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**

Tow Class

Lecture One

CHAPTER ONE

This chapter illustrates the fundamental theory of energy balance without reactions. The concept of energy conservation as expressed by an energy balance equation is essential to chemical engineering calculations. Similar to material balances studied in previous chapters, a balance of energy is important to solving many problems. The chapter begins with definitions of the first law of thermodynamics, each term in the first law, and application for closed and open systems. Next, the three forms of energy, that is, kinetic, potential, and internal, are explained. Mechanical energy balance and Bernoulli's equations are also covered in this chapter. The following items outline the principal learning objectives of this chapter.

Learning Objectives

1. Calculate energy balance for closed and open systems (Section 1.1).
2. Write mechanical energy balance for a non reacting system (Section 1.2).
3. Use Bernoulli's equation to solve mechanical energy problems involving flowing fluids with no work input/output (Section 1.3).
4. Use heat capacities to calculate enthalpy changes (Section 1.4).
5. Use latent heats within energy balances for systems involving phase changes (Section 1.5).

1.1. Energy Balance for Closed and Open Systems

A system is an object or a collection of objects that an analysis is carried out on. The system has a definite boundary, called the system boundary, which is chosen and specified at the beginning of the analysis. Once a system is defined, through the choice of a system boundary, everything external to it is called the surroundings. All energy and material that are transferred out of the system enter the surroundings, and vice versa. ***An isolated system*** is a system that does not exchange heat, work, or material with the surroundings. A ***closed system*** is a system in which heat and work are exchanged across its boundary, but material is not. ***An open system*** can exchange heat, work, and material with the surroundings.

1.1.1 Forms of Energy: The First Law of Thermodynamics

Energy is often categorized as kinetic energy, potential energy, and internal energy. The first law of thermodynamics is a statement of energy conservation. Although energy cannot be created or destroyed, it can be converted from one form to another. Energy can also be transferred from one point to another or from one body to another one. Energy transfer can occur by flow of heat, by transport of mass, or by performance of work [1]. The general energy balance for a thermodynamic process can be expressed in words as the accumulation of energy in a system equals the input of energy into the system minus the output of energy from the system.

1.1.2 Energy Balance for a Closed System1

Energy can cross the boundaries of a closed system in the form of heat and work (Figure1.1). The energy balance of a system is used to determine the amount of energy that flows into or out of each process unit, calculate the net energy requirement for the process, and assess ways of reducing energy requirements in order to improve process profitability and efficiency [2]. The energy balance for a closed system takes the form

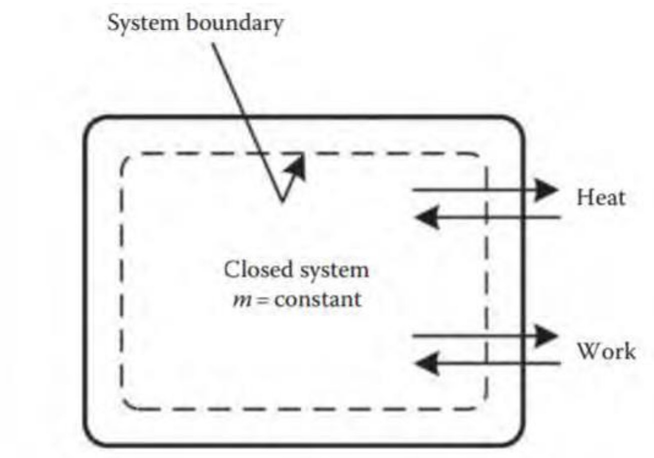


FIGURE1.1 Energy balance for a closed system.

$Q - W = \Delta U + \Delta KE + \Delta PE$ …………………………………………… (1.1)

where heat (Q), work (W), internal energy (U), kinetic energy (KE), and potential energy (PE) are defined as follows.

Heat is the energy that flows due to a temperature difference between the system and its surroundings and always flows from regions at high temperatures to regions at low temperatures. By convention, heat is defined to be positive if it flows to a system (i.e., gained). For systems with no significant heat exchange with the surroundings, Q = 0. Such a system is said to be ***adiabatic***. The absence of any heat transfer can be due to perfect thermal insulation or the fact that the system and surroundings are at the same temperature. ***Work*** is the energy that flows in response to any driving force (e.g., applied force, torque) other than temperature, and is defined as positive if it flows from the system (i.e., work done by the system). In chemical processes, work may, for instance, come from pumps, compressors, moving pistons, and moving turbines. Heat or work only refers to energy that is being transferred to or from the system. If there is no motion along the system boundary, then W=0. ***Internal Energy*** is all the energy associated with a system that does not fall under the earlier definitions of kinetic or potential energy. More specifically, internal energy is the energy due to all molecular, atomic, and subatomic motions, and interactions. Usually, the complexity of these various contributions means that no simple analytical expression is available from which internal energy can be readily calculated. An ***isothermal*** system is one where the temperature does not change with time and in space. This does not mean that no heat crosses the boundaries. ***Kinetic Energy*** is associated with directed motion of the system. Translation refers to straight line motion. If the system is not accelerating, then $\Delta KE=0$. ***Potential Energy*** of a system is due to the position of the system in a potential field. There are various forms of potential energy, but only gravitational potential energy will be considered in this course. If the system is not experiencing a displacement in the direction of the gravitational field, then $\Delta PE=0$.

1.1.2.1 *Kinetic Energy*

Kinetic energy is the energy carried by a moving system because of its velocity. The kinetic energy KE of a moving object of mass m, traveling with speed υ, is given by

$$KE = \frac{1}{2}\dot{m}v^2 \Rightarrow \left(\frac{kg}{s}\right)\left(\frac{m}{s}\right)^2 \left|\frac{N}{kg\ m/s^2}\right|\frac{J}{N\cdot m}\left|\frac{W}{J/s}\right. = W \quad \text{.................................(1.2)}$$

KE has units of energy, *m* has units of mass flow rate (mass/time), and υ has units of velocity (length/time).

Example1.1 Kinetic Energy Calculations

Water flows from a large lake into a process unit through a 0.02 m inside diameter pipe at a rate of 2.0 m3 /h. calculate the change in kinetic energy for this stream in joules per second.

Solution:

Known quantities: Pipe diameter (0.02 m), water volumetric flow rate (2.0 m3 /h), density of water (1000 kg/m3).

Find: Change in kinetic energy

Analysis: First, calculate the mass flow rate from the density and volumetric flow rate, and, next, determine the velocity as the volumetric flow rate divided by the pipe inner cross-sectional area. The rate of change in kinetic energy is calculated by

$$\Delta KE = \frac{1}{2}\dot{m}\Delta v^2 = \frac{1}{2}\dot{m}(v_2^2 - v_1^2) \quad \text{...(1.3)}$$

The mass flow rate, m, is the density (ρ) multiplied by volumetric flow rate (*V*):

$$\dot{m} = \rho\dot{V} = \frac{1000\ \text{kg}}{\cancel{\text{m}}^3}\left|\frac{2\ \cancel{\text{m}}^3}{\cancel{\text{h}}}\right|\frac{\cancel{\text{h}}}{3600\ \text{s}}\Bigg| = 0.56\ \text{kg/s}$$

The water exit velocity (υ2) is calculated from the volumetric flow rate (*V*) divided by pipe inner cross-sectional area of the exit of the pipe (A). The surface of the lake being large, the water surface can be assumed to be almost stagnant. Accordingly, the initial velocity is negligible (υ1=0):

$$v_2 = \frac{\dot{V}}{A = \dfrac{\pi D^2}{4}} = \left(\frac{2.00\ \dfrac{\text{m}^3}{\text{h}}\Big|\dfrac{\text{h}}{3600\ \text{s}}}{\dfrac{3.14 \times (0.02\ \text{m})^2}{4}}\right) = 1.77\ \text{m/s}$$

Substituting the values of mass flow rate and velocities in the kinetic energy equation,

$$\Delta KE = \frac{1}{2}\dot{m}(v_2^2 - v_1^2) = \frac{1}{2}\left(0.56\ \frac{\text{kg}}{\text{s}}\right)\left(\left(1.77\ \frac{\text{m}}{\text{s}}\right)^2 - 0\right)\left(\frac{1\ \text{N}}{\dfrac{\text{kg m}}{\text{s}^2}}\right)$$

$$\times\left(\frac{1\ \text{J}}{1\ \text{N m}}\right) = 0.88\ \text{J/s}$$

1.1.2.2 *Potential Energy*

Potential energy is the energy due to the position of the system in a potential field (e.g., earth’s gravitational field, g=9.81 m/s2). The gravitational potential energy (ΔPE) of an object of mass m at an elevation z in a gravitational field, relative to its gravitational potential energy at a reference elevation z0, is given by

$$\Delta PE = mg(z - z_0) \Rightarrow m(\mathrm{kg})\,g(\mathrm{m/s^2})\,\Delta z(\mathrm{m}) = \mathrm{N \cdot m} = \mathrm{J}$$ ………………..(1.4)

To calculate the change in the rate of potential energy (ΔPE), often, the earth's surface is used as the reference, assigning z0=0:

$$\Delta PE = \dot{m}g(z - z_0)$$ …………………………………………..(1.5)

The unit of the change in transport rate of potential energy is obtained as follows:

$$\Delta PE = \dot{m}(\mathrm{kg/s})\,g(\mathrm{m/s^2})\,\Delta z(\mathrm{m}) = \mathrm{N \cdot m/s} = \mathrm{J/s} = \mathrm{W}$$ ………………..(1.6)

Example1.2 Potential Energy Calculation

Water is pumped at a rate of 10.0 kg/s from a point 200.0 m below the earth's surface to a point 100.0 m above the ground level. Calculate the rate of change in potential energy.

Solution:

Known quantities: Water mass flow rate (10.0 kg/s), initial location of water below the earth's surface (−200.0 m), and final location of water above the earth's surface (100 m).

Find: The rate of change in potential energy.

Analysis: Use the definition of potential energy.

Taking the surface of the earth as a reference, the distance below the earth's surface is negative (z1=−200.0) and above the surface is positive (z2=100):

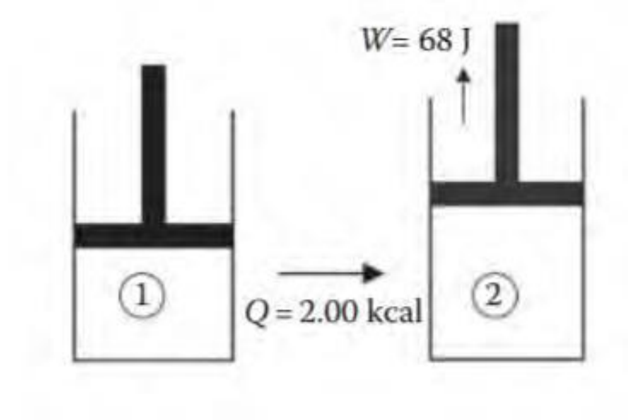
$$\Delta PE = \dot{m}g(z_2 - z_1)$$

Substituting the values of the mass flow rate, gravitational acceleration, and change in inlet and exit pipe elevation from the surface of the earth,

$$\Delta PE = \left(10.0\,\frac{\mathrm{kg}}{\mathrm{s}}\right) \times \left(9.81\,\frac{\mathrm{m}}{\mathrm{s^2}}\right) \times (100.0 - (-200.0))\,\mathrm{m} \left| \frac{\mathrm{J}}{\mathrm{kg \cdot m^2/s^2}} \right. = 29{,}430\ \mathrm{J/s}$$

Example1.3 Internal Energy Calculation

A cylinder fitted with a movable piston is filled with gas. An amount of 2.00 kcal of heat is transferred to the gas to raise the gas temperature 100°C higher. The gas does 68 J of work in moving the piston to its new equilibrium position. Calculate the change in internal energy of the system (Example Figure 1.3.1).



EXAMPLE FIGURE 1.3.1 Heat added to a

cylinder fitted with a piston.

Solution

Known quantities: The difference in gas temperature (100°C), work done by the system (+68 J), and heat added to the system (+2.00 kcal).

Find: Change in internal energy.

Analysis: Use the energy balance equation for a closed system.

System: Gas in the system, closed system

$\Delta U + \Delta KE + \Delta PE = Q - W$

Assumption: No change in kinetic and potential energy; accordingly, both are set to zero. The equation is reduced to

$\Delta U = Q - W$

Substitute the values of Q and W to calculate the change in internal energy (make sure units are consistent). The heat is added to the system (positive value) and the work is done by the system (positive value as well):

$$\Delta U = (2.0 \text{ kcal})\left[\frac{1000 \text{ cal}}{\text{kcal}} \frac{1 \text{ J}}{0.239 \text{ cal}}\right] - 68 \text{ J} = 8300 \text{ J}$$

The change in internal energy ΔU=8.30 kJ. The specific enthalpy (h=H/m) can be calculated using the following equation:

H = u+Pv ………………………….. (1.7)

Substituting the values of specific internal energy (u=U/m), pressure (P), and specific volume (v) in the earlier equations gives the specific enthalpy h.

12

Example1.4 Enthalpy from Internal Energy

The specific internal energy of helium at 25°C and 1 atm is 3.80 kJ/mol, and the specific molar volume under the same conditions is 25 L/mol. Calculate the specific enthalpy of helium at this temperature and pressure, and the rate at which enthalpy is transported by a stream with a molar flow rate of 250 kmol/h.

Solution

Known quantities: Internal energy, pressure, temperature, molar volume, molar flow.

Find: Specific molar enthalpy (h), rate of enthalpy transport (H).

Analysis: Follow the specific enthalpy definition. The specific enthalpy of helium is given by

h= u+Pv

Substituting the values of specific internal energy, pressure (P), and specific volume (v) in the earlier equations,

$$h = \left(3800\ \frac{\text{J}}{\text{mol}}\right) + (1\ \text{atm})\left(25\ \frac{\text{L}}{\text{mol}}\right)\left[\frac{1\ \text{m}^3}{1000\ \text{L}}\ \frac{1.01325\times10^5\ \frac{\text{N}}{\text{m}^2}}{1\ \text{atm}}\ \frac{\text{J}}{\text{N}\cdot\text{m}}\right]$$

$$= 6333\ \text{J/mol}$$

The enthalpy transport rate (H&) is calculated by multiplying the molar flow rate (n&) with the specific molar enthalpy (h):

H = n × h

Substitute the values of molar flow rate (n) and specific enthalpy (h) to find the enthalpy transport rate (H):

$$\dot{H} = \left(250\ \frac{\text{kmol}}{\text{h}}\right)\times\left(6333\ \frac{\text{J}}{\text{mol}}\right)\left[\frac{1000\ \text{mol}}{\text{kmol}}\ \frac{\text{kJ}}{1000\ \text{J}}\right] = 1.58\times10^6\ \text{kJ/h}$$