4.5 The first law applied to open system-process or flow process

The processes associated with open or flow processes may be one of two kinds. First one is the steady flow process, where the mass and energy within the system remain constant and no changes occur within the system. In other word, no accumulation of energy or mass occurs (accumulation may be positive or negative). Mathematically, in this process one can conclude.

\[ m_1 = m_0 \quad ; \quad E_1 = E_0 \quad \& \quad \Delta E_{1-2} = 0 \]

Second type is the unsteady flow process. In this process, there is accumulation of energy and/or mass within the system. Thus for certain time interval, one can write:

\[ m_1 \neq m_0 \quad \& \quad E_1 \neq E_2 \]

To express the energy equation (first law of thermodynamics) for the open system mathematically, one first considers the general case of the unsteady flow energy equation. The energy equation in general form is written as:

\[ Q_{12} - W_{12} = \Delta E = \Delta E_{1-2} + (\Delta E_{\text{outflow}} - \Delta E_{\text{inflow}}) \]
In this equation $\Delta E$ is divided to two parts. First one is the change of energy within the system due to accumulation of energy ($\Delta E_{1-2}$), which is written in details as follows:

\[
\Delta E_{1-2} = m_2 \cdot (IE + FE + KE + PE)_2 - m_1 \cdot (IE + FE + KE + PE)_1
\]

OR

\[
\Delta E_{1-2} = m_2 \cdot \left( u_2 + \frac{1}{2} C_2^2 + gZ_2 \right) - m_1 \cdot \left( u_1 + \frac{1}{2} C_1^2 + gZ_1 \right)
\]

Second part is due to the energy content of mass crossing the system boundaries, which can be written as:

\[
E_{out} = m_o \left( u_o + p_o \, v_o + \frac{1}{2} c_o^2 + g z_o \right)
\]

\[
E_{in} = m_i \left( u_i + p_i \, v_i + \frac{1}{2} c_i^2 + g z_i \right)
\]

According to the definition of enthalpy; $h = u + p \, v$, the unsteady flow energy equation (USFEE) may be written as:

\[
Q_{12} - W_{12} = \left[ m_2 \left( u_2 + \frac{1}{2} C_2^2 + gZ_2 \right) - m_1 \left( u_1 + \frac{1}{2} C_1^2 + gZ_1 \right) \right]
\]

\[
+ \left[ m_o \left( h_o + \frac{1}{2} C_o^2 + gZ_o \right) - m_i \left( h_i + \frac{1}{2} C_i^2 + gZ_i \right) \right]
\]

Steady flow energy equation. (SFEE) can be derived taking in consideration that, the accumulated mass and energy (storage energy) vanish in this case. Also the inflow mass is equal to the outflow mass. Applying these limitations in the foregoing equation, one obtains the SFEE as:

\[
Q_{12} - W_{12} = m \cdot \left[ h_o + \frac{1}{2} C_o^2 + gZ_o \right] - \left[ h_i + \frac{1}{2} C_i^2 + gZ_i \right]
\]

Where $o$ and $i$ denote the outlet and inlet of the system, respectively.

4.6 Application of the steady flow energy equation to special cases
4.6.1 Boilers

![Figure 4.10 The used symbols of boilers](image)
The function of the boiler is to produce steam by heating water. In boiler, no work done and also the change of kinetic and potential energy may be neglected. Accordingly the SFEE can be written as:

\[ Q_{1-2} = m (h_2 - h_1) \]

And for 1 kg of water:

\[ q_{1-2} = h_2 - h_1 \]

Here 1 and 2 denote the inlet and outlet conditions.

### 4.6.2 Compressors

The function of the compressor is to increase the pressure of certain gas by exerting work on it. Some quantity of heat is lost. Kinetic and potential energy may be neglected. Accordingly in this case, the steady flow energy equation takes the following form:

\[ Q_{12} - W_{12} = m \cdot (h_2 - h_1) \]

And for 1 kg:

\[ q_{12} - w_{12} = h_2 - h_1 \]

### 4.6.3 Turbines

The function of turbine is to produce work. The heat lost to surrounding as well as the change of kinetic and potential energy is neglected. Thus, the energy equation takes the following form:

\[ W_{12} = m \cdot (h_1 - h_2) \]

And for 1 kg:

\[ w_{12} = h_1 - h_2 \]
4.6.4 Nozzles

The function of nozzles is to increase the kinetic energy of working medium. Neither heat nor work is transferred across the system boundary, i.e. \( Q_{12} = W_{12} = 0 \). Accordingly energy equation is written as:

\[
C_2^2 = C_1^2 + 2 (h_1 - h_2)
\]

Sometimes the velocity of approach \( C_2 \) is neglected compared with the exit velocity. In this equation, \( h \) is measured in Joules.
4.6.5 Throttling valve

Through this process no heat or work crosses the system boundary. The change in kinetic and potential energy may be neglected. Applying the steady state energy equation yields to:

\[ h_2 = h_1 \]

According to this equation the throttling process is considered a constant enthalpy process. Although the enthalpy remains constant, the pressure is reduced through this process.

4.7 The steady flow energy equation and cycle processes

To check the validity of first law of thermodynamics for open system processes-cycle, the SFEE is applied for every component of the shown simple power cycle in figure (4.15).

For boiler:

\[ Q_4 = h_1 - h_2 \]

For condenser:

\[ Q_R = h_3 - h_2 \]

For Turbine:

\[ W_T = h_1 - h_2 \]

For pumps:

\[ W_{p1} = h_4 - h_5 \]
\[ W_{p2} = h_3 - h_4 \]

Considering the power cycle as a single system:

\[ \sum_{cycle} Q = Q_A + Q_R = (h_1 - h_5) + (h_3 - h_2) = h_1 + h_3 - h_2 - h_5 \]
Applying the first law of thermodynamics for the cycle as a whole, one can write:

\[ \sum_{\text{cycle}} W = \sum_{\text{cycle}} Q = 0 \]

We can conclude that the first law of thermodynamics is valid for both closed and open system cycles.

Considering the power cycle, the net useful work (positive work) \( W_{\text{net}} \) is evaluated through the following equation:

\[ W_{\text{net}} = W_T - (|W_{p1}| + |W_{p2}|) \]

This useful work is produced due to the addition of quantity of heat \( Q_A \). The ratio between the useful work \( (W_{\text{net}}) \) and the added heat \( (Q_A) \) is known as the efficiency of the cycle \( (\eta) \):

\[ \eta = \frac{W_{\text{net}}}{Q_A} = \frac{Q_A - Q_R}{Q_A} = \left(1 - \frac{Q_R}{Q_A}\right) < 1 \]