Energy balance for a closed system

Systems of units

Systems of units are defined with reference to Newton's second law for a system of constant mass: $F = ma$ (mass–length/time^2)

where F is the force required to accelerate a body of mass, m, at a rate a (length/time^2)

System	Length	Time	Mass	Force	g_c
SI	Meter m	Second s	Kilogram kg	Newton N	1.0 (kg.m)/(N · s^2)
CGS	Centimeter cm	Second s	Gram g	dyne	1.0 (g.cm)/(dyne.s^2)
AES	Foot ft	Second s	Pound mass lb_m	Pound force lb_f	32.17 (lb_m.ft)/(lb_f.s^2)

1.0 N = Force that will accelerate a mass of 1.0 kg by 1.0 m/s^2
1.0 dyne = Force that will accelerate a mass of 1.0 g by 1.0 cm/s^2
1.0 lb_f = Force that will accelerate a mass of 1.0 lb_m by 32.174 ft/s^2

Metric prefixes

10^{12}	T	Tera	Trillion	10^{-1}	d	Deci	Tenths
10^{9}	G	Giga	Billion	10^{-2}	c	Centi	Hundredths
10^{6}	M	Mega	Million	10^{-3}	m	Milli	Thousandths
10^{3}	k	Kilo	Thousand	10^{-6}	μ	Micro	Millionths
10^{2}	h	Hector	Hundred	10^{-9}	n	Nano	Billionths
10^{1}	da	Deca	Ten	10^{-12}	p	Pico	Trillionths

Acceleration of gravity	$g = 9.8066$ m/s^2 (sea level, 45° latitude) $g = 32.174$ ft/s^2
Gas constant	$R = 10.731$ psia-ft^3/lbmol = 0.7302 atm-ft^3/lbmol $R = 0.082056$ atm-L/mol-K = 8.3143 Pa-m^3/mol-K $R = 0.08314$ L-bar/mol-K = 1.987 Btu/lb mol = 8314.3 J/kg mol-K $R = 8.3143$ J/mol-K = 62.36 L-mmHg/mol-K = 1.987 cal/mol-K
Density of water at 4°C	ρ (H_2O, 4°C) = 1.0 g/cm^3 = 1.0 kg/L = 10^3 kg/m^3 ρ(H_2O, 4°C) = 8.34 lb_m/gal = 62.43 lb_m/ft^3
Specific gravity of water	= 1.0
Specific gravity of Hg	= 13.6

Conversion factors:

Mass	1 lb_m = 5 × 10^{-4} t = 0.453593 kg = 453.593 g = 16 oz
	1 kg = 1000 g = 2.20462 lb_m = 0.001 t
	1 t = 2000 lb_m; 1 t = 1000 kg
Length	1 ft = 12 in.; 1 ft = 0.3048 m = 30.48 cm; 1 in. = 2.54 cm; 1 mile = 5280 ft
	1 m = 10^{10} Å = 39.37 in. = 3.2808 ft = 1.0936 yd = 0.0006214 mi
Volume	1 ft^3 = 7.481 gal = 1728 $in.^3$ = 28.317 L = 28,317 cm^3
	1 gal = 231 $in.^3$; 1 $in.^3$ = 16.387 cm^3
	1 cc = 1 cm^3 = 1 mL; 1000 mL = L
	1000 L = 1 m^3 = 35.3145 ft^3 = 220.83 imperial gallons = 264.17 gal = 1056.68 qt
	8 fl oz = 1 cup; 4 cup = 1 quart; 4 quart = 1 gal = 128 fl oz
Density	1 g/cm^3 = 1 kg/L = 1000 kg/m^3 = 62.428 lb/ft^3 = 8.345 lb_m/gal
Force	1 lb_f = 32.174 lb_m-ft/s^2 = 4.448222 N = 4.4482 × 10^5 dynes
	1 N = 1 kg-m/s^2 = 10^5 dynes = 10^5 g-cm/s^2 = 0.22481 lb_f
Pressure	1 bar = 10^5 Pa = 100 kPa = 10^5 N/m^2
	Pascal (Pa) is defined as 1 N/m^2 = 1 kg/m-s^2
	1 atm = 1.01325 bar = 14.696 lb_f/$in.^2$ = 760 mmHg at 0°C (torr) = 29.92 in Hg at 0°C
	1 psi = 1 lb_f/$in.^2$; psia (absolute) = psig (gauge) + 14.696
Temperature	1 K = 1.8°R (absolute temperature)
	T (°C) = T (K) − 273.15
	T (°F) = T (°R) − 459.67
	T (°F) = 1.8T (°C) + 32
Energy	1 J = 1 N-m = 1 kg-m^2/s^2 = 10^7 ergs = 10^7 dyne-cm = 2.778 × 10^{-7} kW-h
	= 0.23901 cal = 0.7376 ft-lb_f = 9.486 × 10^{-4} Btu
	1 cal = 4.1868 J; 1 Btu = 778.17 ft-lb_f = 252.0 cal
	1 Btu/lb_m-F = 1 cal/g-°C
Power	1 hp = 550 ft-lb/s = 0.74570 kW
	1 W = 1 J/s = 0.23901 cal/s = 0.7376 ft-lb_f/s = 9.486 × 10^{-4} Btu/s
	1 kW = 1000 J/s = 3412.1 Btu/h = 1.341 hp

8.1 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.

8.1.1 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.

8.1.2 Energy Balance for a Closed System

Energy can cross the boundaries of a closed system in the form of heat and work (Figure 8.1).

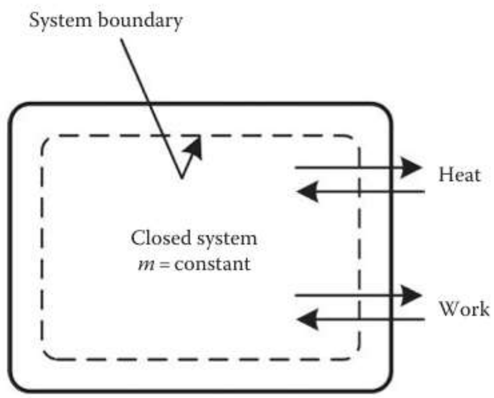

Figure 8.1: Energy balance for a closed system

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

$$Q - W = \Delta U + \Delta KE + \Delta PE \qquad (8.1)$$

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 $\Delta PE = 0$.

8.1.2.1 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

$$KE = \frac{1}{2}\dot{m}v^2 \Rightarrow \left(\frac{\text{kg}}{\text{s}}\right)\left(\frac{\text{m}}{\text{s}}\right)^2 \left| \frac{\text{N}}{\text{kg m/s}^2} \right| \frac{\text{J}}{\text{N}\cdot\text{m}} \left| \frac{\text{W}}{\text{J/s}} \right. = \text{W} \qquad (8.2)$$

KE has units of energy, $\dot{m}$ has units of mass flow rate (mass/time), and υ has units of velocity (length/time).

Example 8.1: Kinetic energy calculations

Problem

Water flows from a large lake into a process unit through a 0.02 m inside diameter pipe at a rate of 2.0 m^3/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 m^3/h), density of water (1000 kg/m^3).

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

$$\Delta KE = \frac{1}{2}\dot{m}\Delta v^2 = \frac{1}{2}\dot{m}(v_2^2 - v_1^2) \qquad (8.3)$$

The mass flow rate, $\dot{m}$, is the density (ρ) multiplied by volumetric flow rate ($\dot{V}$):

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

The water exit velocity (v_2) is calculated from the volumetric flow rate ($\dot{V}$) 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 ($v_1 = 0$):

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

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

$$\Delta KE = \frac{1}{2}\dot{m}(\upsilon_2^2 - \upsilon_1^2) = \frac{1}{2}\left(0.56\ \frac{\text{kg}}{\text{s}}\right)\left(\left(1.77\ \frac{\text{m}}{\text{s}}\right)^2 - 0\right)\left(\frac{1\ \text{N}}{\frac{\text{kg m}}{\text{s}^2}}\right) \times \left(\frac{1\ \text{J}}{1\ \text{N m}}\right) = 0.88\ \text{J/s}$$

8.1.2.2 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/s^2). 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 z_0, is given by

$$\Delta PE = mg(z - z_0) \Rightarrow m(\text{kg})\,g(\text{m/s}^2)\,\Delta z(\text{m}) = \text{N}\cdot\text{m} = \text{J} \qquad (8.4)$$

To calculate the change in the rate of potential energy (*ΔPE*), often, the earth's surface is used as the reference, assigning z_0= 0:

$$\Delta PE = \dot{m}g(z - z_0) \qquad (8.5)$$

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

$$\Delta PE = \dot{m}(\text{kg/s})\,g(\text{m/s}^2)\,\Delta z(\text{m}) = \text{N}\cdot\text{m/s} = \text{J/s} = \text{W} \qquad (8.6)$$

Example 8.2 Potential Energy Calculation

Problem

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 (z_1= −200.0) and above the surface is positive (z_2= 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,

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

The rate of change in potential energy $\Delta PE = 29.43\,\frac{\text{kJ}}{\text{s}} = 29.43\ \text{kW}$.