Pearson BTEC Levels 4 Higher Nationals in Engineering (RQF)

Unit 13: Fundamentals of Thermodynamics and Heat Engines

Unit Workbook 3

in a series of 4 for this unit

Learning Outcome 3

Heat Transfer for Industrial Applications

Contents

INTRODUCTION

Examine the principles of heat transfer to industrial applications.

- Modes of heat transmission, including conduction, convection & radiation.
- Heat transfer through composite walls and use of U and k values.
- Application of formulae to different types of heat exchangers, including recuperator and evaporative.
- Regenerators.
- Heat losses in thick and thin walled pipes, optimum lagging thickness.

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.

3.1 Methods of Heat Transfer

3.1.1 Conduction

Theory

The conduction of heat is the transfer of energy through particle vibrations. In solids this is through the lattice, with adjacent molecules transferring energy in packets (phonons) to neighbouring molecules. In the case of fluids, the energy is transferred through collisions and diffusion.

The rate of heat loss, $\dot{Q}$ $[W]$ through a solid material (or a fluid with no flow) of length dx is described as Eq. 3.1, where k $[W \cdot m^{-1} \cdot K^{-1}]$ is the thermal conductivity of the material and A is the area of the face.

$$\dot{Q} = -kA\frac{dT}{dx} \qquad \text{(Eq. 3.1)}$$

Since k will always be a positive, the negative sign indicates that heat flows in the direction of decreasing temperature. With Eq. 3.1 we can see that the temperature drop through the wall is linear, as demonstrated in Fig. 3.1.

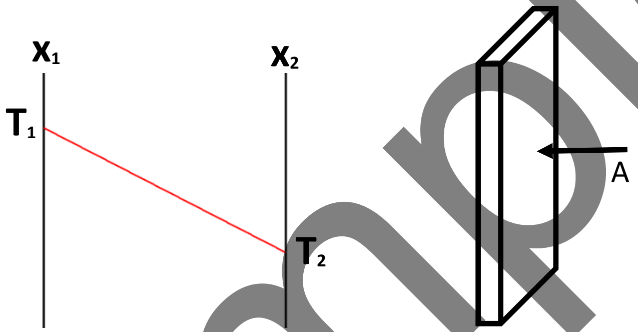


Fig. 3.1: 1-D steady heat conduction through a planar wall.

Table 3.1 gives the thermal conductivity for various materials

Table 3.1: Thermal conductivity values for materials

Material	k
Diamond	2300
Copper	401
Aluminium	237
Iron	80
Glass	0.78
Water	0.61
Air	0.026

3.1.2 Convection

Theory

Convection is the transfer of heat between flowing fluid and solid boundaries. When the fluid flow is driven by the Earth's atmosphere this is known as *natural convection*. Many engineering applications will use a fluid flow generated by the motion of an object or with an imposed pressure difference, known as *forced convection*.

Due to the presence of a viscous boundary layer close to the wall, shown by Fig. 3.2, the flow velocity at the wall is zero. This means that heat is transferred through conduction at the surface of the solid. The role of convection is to make the thermal boundary layer thin (its thickness is related to thickness of the velocity boundary layer). This leads to large temperature gradients and higher overall heat transfer rates.

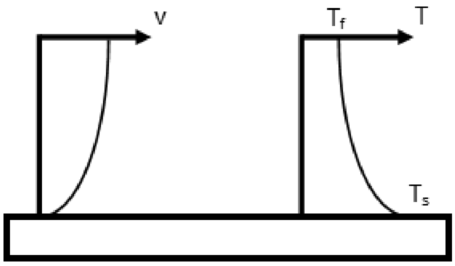


Fig. 3.2: Velocity and temperature change with convective heat transfer

In engineering, the rate of heat transfer is given as Eq. 3.2, where $h\ [W \cdot m^{-2} \cdot K^{-1}]$ is the convective heat transfer coefficient, T_f is the average temperature of the fluid and T_s is the temperature of the surface of the solid.

$$\dot{Q} = hA(T_s - T_f) \qquad \text{(Eq. 3.2)}$$

To evaluate how much more effective convection is than conduction of a certain length L, the dimensionless Nusselt number (Nu) is defined using Eq. 3.3

$$\frac{\dot{Q}_{conv}}{\dot{Q}_{cond}} = \frac{UL}{k} = Nu \qquad \text{(Eq. 3.3)}$$

3.1.3 Radiation

Theory

Radiation is the weakest of the three forms of heat transfer, and in most heat transfer simulations is ignored. The only time radiation is realistically considered is when there is no convection or conduction possible (in space). There are two important aspects of radiative heat transfer: emission, and absorption of the radiation.

Black bodies: A black body is an ideal material which absorbs all radiation at all wavelengths, nothing is reflected off it. A black body is also a perfect emitter of radiation, and it emits radiation uniformly in all direction, so it is described as a diffuse emitter. If the body itself did not emit radiation, it would appear black.

The predicted electromagnetic spectrum emitted by a black body is shown by Fig. 3.3. Integrating the rate of emission at each wavelength gives the total rate of radiation emission.

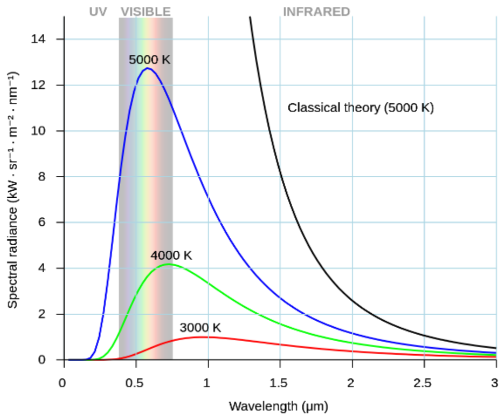


Fig. 3.3: Radiation spectrum for a black body

For a black body of area A and temperature T, the rate at which energy is emitted is calculated using Eq. 3.4. This is also known as Stefan's law, where σ is the Stefan-Boltzmann constant $(5.67 \times 10^8\ Wm^{-2}K^{-1})$

$$\dot{Q} = \sigma A T^4 \qquad \text{(Eq. 3.4)}$$

Grey bodies: Grey bodies are the emission from a real object, dependent on the material's emissivity, ϵ, in practice $0 \leq \epsilon \leq 1$, meaning Eq. 3.4 becomes Eq. 3.5.

$$\dot{Q} = \epsilon \sigma A T^4 \qquad \text{(Eq. 3.5)}$$

The fraction of incident radiation that is reflected is known as the reflectance (ρ). The fraction that passes through the object without being absorbed is the transmissivity (τ), and the fraction that heats the object is the absorptivity (α). This accounts for all the incident radiation so $\rho + \tau + \alpha = 1$. For solid materials, the transmissivity is usually zero, and $\alpha = \epsilon$. Therefore, if a grey body at temperature T has surroundings that behave as a black body at temperature T_s, the net heat transfer *from* the grey body (power emitted minus absorbed power) will be demonstrated by Eq. 3.6.

$$\dot{Q}_{net} = \epsilon \sigma A (T^4 - T_s^4) \qquad \text{(Eq. 3.6)}$$

The rate of heat transfer also depends on the visible area of the object.

3.2.1 Resistance Networks and Heat Transfer Through a Planar Wall

Theory

One of the best ways to model heat transfer is to consider the system as an electrical circuit. Looking at the potential difference across a resistor with a current, I, we can model Ohm's law as Eq. 3.7.

$$I = \frac{V_1 - V_2}{R} \qquad \text{(Eq. 3.7)}$$

And considering Eq. 3.1, we can define it as:

$$\dot{Q} = \frac{kA}{L}(T_1 - T_2)$$

And define thermal resistance for 1-D conduction as Eq. 3.8:

$$\boldsymbol{R_{cond} = \frac{L}{kA_s}} \qquad \textbf{(Eq. 3.8)}$$

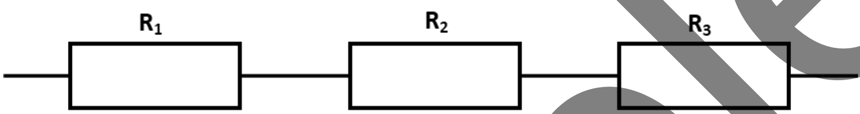
The same approach can be used for convective and radiative shown in Eq. 3.9 and Eq. 3.10, respectively:

$$\boldsymbol{R_{conv} = \frac{1}{hA_s}} \qquad \textbf{(Eq. 3.9)}$$

$$R_{rad} = \frac{1}{\sigma \epsilon \mathrm{A_S} (T_1^2 + T_S^2)(T_1 + T_S)} \qquad \text{(Eq. 3.10)}$$

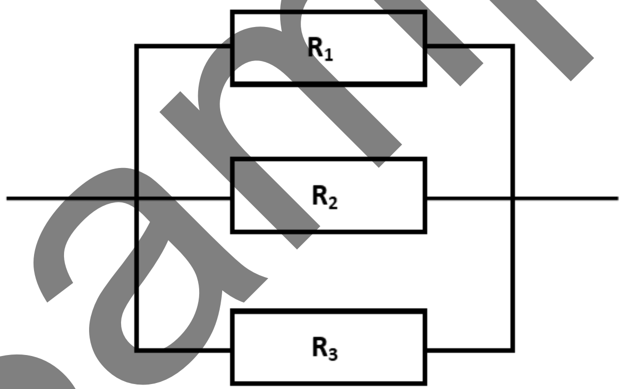
We can use this analogy to build a resistance circuit to construct series and parallel thermal circuits. As a quick reminder, resistance in series is calculated using Eq. 3.11.

$$R = R_1 + R_2 + R_3 + \cdots + R_n \qquad \text{(Eq. 3.11)}$$



and, in parallel using Eq. 3.12:

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \cdots + \frac{1}{R_n} \qquad \text{(Eq. 3.12)}$$



Or we can use the overall heat transfer coefficient, U, which is essentially just Eq. 3.13.

$$U = 1/R \qquad \text{(Eq. 3.13)}$$

We can find out the rate of heat transfer through a system with Eq. 3.14.

$$\dot{Q} = A\frac{T_1 - T_2}{R} = UA(T_1 - T_2) \qquad \text{(Eq. 3.14)}$$

Example 1A

The inside temperature of the air in a room is $18^{\circ}C$, and the temperature of the air outside the room is $13^{\circ}C$. There is only a brick wall separating the room from the outside. The wall is 3 m high and 2 m wide, and the