THERMODYNAMIC THEORY

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Contents

Summary

The subject of thermodynamics is related to the use of thermal energy or heat to produce dynamic forces or work. Heat, energy and work are all measured in the same

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units but are not equivalent to one another. Conservation of energy indicates that one can be converted into another without loss. All work can be converted into heat by friction. However not all heat can be converted into work. This places a limit on the efficiency of any heat engine which uses heat to produce work. There is an idealistic efficiency which is the maximum theoretical efficiency that can be achieved under given conditions. The actual efficiency of heat engines is measured against this ideal efficiency to determine how good they are at producing work given the imposed limitations.

The laws of thermodynamics govern the considerations above. The First Law is a statement of the conservation of energy while the Second Law governs the conversion of heat to work. In order to convert heat to work it is necessary to establish a thermodynamic cycle with a working fluid that receives heat, does work and rejects heat. There is thus a net flow of heat from a high temperature reservoir to a low temperature sink via the thermodynamic cycle while work is being produced. Every thermodynamic cycle is made up of a series of distinct processes, typically four, and the working fluid is subjected to these processes in sequence. Knowledge of the processes and the equations governing them allow the conditions of the fluid at each point in the cycle or the quantity of heat received or rejected or the amount of work done to be determined.

The most interesting part of the thermodynamic cycle is that part where work is produced. Most power producing thermodynamic cycles utilize a turbine for this phase as turbines have very favorable power to weight ratios and can be built with large outputs. The theory governing the conversion of fluid energy to mechanical energy comes from fluid mechanics. Momentum is the key factor as a change in direction of a high energy jet can create significant forces according to the laws of motion. Theoretically all the kinetic energy in a jet can be converted into mechanical energy but friction losses and practical considerations make the conversion efficiency somewhat less in reality.

1. Introduction

In all thermal power plants heat is converted into work by utilizing a thermodynamic cycle. The working fluid of the cycle receives heat from a suitable source, such as a combustible or fissile fuel, converts part of it into work and rejects the remainder to the environment. The amount of heat that can be converted into work is governed by the laws of thermodynamics. This establishes the theoretical efficiency of the system. Generally the ideal thermodynamic efficiency is determined by the maximum and minimum temperatures of the working fluid in the cycle. These temperatures in turn are limited by material constraints and environmental conditions. Various thermodynamic cycles have been conceived and all can be analyzed theoretically. In practice the objective is to reduce various losses so that the actual cycle efficiency can approach the ideal cycle efficiency as closely as possible.

2. Fundamental Equations

2.1. Equation of State

The equation of state is a definite relationship between the properties of an ideal gas. It is given by:

$$p\,v = R\,T \quad \text{or} \quad p = \rho\,R\,T \tag{1}$$

Here p is pressure, v specific volume, ρ density, T absolute temperature and R the specific gas constant. The specific gas constant in turn is defined as follows:

$$R = c_p - c_v \tag{2}$$

Here c_p and c_v are the specific heats at constant pressure and constant volume respectively. The ratio of these specific heats k is defined as:

$$k = c_p / c_v \tag{3}$$

2.2. Continuity Equation

The continuity equation simply states that, for steady flow through a system, the mass flow rate at the inlet to the system must be equal to the mass flow rate at the outlet from the system.

$$\rho_1\,V_1\,A_1 = \rho_2\,V_2\,A_2 \tag{4}$$

Here ρ is the density, V the velocity and A the flow area. This is based on the law of conservation of mass.

2.3. Energy equation

Thermodynamics is a science that combines heat energy and mechanical work. A very important practical application of this is the conversion of heat to work. In all conversion processes, energy is conserved such that the total energy before the process is equal to the total energy after the process. Various energies may be defined as follows:

- Potential Energy $m\,z\,g$ (J) or $z\,g$ (J/kg)
- Kinetic Energy ½ $m\,V^2$ (J) or ½ V^2 (J/kg)
- Internal Energy U (J) or u (J/kg)
- Flow Work $p\,V$ (J) or $p\,v$ (J/kg)
- Mechanical Work W (J) or w (J/kg)
- Heat Q (J) or q (J/kg)

Potential Energy is the energy that the fluid has by virtue of its elevation z above a given datum. Kinetic Energy is the energy of the fluid due to its velocity V. Internal Energy U is the energy of motion of the molecules of the fluid. Internal energy per unit

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mass is u. This in turn is dependent upon the temperature of the fluid. Flow Work is the work done in driving a slug of fluid of volume V across the boundaries of a system against a pressure p. The product of these pV is work. The term pv is work per unit mass since v is specific volume. W is work and w work per unit mass. Similarly Q is heat and q heat per unit mass.

If all these energies are added before and after any process they must be equal and the general energy equation may be set up:

$$z_1 g + V_1^2/2 + u_1 + p_1 v_1 + w_{\text{in}} + q_{\text{in}} = z_2 g + V_2^2/2 + u_2 + p_2 v_2 + w_{\text{out}} + q_{\text{out}} \tag{5}$$

This is the completely generalized form of the energy equation. In practice it is modified in various ways.

In many cases some of these energies, such as potential and kinetic energies, are very small in comparison with the others and may be neglected. The internal energy u is the energy of vibratory motion of the fluid molecules while the flow work pv is the energy required to pump the fluid into the thermodynamic system at the pressure specified. Since internal energy, pressure and specific volume are fixed parameters at given conditions, it is convenient to combine them into a single new parameter, enthalpy h, defined as follows:

$$h = u + pv \tag{6}$$

The general energy equation therefore reduces to the thermodynamic energy equation:

$$z_1 g + V_1^2/2 + h_1 + w_{\text{in}} + q_{\text{in}} = z_2 g + V_2^2/2 + h_2 + w_{\text{out}} + q_{\text{out}} \tag{7}$$

In many cases the change in elevation in heat engines is negligible and the potential energy term may be neglected as well. Thus for a heat engine using heat to produce work the equation becomes:

$$V_1^2/2 + h_1 + q_{\text{in}} = V_2^2/2 + h_2 + w_{\text{out}}$$

In fluid mechanics there is normally no interchange of heat and changes in temperature are insignificant. The general energy equation in this case reduces to:

$$z_1\, g + V_1^2/2 + p_1 v_1 + w_{\text{in}} = z_2\, g + V_2^2/2 + p_2 v_2 + w_{\text{out}}$$

In hydraulics it is convenient to express energy in terms of head or elevation. Changing the units by dividing by g and changing specific volume v into density ρ gives:

$$z_1 + V_1^2/2\,g + p_1/\rho_1\, g + w_{\text{in}}/g = z_2 + V_2^2/2\,g + p_2/\rho_2 g + w_{\text{out}}/g$$

For incompressible flow and no work interchange the familiar Bernoulli Equation is

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obtained:

$$p_1 / \rho g + z_1 + V_1^2 / 2g = p_2 / \rho g + z_2 + V_2^2 / 2g \qquad (8)$$

The thermodynamic energy equation may be used in many different ways by making appropriate assumptions. In a boiler for example if the elevation and velocity terms are neglected and if no work is exchanged the equation becomes:

$$h_1 + q_{\mathrm{in}} = h_2$$

$$q_{\mathrm{in}} = h_2 - h_1$$

In a turbine if the elevation and velocity terms are neglected and if no heat is exchanged the equation becomes:

$$h_1 = h_2 + w_{\mathrm{out}}$$

$$w_{\mathrm{out}} = h_1 - h_2$$

In a nozzle, where a high velocity jet is produced to drive, for example, turbine blades, if the elevation terms are neglected and if there is no exchange of work or heat, the following is obtained:

$$V_1^2 / 2 + h_1 = V_2^2 / 2 + h_2$$

$$V_2^2 - V_1^2 = 2(h_1 - h_2)$$

For a low inlet velocity V_1, V_1^2 is negligible relative to V_2^2 and this equation can be further simplified to give the outlet velocity V_2 directly in terms of the square root of the enthalpy drop Δh across the nozzle.

Another definition that can be usefully applied is that of specific heat. When heat is added to a fluid under constant pressure conditions, specific heat c_{p} is defined as follows:

$$c_{\mathrm{p}} = q / \Delta T \qquad (9)$$

Under constant pressure conditions the enthalpy change Δh is equal to the heat q added so that the specific heat becomes:

$$c_{\mathrm{p}} = \Delta h / \Delta T$$

$$\Delta h = c_{\mathrm{p}} \Delta T \qquad (10)$$

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If therefore the specific heat of a fluid and its temperature change are known, the change in enthalpy or heat gained or lost can be determined.

This last equation can be applied to the equation for a turbine to give the work output in terms of temperatures:

$$w_{out} = c_p (T_1 - T_2)$$

This is a convenient form of the equation when applied to gas turbines.

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Biographical Sketch

Robin Chaplin obtained a B.Sc. and M.Sc. in mechanical engineering from University of Cape Town in 1965 and 1968 respectively. Between these two periods of study he spent two years gaining experience in the operation and maintenance of coal fired power plants in South Africa. He subsequently spent a further year gaining experience on research and prototype nuclear reactors in South Africa and the United Kingdom and obtained M.Sc. in nuclear engineering from Imperial College of London University in 1971. On returning and taking up a position in the head office of Eskom he spent some twelve years initially in project management and then as head of steam turbine specialists. During this period he was involved with the construction of Ruacana Hydro Power Station in Namibia and Koeberg Nuclear Power Station in South Africa being responsible for the underground mechanical equipment and civil structures and for the mechanical balance-of-plant equipment at the respective plants. Continuing his interests in power plant modeling and simulation he obtained a Ph.D. in mechanical engineering from Queen's University in Canada in 1986 and was subsequently appointed as Chair in Power Plant Engineering at the University of New Brunswick. Here he teaches thermodynamics and fluid mechanics and specialized courses in nuclear and power plant engineering in the Department of Chemical Engineering. An important function is involvement in the plant operator and shift supervisor training programs at Point Lepreau Nuclear Generating Station. This includes the development of material and the teaching of courses in both nuclear and non-nuclear aspects of the program.

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