4.2E Applications of Overall Energy-Balance Equation (CORRECTED)

This version of 4.2E includes the correct Examples 4.2-2 and 4.2-3 (as well as the correct associated figure). (In the print version, the correct Example 4.2-2 was accidently deleted.)

4.2E Applications of Overall Energy-Balance Equation

The total energy balance, Eq. (4.2-10), in the form given is not often used when appreciable enthalpy changes occur or appreciable heat is added (or subtracted), since the kinetic- and potential-energy terms are usually small and can be neglected. As a result, when appreciable heat is added or subtracted or large enthalpy changes occur, the methods for doing heat balances described in Section 1.7B are generally used. Examples will be given to illustrate this and other cases.

EXAMPLE 4.2-1. Energy Balance on Steam Boiler

Water enters a boiler at 18.33°C and 137.9 kPa through a pipe at an average velocity of 1.52 m/s. Exit steam at a height of 15.2 m above the liquid inlet leaves at 137.9 kPa, 148.9°C, and 9.14 m/s in the outlet line. At steady state, how much heat must be added per kg mass of steam? The flow in the two pipes is turbulent.

Solution: The process flow diagram is shown in Fig. 4.2-2. Rearranging Eq. (4.2-10) and setting $\alpha = 1$ for turbulent flow and $W_S = 0$ (no external work),

$$Q = (z_2 - z_1)g + \frac{v_2^2 - v_1^2}{2} + (H_2 - H_1) \qquad \textbf{(4.2-21)}$$

To solve for the kinetic-energy terms,

$$\frac{v_1^2}{2} = \frac{(1.52)^2}{2} = 1.115 \text{ J/kg}$$

$$\frac{v_2^2}{2} = \frac{(9.14)^2}{2} = 41.77 \text{ J/kg}$$

Taking the datum height z_1 at point 1, $z_2 = 15.2$ m. Then,

$$z_2 g = (15.2)(9.80665) = 149.1 \text{ J/kg}$$

From Appendix A.2, steam tables in SI units, H_1 at $18.33°\text{C} = 76.97$ kJ/kg, H_2 of superheated steam at $148.9°\text{C} = 2771.4$ kJ/kg, and

$$H_2 - H_1 = 2771.4 - 76.97 = 2694.4 \text{ kJ/kg} = 2.694 \times 10^6 \text{ J/kg}$$

Substituting these values into Eq. (4.2-21),

$$Q = (149.1 - 0) + (41.77 - 1.115) + 2.694 \times 10^6$$

$$Q = 189.75 + 2.694 \times 10^6 = 2.6942 \times 10^6 \text{ J/kg}$$

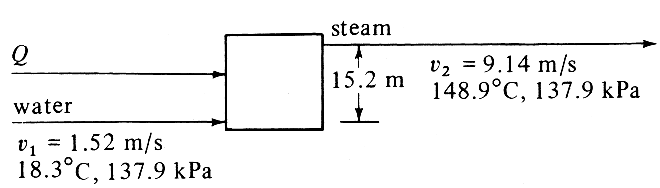

FIGURE 4.2-2. Process flow diagram for Example 2.7-1.

Hence, the kinetic-energy and potential-energy terms totaling 189.75 J/kg are negligible compared to the enthalpy change of 2.694×10^6 J/kg. This 189.75 J/kg would raise the temperature of liquid water about 0.0453°C, a negligible amount.

EXAMPLE 4.2-2. Energy Balance on a Flow System with a Pump

Water at 85.0°C is being stored in a large, insulated tank at atmospheric pressure, as shown in Fig. 4.2-3. It is being pumped at steady state from this tank at point 1 by a pump at the rate of $0.567\ \text{m}^3/\text{min}$. The motor driving the pump supplies energy at the rate of 7.45 kW. The water passes through a heat exchanger, where it gives up 1408 kW of heat. The cooled water is then delivered to a second large open tank at point 2, which is 20 m above the first tank. Calculate the final temperature of the water delivered to the second tank. Neglect any kinetic-energy changes, since the initial and final velocities in the tanks are essentially zero.

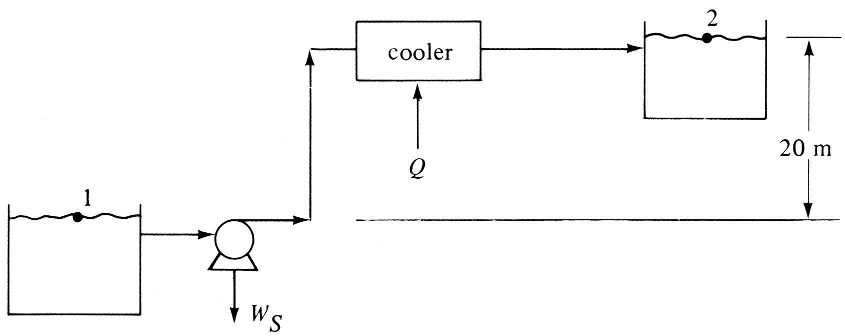

FIGURE 4.2-3. Process flow diagram for energy balance for Example 4.2-2.

Solution: From Appendix A.2, steam tables, $H_1\ (85°\text{C}) = 355.90 \times 10^3$ J/kg and $\rho_1 = 1/0.0010325 = 968.5\ \text{kg/m}^3$. Then, for steady state,

$$m_1 = m_2 = (0.567)(968.5)\left(\tfrac{1}{60}\right) = 9.152\ \text{kg/s}$$

Also, $z_1 = 0$ and $z_2 = 20\ \text{m}$. The work done by the fluid is W_S, but in this case work is done on the fluid and W_S is negative:

$$W_S = -(7.45 \times 10^3\ \text{J/s})(1/9.152\ \text{kg/s}) = -0.8140 \times 10^3\ \text{J/kg}$$

The heat added to the fluid is also negative since it gives up heat and is

$$Q = -(1408 \times 10^3\ \text{J/s})(1/9.152\ \text{kg/s}) = -153.8 \times 10^3\ \text{J/kg}$$

Setting $(v_1^2 - v_2^2)/2 = 0$ and substituting into Eq. (2.7-10),

$$H_2 - 355.90 \times 10^3 + 0 + 9.80665(20 - 0) = (-153.8 \times 10^3) - (-0.814 \times 10^3)$$

Solving, $H_2 = 202.71 \times 10^3$ J/kg. From the steam tables this corresponds to $t_2 = 48.41°\text{C}$. Note that in this example, W_S and $g(z_2 - z_1)$ are very small compared to Q.

EXAMPLE 4.2-3. Energy Balance in Flow Calorimeter

A flow calorimeter is being used to measure the enthalpy of steam. The calorimeter, which is a horizontal insulated pipe, consists of an electric heater immersed in a fluid flowing at steady state. Liquid water at 0°C at a rate of 0.3964 kg/min enters the calorimeter at point 1. The liquid is vaporized completely by the heater, where 19.63 kW is added, and steam leaves point 2 at 250°C and 150 kPa absolute. Calculate the exit enthalpy H_2 of the steam if the liquid enthalpy at 0°C is set arbitrarily as 0. The kinetic-energy changes are small and can be neglected. (It will be assumed that pressure has a negligible effect on the enthalpy of the liquid.)

Solution: For this case, $W_S = 0$ since there is no shaft work between points 1 and 2. Also, $(v_2^2/2\alpha - v_1^2/2\alpha) = 0$ and $g(z_2 - z_1) = 0.$ For steady state, $m_1 = m_2 = 0.3964/60 = 6.607 \times 10^{-3}$ kg/s. Since heat is added to the system,

$$Q = \frac{19.63\ \text{kJ/s}}{6.607 \times 10^{23}\ \text{kg/s}} = 2971\ \text{kJ/kg}$$

The value of $H_1 = 0.$ Equation (4.2-10) becomes

$$H_2 - H_1 + 0 + 0 = Q - 0$$

The final equation for the calorimeter is

$$H_2 = Q + H_1 \qquad \textbf{(4.2-22)}$$

Substituting $Q = 2971\ \text{kJ/kg}$ and $H_1 = 0$ into Eq. (4.2-22), $H_2 = 2971\ \text{kJ/kg}$ at 250°C and 150 kPa, which is close to the value from the steam table of 2972.7 kJ/kg.