.307 m3/kg.

1.1.4 Steam Turbine

Steam turbines are open systems used to generate electricity; in most cases, the turbine operates adiabatically. The exit pressure of turbine is lower than the inlet pressure. Turbines produce work; by contrast, work should be provided to a compressor or a pump. The following examples explain the possible operations for a steam turbine.

Example 1.7 Steam Table and Turbine Work

Steam at a rate of 1500 kg/s enters a turbine at 40 bar and 400°C. It comes out of the turbine as wet steam at 4 bar. The turbine operates adiabatically and produces 1000 MW of work. What is the temperature of the steam leaving the turbine? What is the mass fraction of vapor in the stream leaving the turbine?

Solution

Known quantities: Steam mass flow rate (1500 kg/s), inlet conditions (40 bar and 400°C), exit steam conditions (4 bar, wet steam).

Find: Mass fraction of vapor in the stream leaving the turbine.

Assumptions: No change in kinetic and potential energy.

Analysis: Use steam tables to find inlet and exit enthalpy and the first law for an open system. Inlet and exit steam enthalpies: Saturated steam (Table A.4), superheated steam (Table A.5).

Inlet steam conditions: at 40 bar and 400°C: the enthalpy of the incoming steam is 3216 kJ/kg (Table A.5). Exit steam conditions: at 4 bar: steam is either wet or saturated (Table A.4). Since the steam leaving the turbine is a vapor–liquid mixture,

it must be saturated. From Table A.4, for saturated steam at 4 bar the enthalpies of the liquid and vapor are 604.7 and 2737.6 kJ/kg,

$$\Delta \dot{H} = -\dot{W}_s$$

respectively, and the temperature is 143.6°C. The general energy balance applied to this process, after neglecting the potential and kinetic energy terms and bearing in mind that the turbine is adiabatic, can be expressed as

Rearranging the earlier equation,

$$-\dot{W}_s = \Delta \dot{H} = \dot{H}_{out} - \dot{H}_{in} = \dot{m}(h_{out} - h_{in})$$

Substituting known values of shaft work, mass flow rate, and inlet specific enthalpy, since the turbine is producing work, the sign of *W*s is +:

$$-W_s = -1000\ \text{MW} = -1\times 10^6\ \frac{\text{kJ}}{\text{s}} = 1500\ \frac{\text{kg}}{\text{s}}(h_{out} - 3216)\frac{\text{kJ}}{\text{kg}}$$

The specific enthalpy of the exit steam is h out = 2549.3 kJ/kg

Let x be the mass fraction of the steam that is in the vapor phase, then

$$h_{out} = 2549.3\ \frac{kJ}{kg} = h_f + xh_{fg} = 604.7\ \frac{kJ}{kg} + x(2133.0\ kJ/kg)$$

The steam quality is $x = 0.912$ → The wet steam is 91.2 wt% vapor. The wet contains 91.2% water vapor and 8.80 wt% liquid water.

Example 1.8 Steam Turbine

Steam enters a turbine at a pressure of 10.0 bar (absolute) and a temperature of 600°C. The steam leaving the turbine is at 1 atm (absolute) pressure and is of 90% quality (90 wt% steam, 10 wt% liquid). How much steam has to go into the turbine to yield 1.5 × 106 kW of shaft work?

Solution

Known quantities: Steam inlet conditions (10 bar, 600°C), exit steam conditions (1 atm, 90% quality), shaft work is 1.5 × 106 kW.

Find: Amount of steam that has to go into the turbine.

Assumptions: No change in kinetic and potential energy, turbine is adiabatic.

Analysis: Use steam tables to find inlet and exit enthalpy and the first law for an open system. From the first law

$$\Delta H + \Delta KE + \Delta PE = Q - W_s$$

After applying the earlier assumptions, the equation is reduced to

$$\Delta \dot{H} = \dot{m}(h_{out} - h_{in}) = -W_s$$

To find the enthalpy of the steam leaving the turbine, use Table A.4. At 1 atm the enthalpies of saturated water and steam are 419.1 and 2676.0 kJ/kg, respectively.

Thus, the enthalpy of the steam leaving the turbine is

$$h_{out} = h_f + xh_{fg} = 419.1 + 0.9(2676.0 - 419.1) = 2450.3\ kJ/kg$$

The enthalpy of the input steam can be found from Table A.5 to be 3697 kJ/kg. values

$$\dot{m}(2450.3 - 3697) = -(1.5 \times 10^6\ kJ/s)$$

Substitute the of inlet and outlet specific enthalpy and shaft work in the first law:

The required steam mass flow rate is *m* = 1.20 ×103 kg/s

1.1.5 Heaters and Coolers

Heaters and coolers such as shell and tube heat exchangers are open systems employed to cool down or heat up certain fluid streams. In most cases, the external surface of heaters and coolers is insulated and heat is just transferred between the cold and hot streams across the walls of the exchanger tubes. The following example illustrates the use of heat exchangers for cooling and heating purposes.

Example 1.9 Heat Exchanger

Steam at a rate of 60 kg/h, at 200°C, and 1 bar enters the tube side of a shell and tube heat exchanger. The steam is used to heat cold water flowing on the shell side; the steam leaves as saturated liquid. Neglect pressure drop of the steam on the tube side and the water on the shell side of the heat exchanger. How much heat must be transferred from the steam to the water side?

Solution

Known quantities: Mass flow rate (60 kg/h), inlet temperature and pressure (200°C, 1 bar), exit conditions (saturated water, 1 bar).

Find: Heat transfer rate from steam to water.

Assumptions: Pressure drop across the boiler is neglected, so exit pressure is at 1 bar.

Analysis: Use steam tables to find inlet and exit enthalpy.

Basis: 60 kg/h of feed steam. The schematic diagram of the problem is shown in Example Figure 8.9.1. From the superheated steam table (Table A.5),

Inlet: (1 bar, 200°C): h_1 = 2875 kJ/kg Using saturated steam table (Table A.4), Outlet: (1 bar, saturated water): $h_2 = h_f$ at 1 bar = 417 5. KJ/kg

No change in steam mass flow rate: *m* = *m* in = *m* out = 60 kg/h

The general energy balance equation for an open system is

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

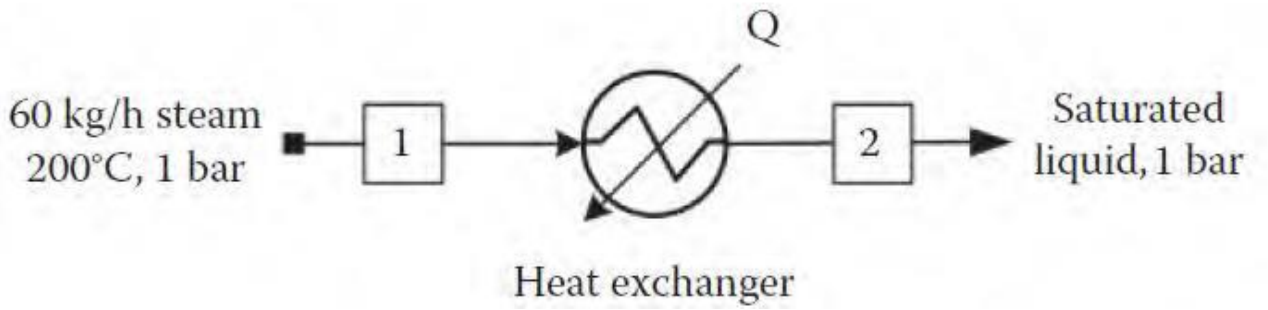
The following simplifying assumptions for the condenser are used:

No shaft work: $W_s = 0$.

No change in elevation. The inlet and outlet lines are at the same level: $\Delta PE = 0$.

Since we do not know anything about the diameters of the inlet and exit pipes, same pipe diameters are used for inlet and exit streams; accordingly, there is no change in velocity, and change in kinetic energy is negligible: $\Delta KE = 0$.

EXAMPLE FIGURE 1.9.1 Schematic of a heat exchanger system.



The simplified form of the energy balance is therefore

$$\dot{Q} = \Delta\dot{H} = \dot{H}_{out} - \dot{H}_{in}$$

The rate of enthalpy transport (*H*) as a function of specific enthalpy (*h*),

$$\Delta\dot{H} = \dot{m}\Delta h$$

Replacing enthalpy change rate (Δ*H*) with specific enthalpy (Δ*h*) at constant mass flow rate,

$$Q = \dot{m}\Delta h = \dot{m}(h_{out} - h_{in})$$

Substituting the values of mass flow rate and exit and inlet specific enthalpy in the earlier equation,

$$Q = \left(60\ \frac{kg}{h}\right)(417.5 - 2875)\ \frac{kJ}{kg} = -147,450\ kJ/h$$

The value of heat transfer is negative; that is, heat is transferred from the system (steam) to the surrounding (cold water).