Pearson BTEC Level 5 Higher Nationals in Engineering (RQF)

Unit 64: Thermofluids

Unit Workbook 1

in a series of 4 for this unit

Learning Outcome 1

Thermodynamic Systems

Sample

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Contents

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INTRODUCTION

Review industrial thermodynamic systems and their properties

- *Thermodynamic systems:*
    - Power generation plant.
    - Significance of first law of thermodynamics.
    - Analysis of Non-Flow Energy Equation and Steady Flow Energy Equation systems.
    - Application of thermodynamic property tables.
    - Energy transfer systems employing polytropic processes.
    - Pressure/volume diagrams and the concept of work done.
    - The application of the Gas Laws and polytropic laws for vapours and gases.

GUIDANCE

This document is prepared to break the unit material down into bite size chunks. You will see the learning outcomes above treated in their own sections. Therein you will encounter the following structures;

Purpose	Explains *why* you need to study the current section of material. Quite often learners are put off by material which does not initially seem to be relevant to a topic or profession. Once you understand the importance of new learning or theory you will embrace the concepts more readily.
Theory	Conveys new material to you in a straightforward fashion. To support the treatments in this section you are strongly advised to follow the given hyperlinks, which may be useful documents or applications on the web.
Example	The examples/worked examples are presented in a knowledge-building order. Make sure you follow them all through. If you are feeling confident then you might like to treat an example as a question, in which case cover it up and have a go yourself. Many of the examples given resemble assignment questions which will come your way, so follow them through diligently.
Question	Questions should not be avoided if you are determined to learn. Please do take the time to tackle each of the given questions, in the order in which they are presented. The order is important, as further knowledge and confidence is built upon previous knowledge and confidence. As an Online Learner it is important that the answers to questions are immediately available to you. Contact your Unit Tutor if you need help.
Challenge	You can really cement your new knowledge by undertaking the challenges. A challenge could be to download software and perform an exercise. An alternative challenge might involve a practical activity or other form of research.
Video	Videos on the web can be very useful supplements to your distance learning efforts. Wherever an online video(s) will help you then it will be hyperlinked at the appropriate point.

1.1 Fundamental Systems

1.1.1 Forms of Energy and Basic Definitions.

Thermodynamics is the study of behaviour and dynamics of energy. Energy comes in a wide variety of forms, for example; if your lightbulb was powered by a gas power station, the energy changes several times before coming out of the bulb as light and heat, shown by Fig.1.1. None of the processes will be 100% efficient, and realistically will lose a lot of temperature as heat.

Figure 1.1: An energy flow chart from gas to a lightbulb.

Fig.1.1 shows several different energies, but energy can be categorised into larger groups:

- Kinetic energy is the energy of a moving object, in Fig.1.1, this would be the generator's shaft spinning to generate electrical energy
- Potential energy is the energy that an object has due to its position relative to others, for example, electrical energy moves from high charge to low charge. Or an object on a table has more potential energy than an object on the floor (the potential energy would be converted to kinetic when it drops).
- Internal energy is the energy that is holding the bonds of the molecules together, such as the chemical energy holding a fuel's molecules together.

1.1.2 First Law of Thermodynamics

The first law of thermodynamics is simple: "energy cannot be created or destroyed, it can only be transferred from one form to another". The first law of thermodynamics can be expressed as where Q is the heat of the system, W is the work ΔU is the internal energy change, ΔKE is the kinetic energy change and ΔPE is the potential energy change.

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

This means that all thermodynamic equations can be expressed as Eq.1.1, where c is the velocity of the fluid, g is the acceleration due to gravity, and z is the height of the system.

$$Q - W = \left(U_2 + \frac{1}{2}mc_2^2 + mgz_2\right) - \left(U_1 + \frac{1}{2}mc_1^2 + mgz_1\right) \qquad \text{(Eq.1.1)}$$

1.3.1 Closed Systems and the Non-Flow Energy Equation

A system is defined as either open or closed, and where the system meets its surroundings is called the boundary. A closed system is one that only has an input or output of energy in some form, shown by Fig.1.2, the boundary encloses the entire system, a closed system is typically used when modelling an engine's cylinder. The equation for closed systems (also known as the non-flow energy equation, is shown as Eq.1.2.

$$Q - W = U_2 - U_1 \qquad \text{(Eq.1.2)}$$

The assumptions when calculating a closed system are:

- The fluid is compressible
- The system is insulated – meaning that heat is not lost to the environment over time (*heat can be put in, or taken out, but it is not slowly lost over time*)

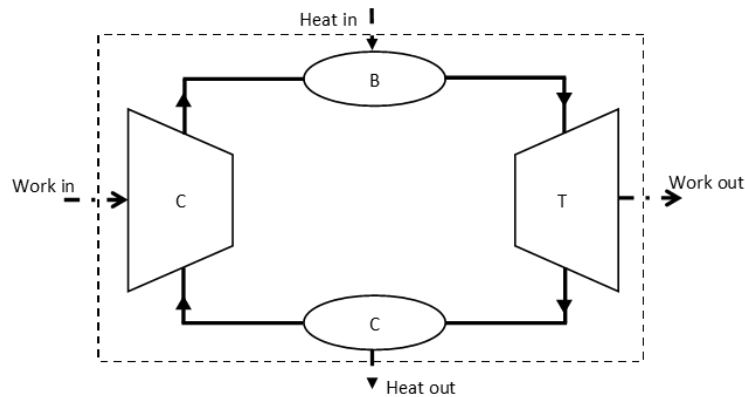- ΔKE and ΔPE are negligible $(= 0)$

Figure 1.2: A diagram of a closed system

1.1.1 Open Systems and the Steady Flow Energy Equation

An open system also has a mass flow, the boundary will surround the equipment, but will also have an intake and exhaust of mass through the boundary. Most thermodynamic systems will use an open system, such as heat pumps and refrigeration cycles. Fig.1.3 shows the boundaries for an open system.
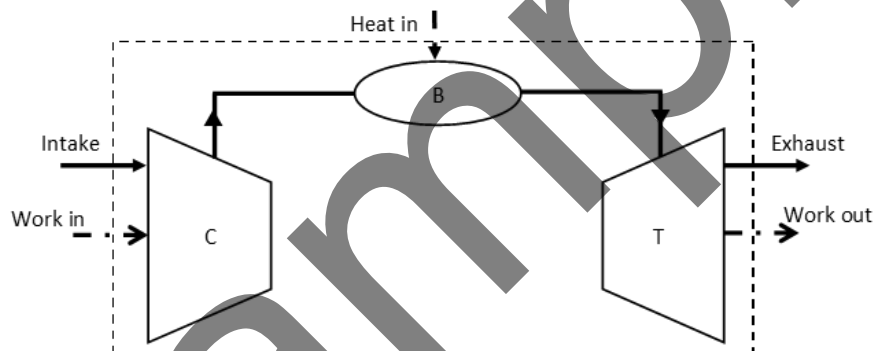

Figure 1.3: An open system and its boundaries

Remembering the overall equation of the first law (Eq.1.1), we have:

$$Q - W = \left(U_2 + \frac{1}{2}mc_2^2 + mgz_2\right) - \left(U_1 + \frac{1}{2}mc_1^2 + mgz_1\right)$$

Many mechanical engineering devices involve open systems where the flow can be analysed as being in steady state, such as a gas turbine or a refrigeration cycle. For steady flows undergoing changes in volume, the enthalpy, represented by Eq.1.3 is the most convenient variable to represent that static energy of the flow.

$$h = U + PV \qquad \text{(Eq.1.3)}$$

For these applications the first law of thermodynamics is expressed as Eq.1.4, known as the Steady Flow Energy Equation.

$$\dot{Q} - \dot{W}_x = \dot{m}_2\left(h_2 + \frac{1}{2}c_2^2 + gz_2\right) - \dot{m}_1\left(h_1 + \frac{1}{2}c_2^2 + gz_1\right) \qquad \text{(Eq.1.4)}$$

An important aspect is the introduction of mass flow, the system must follow the conservation of mass. If there is a change of area, speed or density then the mass flow will change. Shown by Eq.1.5, where ρ is the density of the fluid, A is the cross-sectional area of the pipe, and c is the velocity of the fluid.

$$\dot{m} = \rho A c \qquad\qquad \text{(Eq.1.5)}$$

Since the flow can change, or flows can be added or diverted from the pipes, we build Eq.1.6 for mass flow continuity.

$$\sum \dot{m}_{IN} = \sum \dot{m}_{OUT} \qquad\qquad \text{(Eq.1.6)}$$

Example 3

Two water pipes are converging into one large pipe, the first pipe has an area of $0.01m^2$ and its water is flowing at $160ms^{-1}$. The second pipe has an area of $0.03m^2$ and its water is flowing at $20ms^{-1}$. The larger pipe has an area of $0.45m^2$. Calculate:

a) The mass flow rate of the larger pipe.
b) The velocity of the larger pipe.

Answers:

a) The continuity of mass equation gives:

$$\dot{m}_1 + \dot{m}_2 = \dot{m}_3 = \rho A_1 c_1 + \rho A_2 c_2 = 1000(0.01 \cdot 160 + 0.03 \cdot 20) = 2200 kg \cdot s^{-1}$$

b) Using Eq.2.5, we can find velocity as

$$\dot{m}_3 = \rho A_3 c_3 \therefore c_3 = \frac{\dot{m}_3}{\rho A_3} = \frac{2200}{1000 \cdot 0.45} = 4.89 ms^{-1}$$

1.1.3 Heat and Work

When calculating heat and work, it's important to know the convention for calculations. Consider Eq.1.7 below.

$$Q - W = U_2 - U_1 \qquad\qquad \text{(Eq.1.7)}$$

This is the equation used in a closed system, typically the compression or expansion stroke of a piston (where there is negligible change in kinetic or potential energy). The convention for energy transfer is:

- if heat is transferred from the surroundings into the system, then Q is *positive*,
- if heat is released from the system into the surroundings, then Q is *negative*,
- if external work is done *on* the fluid or engine, then W is **negative**,
- If external work is done *by* the fluid or engine, then W is *positive*.

Example 1

Calculate the work of an engine for one stroke if the if the heat is transferred out of the system is $300 \ kJ/kg$ and the internal energy has decreased by $900 \ kJ/kg$. State whether work is done on or by the fluid.

$$Q - W = U_2 - U_1$$

Heat is transferred out of the system, so Q is **negative**, and $U_2 - U_1$ is also **negative** since there is a decrease in internal energy.

$$-300 - W = -900$$

$$-W = -900 + 300$$

$$-W = -600$$

$$W = 600 \, kJ/kg$$

The work is positive; therefore, work is done **by** the fluid.

1.2 Fundamental Equations

1.2.1 Moles

Before moving onto gas laws, a brief explanation of the term "moles" is required. Moles define the number of atoms or molecules that are present in a material. The equation to calculate the number of moles, n, is given by Eq.1.8, where m is the overall mass of the substance, and M_r is the molecular mass of the substance.

$$n = \frac{m}{M_r} \qquad \text{(Eq.1.8)}$$

For example, one mole of Helium ($M_r = 4$) would weigh 4 grams. To find the number of atoms or molecules present in the substance, the number of moles is multiplied by Avogadro's constant ($N_A = 6.022 \times 10^{23} mol^{-1}$).

> **Example 2**

Find the number of molecules present in:

a) $3.5g$ of methane
b) $80g$ of Sodium Chloride

Answers:

a) Methane's chemical formula is CH_4, meaning there are 4 Hydrogens ($M_r = 1$) to every Carbon ($M_r = 12$), so the total molecular mass is $(4 \times 1) + 12 = 16$.

   The number of moles is therefore $n = \frac{3.5}{16} = 0.2188 mol$

   Which then gives the number of atoms as $0.2188 \times 6.022 \times 10^{23} = 1.32 \times 10^{23}$ atoms

b) Sodium Chloride's chemical formula is $NaCl$. One chlorine atom ($M_r = 35.5$) for every sodium atom ($M_r = 23$), the total molecular mass is $35.5 + 23 = 58.5$

   The number of moles is therefore $n = \frac{80}{58.5} = 1.3675$

   Which gives the number of molecules as $1.3675 \times 6.022 \times 10^{23} = 8.24 \times 10^{23}$ molecules

1.2.2 The Ideal Gas Equation

When the working fluid is modelled as a gas, it is useful to model it as an "ideal gas". An ideal gas is an imaginary substance that obeys the relationship in Eq.1.9, where P is the pressure, V is the volume, n is the number of moles, R_u is the universal gas constant ($8.314 J \cdot mol^{-1} \cdot K^{-1}$) and T is the temperature in Kelvin.

$$PV = nR_uT \qquad \text{(Eq.1.9)}$$

We can also change the ideal gas equation to incorporate the mass of the gas in question, by using the individual gas constant R, which is calculated using Eq.1.10.

$$R = M_R R_u \qquad \text{(Eq.1.10)}$$