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Malaysia | Kolmetz Handbook
of Process Equipment Design

THERMODYNAMICS
AND HEAT TRANSFER

(ENGINEERING FUNDAMENTALS) | Editor / Author

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INTRODUCTION

Scope

This Engineering Fundamental Module provides an overview one of the basic fundamentals of engineering. The knowledge of the thermodynamics and heat transfer is essential to design efficient process equipment.

At the first part of this module, the engineer will deal with the science of thermodynamics. The science of thermodynamics deals with the amount of heat transfer as a system undergoes a process from one equilibrium state to another, and makes no reference for how long the process will take.

The fundamental concepts of thermodynamics form the framework for heat transfer. Based on this thermodynamic framework the module will present the three basic mechanisms of heat transfer, which consists of: (1) Conduction, (2) Convection, and (3) Radiation.

Basic Concepts

The word thermodynamics stems from the Greek words *therme* (heat) and *dynamis* (force). The formal study of thermodynamics began in the early 19th century through consideration of the motive power of heat, the capacity of hot bodues to produce work. Thermodynamics could be define simply as the science of energy.

Engineers use principles drawn from thermodynamics and other engineering sciences, in example fluid mechanics and heat and mass transfer, to analyze and design things intended to meet industrial needs. One of the fundamentals laws of nature is the conservation of energy principle. The conservataion of energy differs from that of mass in the energy can be generated in a chemical process.

Energy can exist in several forms, including chemical energy, heat, mechanical energy and electrical energy. The total energy is conserved, but energy can be transformed from one kind of energy to another. The change in the energy content of a body or any other system is equal to the difference between the energy input and the energy output, and the energy balance could be formulated as

$$E_{in} – E_{out} = \Delta E$$

The first law of thermodynamic is cites an expression of the conservation of energy principle, and it asserts that energy is a thermodynamic property. The second law of thermodynamics asserts that energy has quality as well as quantity, and actual processes occur in the direction of decreasing quality of energy.

There is an important consideration that thermodynamics do not establish the rates of chemical of physical processes. Rates are depend on driving force and resistance. Although driving forces are thermodynamic variables, resistance are not. Neither can thermodynamics (a macroscopic – property formulation) reveal the microscopic mechanisms of physical or chemical processes. On the other hand, knowledge of the microscopic behavior or matter can be useful in the calculation thermodynamic properties. Thus, property values are important to the practical application thermodynamic properties.

Thermodynamic System

A system is could be defined as a quantity of matter or a region in space chosen for study. A system could be a closed or open system. A closed system conssits of a fixed amount of mass, and no mass can across its boundary. On the other hand, an open system is usually encloses a device that involves mass flow such as compressor, nozzle or turbine. Both of thecase, energy transfer can occur across the system boundary in any of irs various forms, in example like : Heat, Work, Electrical / Magnetic Energy. Unlike closed and open system, isolated system is enclosed by a boundary that allows neither mass nor energy to transfer.

All matter external to the system constitues the surroundings. The combination of the system and the surroundings is what made of the universe. The real or imaginary surface that separates the system from its surroundings is called the boundary. For practical purposes, in any thermodynamic analysis of a system it is necessary to include only the immediate surroundings in which the effects are felt.

Figure 1 shows a very common example of thermodyanmic system. The system consists of gas contained in a piston-and-cylinder arrangement derived from the idea of steam engines, which may typically exchange heat or work with its surroundings.

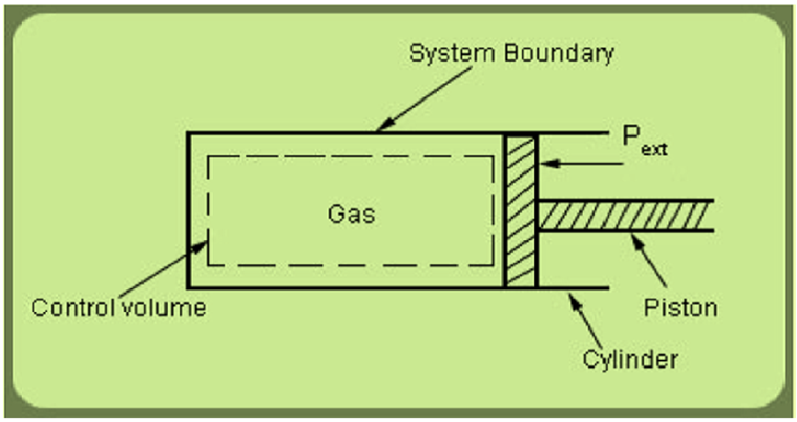

Figure 1. A simple example of thermodynamic system.

The dotted reactangle represents the ‘control volume’ which essentially encloses the mass of gas in the system and walls from the boundary of the system. If the internal gas pressure and the external pressure from the acting of moveable piston is the same, there is no net force operates that work on the system.

However, if there is an imbalancing force event, the piston would move until the internal and external pressures equalize. In the process some net work would be either delivered to or by the system, depending on whether the initial pressure of the gas is lower or higher than the externally applied pressure. In addition, if there is a temperature differential between the system and the surroundings the former may gain or lose energy through heat transfer across its boundary.

Any characteristic of a system is called a property. Some familiar properties that often heard in industrial application including : Pressure (P), Temperature (T), Volume (V) and also mass (m). The thermodynamic properties are typicall classified as extensive and intensive. Intensive properties are those that are independent of the mass of a system, such as Temperature (T), Pressure (P), and Density (ρ). While extensive properties are those whose values depend on the size of the system. Total mass, total volume and total momentum are several examples of an extensive properties. Extensive properties per unit mass are called specific properties. Specific volume and specific total energy are the example of specific properties.

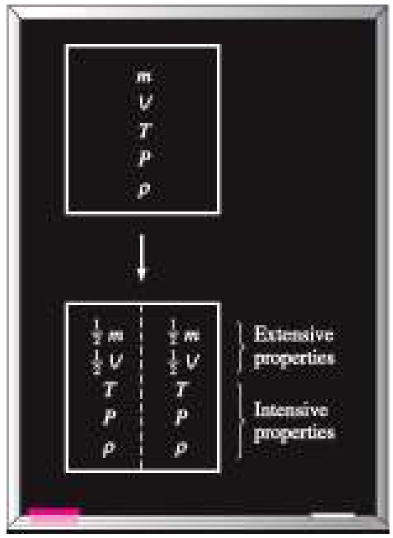

Figure 2. Criterion of Thermodynamic Properties.

The ‘state’ refers to the condition of a system as described by its properties. Since there are normally relations among the properties of a system, the state often can be specified by providing the values of a subset of the properties. All other properties can be calculated in terms of these few. When any of the properties of a system change, the state changes and the system is said to have undergone a ‘Process’.

A ‘process’ is a transformation from one state to another. If a system exhibits the same values of its properties at two different times, it is in the same state at these times. A system is said to be at ‘Steady state’ if none of its properties changes with time (Figure 3).

A thermodynamic cycle is a sequence of processes that begins and ends at the same state. At the conclusion of a cycle all properties have the same values they had at the beginning. Consequently, over the cycle the system experiences no net change of state. Cycles that are repeated periodically play prominent roles in many areas of application. Steam circulating through an electrical power plant is a common example that could be found in industrial application.

Thermodyanmics deals with equilibrium states. The term of ‘equilibrium’ implies a state of balance. In an equilibrium state there are no unbalanced potentials (or driving forces) within the system. A system in equilibrium experiences no changes when it is isolated from its surroundings.

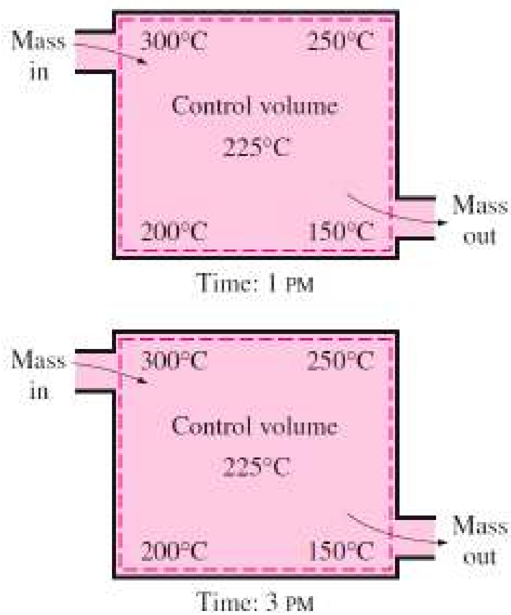

Figure 3. Steady state Process.

Process are sometimes modeled as an idealized type of process called a ‘quasiequilibrium’. A quasiequilibrium process is one in which the departure from thermodynamic equilibrium is at most infinitesimal. Because nonequilibrium effects are inevitably present during actual processes, systems of engineering interest could be at best approachment but never realize, a quasiquilibrium process. The main interest in the quasiequilibrium process concept stems from two major considerations :

- Simple thermodynamic models giving at least qualitative information about the behavior of actual systems of interest often can be developed using the quasiequilibrium process concept. This is akin to the use idealizations such as the point mass or the frictionless pulley in mechanics for the purpose of simplifying an analysis.

- The quasiequilibrium process concept is instrumental in deducing relationships that exist among the properties of systems at equilibrium.

There are many types of equilibrium and a system is not thermodynamic equilibrium unless the conditions of all the relevant types of quilibrium are satisfied. In example, a system is in 'Thermal equilibrium' if the temperature is the same throughout the entire system. The system involves no temperature differential, which is the driving foorce for heat flow. Mechanical equilibrium is related to pressure and a system is in mechanical equilibrium if there is no change in pressire at anypoint of the system with time.

On the other hand, if a system involves two phases, it is in phase equilibrium when the mass of each phase reaches an equilibrium level and stays there. A system could be in 'Chemical equilibrium' if its chemical compositin does not change with time, that is, no chemical reactions ccur. A system will not be in equilibrium unless all the relevant equilibrium criteria are satisfied.

The Law of Thermodynamics (General review)

The Zeroth Law of Thermodynamics

The level of temperature qualitatively measured with words like cold, warm, and hot. Nevertheless, the measurement of things qualitatively could be misleading due to the material properties, at same temperature, a metal could be colder than the woods.

The zeroth law of thermodynamics states that if two bodies are in thermal equilibrium with a third body, they are also in thermal equilibrium with each other. The zeroth law was first formulated by R. H. Fowler in 1931, it was cited a century after the formulation of the first and the second laws of thermodynamics. It was named 'the zeroth; since it should have preceeded the first and the second laws of thermodynamics.

First Law of Thermodynamics

The energy change of any system together with its surrounding is zero. Implicit in this declaration is the affirmation that there exists a form of energy, known as internal energy, which for systems in equilibrium states in an intrinsic property of the system. Internal energy is separate from the external energy forms. Nevertheless, internal energy originates in the kineteic and potential energues of molecules and submolecular particles. In applications of the first law of thermodynamics energy at its forms (internal and external) should also be considered.

The Second Law of Thermodynamics

The use of the second law of thermodynamcs is not limited to identifying the direction of processes. However, the second law also asserts that energy has quality as well as quantity. The first law is concerned with the quantity of energy and the transformations of energy from one form to another with no regard to its quality.

Preserving the quality of energy is a major concern to engineers, and the second law provides the necessary means to determine the quality as well as the degree of degradation of energy during a process. The second law of thermodynamics is also used in determining the theoretical limits for the performance of commonly used engineering systems, such as heat engines and refrigerators, as well as predicting the degree of completion of chemical reactions.

The Third Law of Thermodynamics

Nernst and Planck at the beginning of the twentieth century lead a postulate that: "The absolute entropy is zero for all perferct crystalline substances at absolute zero temperature" by recent studies at very low temperatures have increased confidence in this postulate which is now accepted as the third law of thermodynamics.

The 'Heat' could be described as an energy that is transferred because of the existence of a temperature difference between two systems or two parts of asystem. Heat usually refer to energy in transit. It cannot be said that a system accumulates heat. Heat is only transferred to a system and once it enters the system, this type of energy is transformed in other types of energy like kinetic energy or mechanical work.

Heat Transfer

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Conduction is the transfer of energy from the more energetic particles of a substance to the adjacent, less energetic ones as a result of interaction between the particles. Meanwhile, convection is the mode of heat transfer between solit surface and the adjacent liquid or gas that is in motion event, and it involves the combined effects of conduction and fluid motion. Radiation is the energy emitted by matter in the form of electromagnetic waves (or photons) as a result of the changes in the electronic configurations of the atoms or molecules.

Heat exchangers, Heaters, Refrigerators, Solar collectors, Boilers, Condensers, Radiators, Furnaces, Boilers are a common example of Heat transfer equipment that widely used in industrial application. Every equipment design is basically designed on the basis of heat transfer analysis. As in general, the heat transfer problems encountered in practice could be considered in two main groups

- Rating problems.
- Sizing problems.

The rating groups will deal with the determination of the heat transfer rate for an existing system at a specified temperature difference. Nonetheless, the sizing problems deal with the determination of the size of a system in order to transfer heat at a specified rate for a specified temperature difference.

A heat transfer process or equipment can be studied either experimentally or analytically. The experimental approachment has the advantage that deals directly with the actual physical system and also the desired quantity. On the on contrary, the experimental approachment will cost a a expensive budget, very time-consuming and also often impractical. Hence, The analytical approachment has the advantage such as fast data-track, cheap, but sometimes leak of the accuracy of the assumptions and idealizations made in the analysis.

DEFINITION

Conduction – The transfer of internal energy by microscopic diffusion and collisions of particles or quasi-particles within a body due to a temperature gradient.

Convection – The concerted, collecitve movememtn of groups of aggregrates of molecules within fluids and rheids.

Entropy – A quantity of the number of specific ways in which a thermodynamic system may be arranged, commonly uncerstood as a measure of disorder.

Equation of State – A relation between state variables such as Temperature, Pressure and Specific Volume of substance.

Heat Balance – Often called an ‘energy balance’, a version of law of conservation of energy adapted thermodynamic systems.

Heat Transfer – Exchange of thermal energy between physical systems depending on the temperature and pressure of substance.

Phase - Region of space throughout which all physical properties of a material are essentially uniform.

Radiation – A process in which electromagnetic waves (EMR) travel through a vacuum or through matter-containing media..

Specific Heat – Physical quantity unit that determine the ratio of the added to (or substract from) an object to the resulting temperature change.

Thermal Insulation – The reduction of heat transfer between objects in thermal contact or in range of radiactive influence.

Thermal resistance – A heat property and a measurement f a temperature difference by which an object or material resists a heat flow.

Thermodynamic – A branch of physics that concerned with heat and temperature and relation to energy and work.

NOMENCLATURE

A : Area perpendicular of the x direction (m^2)
Cp : Specific heat at constant pressure
Cv : Specific heat at constant volume
COP : Coefficient of Perfomance (%)
g : Gravitational Acceleratio (m/s2)
H : Enthalpy (Joule)
k : Thermal conductivity (W/m.K)
L : Length of substances or materials (m).
P : Pressure (kPa)
P_{cr} : Critical Pressure (kPa)
P_R : Reduced Pressure (kPa)
P^{sat} : Vapor pressure
Q : Heat (Joule)
$\dot{Q}$: The rate of heat transfer (W)
R : An Ideal Gas Constant (8.314 J/mol.K)
S : Entropy (J/K)
T : Temperature (K)
T_{cr} : Critical Temperature (K)
T_R : Reduced Temperature (K)
U : Internal Energy (Joule)
v : Volume of substances (m^3)
W : Work (Joule)
Z : Compressibility factor
Δx : The thickness of the plane (m)

SYMBOLS

β : Volume expansivity
κ : Isothermal compressibility
γ : Specific heat ratio
η_{th} : Thermal Efficiency

THEORY

Thermodynamics

Properties of Pure Substances

Phases

Pure substance could be define as a asubstance that has a fixed chemical composition. An example of pure substance including : Helium, Water, Nitrogen, and Carbon Dioxide (CO2). A mixture of two or more phases of a pure substance is still a pure substance as long as the chemical composiition of all phases is the same.

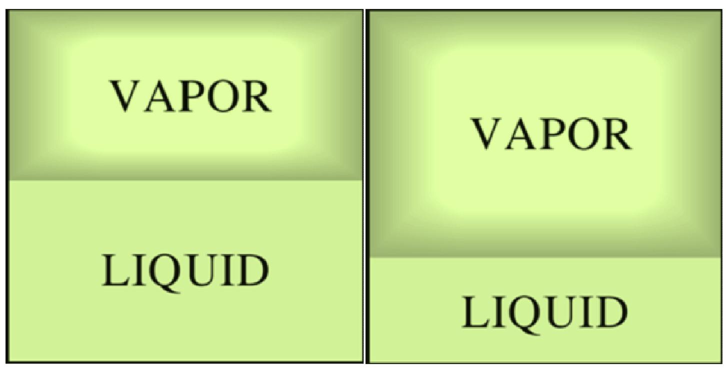

Figure 4. An example of pure substance (left, water) and mixture (right, air).

The molecules in a solid state are arranged in a three-dimensional pattern that is the same throughout. Due to the small distances between molecules in a solid, the attractive forces of molecules on each other are large and keep the molecules at fixed positions. Hence, the molecular spacing in the liquid phase is not much different from that of the solid phase, except the molecules are no longer at fixed positions relative to each other and they can rotate and translate freely.