

ThermoAssessment_JamesTreviso_1503023

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1.1 Objective

To develop an understanding of thermofluid elements, gaining knowledge of fundamental modes of heat transfer and fluid flow thus analysing a more complex phenomena.

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2.1 Introduction

Heat transfer occurs when two bodies at different temperatures are brought into thermal contact with each other. There are three different modes of heat transfer in which the energy may be transferred, by conduction, convection and radiation. In this report we develop an understanding of heat transfer, evaluating characteristics of insulation materials and the effect of temperature on the thermal conductivity. By discussing dimensionless groups we evaluate their significance affecting heat transfer.

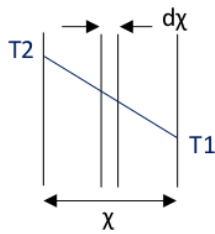
3.1 Element A - Conduction

Conduction is the process that heat is transferred along a metallic surface, calculated through the Fourier equation. $Q = KA \frac{dt}{dx}$

Where K = Thermal conductivity (W/mK), A = Area (m²) and $\frac{dt}{dx}$ = Temperature difference.

Heat transfer through a metallic slab can be seen as $Q = \frac{KA}{\chi} \times (T_2 - T_1)$ as shown below.

3.2 Conduction- Heat transfer through a slab



T_1 and T_2 , the temperatures inside and outside of the surface, χ being the thickness of the slab. Dependant on the parameters of the slab and temperature different can result in a change of the heat transfer of the slab measured in Joules (J).

Heat transfer through a cylinder can be seen as,

$$Q = \frac{2\pi K (T_2 - T_1)}{\ln r_2/r_1}$$

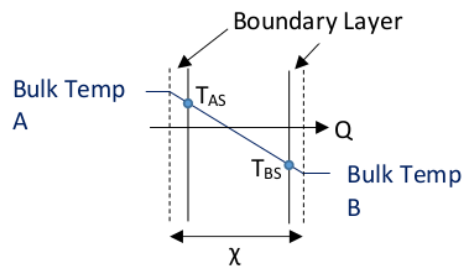
Heat transfer through a sphere can be seen as,

$$Q = \frac{4\pi K (T_2 - T_1)(r_1 r_2)}{(r_2 - r_1)}$$

4.1 Convection

Like most non-metallic components, these are poor conductors of heat. Convection depends on movement of the fluid, this can be caused by a pump known as forced convection. This can also be caused due to differences in density caused by changes in temperature, Cooper 2017 describes it as convection above a hot surface occurs because hot air expands, becomes less dense and rises. Heat transfer due to convection can be seen below.

4.2 Heat Transfer due to convection



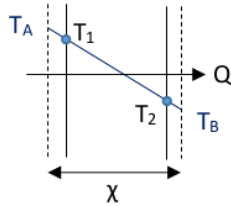
Heat transfer due to convection is determined through Newton's Law of Cooling where $Q = h_a (T_2 - T_1)$

As the transfer of heat from a fluid travels from 'A' to 'B' through the wall thickness ' χ ' and the boundary layer is the thermal conductivity where heat transfer in this area is conduction only. Fluid passes through the boundary layer where viscosity plays a dominant role whereby the fluid can be either laminar or turbulent. Reynolds Number $\frac{\rho V L}{\mu}$ determining the flow of fluid, if $< 2,000$ the flow is laminar, if $> 4,000$ the fluid flow is turbulent.

The variation of temperature is shown as a gradient in the wall of thickness where in fluid 'A', the temperature decreases rapidly from its bulk temperature 'A' to T_A likewise at T_B where the temperature decreases to its bulk temperature 'B'.

5.1 Combined Conduction and Convection

5.2 Conduction and Convection



This is known as an effective process with a temperature dependant thermal conductivity utilising conduction and convection where it includes is a combination of Fourier's Law of Conduction and Newton's Law of cooling. When a slab is subjected to combined conduction and convection, as fluid 'A' travels to T_1 (convection) $Q = h_A A (T_A - T_1)$. Within the slab T_1 to T_2 (conduction) $Q = \frac{KA}{\chi} \times (T_2 - T_1)$, the third equation, fluid 'B' (convection) $Q = h_B A (T_2 - T_B)$. Results are reported in terms of the average Nusselt number and dimensionless temperature distribution, the ratio of conductive and convective heat transfer across the boundary layer. It is found that as the temperature jump 'coefficient increases, the Nusselt number decreases.' (Dehghan, Mahmoudi, Valipour, & Saedodin, 2015). A laminar flow will show a $Nu = 1$, if a turbulent flow $Nu = 100-1000$.

6.1 Radiation

Radiation differs from conduction and convection as there is no direct contact between a body or fluid, rather energy is travelled through a vacuum and is transmitted as electromagnetic waves. Materials radiate energy, thermal electromagnetic radiation is absorbed into the surrounding body in thermodynamic equilibrium known as black body radiation.

Stefan Boltzmann law tells us that the total radiant heat emitted to a surface is proportional to the forth power of its absolute temperature (Montambaux, 2018) this can be seen as $\dot{E} = \sigma A T^4$. When the body is not black, the relationship becomes $\dot{E} = \epsilon \sigma A T^4$ as less energy is

radiated. If temperature T_1 is absolute surrounded by a black surface at absolute temperature T_2 of a black body area 'A', the rate of heat transfer can be calculated as $Q = \sigma A (T_1^4 - T_2^4)$.

7.1 Element B - Characteristics of Insulation Materials

Using insulation materials can alter the outcome of temperature that is required, where materials barricade the outside temperature dependant on the heat of the enclosure. High temperature materials diatomaceous earth demonstrates a thermal insulating effect temperature up to 650° C (United States of America Patent No. US6033591A, 1998). Talc, similar to asbestos are also major types of high temperature insulation, known as non-fibrous materials. These materials are used in insulation maintaining a high temperature in its enclosure therefore preventing heat loss from its surroundings. Fibrous materials such as textiles and composites are low temperature insulators, these are used preventing the enclosed temperature from gaining heat such as mineral wool. Fibrous materials structure is their low thermal conductivity 'k' usually 'lower than 0.1 W/mk.' (Karamanos, Papadopoulos, & Anastasellos, 2004). This is due to the quantity of gas, usually air embodied into the materials mass. Metal foam, a cellular like structure, has a low thermal conductivity due to the honeycomb like assembly, therefore the heat transfer occurs at a lower rate. On the contrary the defining characteristics of the metal proposes a high porosity. Thermal conductivity and porosity in materials are entwined, the higher the porosity, the lower the thermal conductivity. With its cellular structure, the high surface area porous metals promise a high heat transfer coefficient.

8.1 Element C - Effect of Temperature on the Thermal Conductivity

Thermal conductivity represented by k measured at W/mK, this is a property that relates to the rate of heat loss per unit area of a material to its rate of change of temperature. Most metals have a high thermal conductivity therefore are efficient conductors of heat, such materials as aluminium and copper with thermal conductivities of 240 and 400 W/mK (Learning, 2017) respectively at room temperature. In solid materials there are two ways in which heat can be conducted through lattice vibrations and flow of free electrons thus

metals are good electrical and heat conductors. These materials are commonly used for specific applications where heat conductivity is significant. Thermal conductivity predominantly depends on electronic effect, when temperature increases, both number of free electrons and lattice vibrations increase thus thermal conductivity increases. Yet lattice vibrations obstruct the flow of free electrons, this results to a decrease in thermal conductivity with increase in temperature.

Other metallic materials with a high porosity tend to have low thermal conductivity. This is because scattering of pores in the material are no longer effective. Due to the cellular like structure, with much disorder is visible therefore there is high entropy. For metals, thermal conductivity is mainly a function of flow of free electrons, as the temperature increases, the lattice vibrations increase obstructing the flow of these electrons thus reducing conductivity.

Non-metallic insulators such as silica aerogel, a synthetic insulating material derived from a gel has a much lower thermal conductivity at room temperature of 0.02 W/mK (Afework, 2020) respectively and many other low temperature insulation have low thermal conductivity making it more difficult for heat to pass through easily therefore making a good insulation material. Based on Fourier's law of thermal conduction, the rate of heat transfer through a material is proportional to the negative gradient in the temperature where $Q = KA \frac{dt}{dx}$ as mentioned In section (3.1) , Fourier's law is an expression that defines thermal conductivity, a material which is a good thermal conductor has a high value of 'k'. Determining the heat flux through a slab by defining the temperature difference on either sides when Q is known we can determine the total heat loss through the two temperatures and material.

9.1 Element D - Dimensional Analysis

Dimensional analysis, a technique combining many parameters into a lesser number to which reduces the number of variables needed to determine the end result known as the “theory of similarity”. By listing all the primary units that heat transfer coefficient depends on such as,

- η = Dynamic viscosity of the fluid
- ρ = Density of the fluid
- k = Thermal conductivity of the fluid
- C_p = Specific heat capacity of the fluid
- ΔT = Temperature difference over the boundary layer
- V = Velocity of the fluid
- L = Characteristic length

The formulae is seen as $\frac{hL}{k} = \phi \left[\left[\frac{\eta C_p}{k} \right] \left[\frac{\rho V L}{\mu} \right] \right]$

These dimensionless numbers that are used in forced convection heat transfer coefficient correlations.

9.2 Reynolds Number

In fluid mechanics the Reynolds number is a dimensionless number that helps to predict a flow pattern seen as $\frac{\rho V L}{\mu}$ discussed in section (4.2) by determining these figures we can calculate whether the flow of fluid is laminar or turbulent flowing through the boundary layer this is done by means of heat transfer by convection. Fluid passes through the boundary layer where viscosity plays a dominant role, by knowing the density of the fluid, velocity, viscosity and characteristic length we can determine the motion of the fluid.

Laminar flow occurs when the flow of the fluid is at a parallel flow (Wang, N. V. Nikitin, & S. I. Chernyshenko, 2011), this is usually at the lower end of the velocity scale the Reynolds number can be seen as < 2000 . As the velocity flow increases, the flow of fluid becomes more turbulent. The flow of energy becomes more distributive where energy is seen to be lost during a turbulent flow rather than laminar. This is seen then the Reynolds number is > 4000 .

9.3 Nusselt Number

The Nusselt number is the ratio of conductive and convective heat transfer across the boundary layer. It is found that as the temperature jump 'coefficient increases, the Nusselt number decreases.' (Dehghan, Mahmoudi, Valipour, & Saedodin, 2015). Nusselt number can be determined through $\frac{hL}{k}$ as mentioned in section (5.2). The Nusselt number is required to find 'h', the convective heat coefficient. Unlike the Reynolds number which determines the flow of fluid by convection, the Nusselt number is a value that represents heat transfer by convection to heat transfer by conduction. If the value determined is between 1- 10 the characteristics are to be seen as laminar which is seen to have a thick boundary layer. A value of 100- 1000 is a turbulent flow therefore has a thin boundary layer.

9.4 Grashof Number

Similar to that of Reynolds number in forced convection, Grashof number involves situations of natural convection. A dimensionless quantity used to analyse the velocity distribution in free convectonal systems. Caused by a change in the density of the fluid due to the temperature gradient, in free convection, the driving force is a buoyancy force caused by the temperature gradient (Kakimoto, 2015). Essentially the ratio of buoyant forces to viscous force acting on a liquid is termed Grashof number which can be defined for a vertical flat plate as shown below.

$$GR = \frac{\text{Buoyant forces}}{\text{Viscous forces}} = \frac{g\beta(T_w - T_\infty)L^2}{\nu^2}$$

Where,

g is acceleration due to Earth's gravity

β is the coefficient of thermal expansion

T_w is the surface temperature

T_∞ is the bulk temperature

L is the vertical length

ν is the kinematic viscosity.

Once the parameters are known, defined for a vertical plate, a Grashof number between $10^3 < Gr_L < 10^6$ under a microscopic circumstances are of a laminar flow. A turbulent flow occurs in the range of $10^8 < Gr_L < 10^9$. The Rayleigh number is linked to the Grashof number and the Prandtl number where $Ra = GrPr$ hence the ratio of buoyancy and viscosity forces multiplied by the ratio of momentum and thermal diffusivities which is closely linked to the Nusselt number.

9.5 Prandtl Number

The Prandtl number is the ratio of heat storage to heat conducted. This number determines the thickness of the boundary layer, a dimensionless number that calculates the heat transfer between a moving fluid and a solid body where,

$$PR = \frac{V}{\alpha} = \frac{\text{Momentum diffusivity}}{\text{Thermal diffusivity}} = \frac{\eta / \rho}{k / (C_p \rho)} \quad \therefore \text{Prandtl Number} = \frac{\mu C_p}{k}$$

When referring to heat transfer the Prandtl number determines the relative thickness of the momentum and thermal boundary layer thus when the PR number < 1 , the boundary layer is much thicker than the velocity boundary layer. This means that the heat diffuses quickly compared to the velocity. Those with a low PR number are free flowing liquids with high thermal conductivity therefore a good choice for heat conducting liquids which indicates heat conduction is more prominent compared to convection (Rapp, 2017).

Those that have PR number > 1 the momentum of diffusivity dominates the behaviour, these liquids such as engine oil with a PR number between 100 and 40,000 where convection is more effective in comparison to conduction.

Unlike the Reynolds and Grashof number, the Prandtl number contains no length scale in its definition which is only dependant on the fluid state such as viscosity, thermal conductivity of the fluid and specific heat capacity of the fluid.

10.1 Element E

Internal Diameter = **70mm**, thickness layer = **10mm**, insulation layer = **20mm**

Pipe carries steam **200°C**, air temperature **10°C**

$$h_i = 5000$$

$$h_o = 25 \text{ W/m}^2\text{K}, \quad Q = \frac{T_i - T_o}{R_T}$$

Resistance across a material wall can be expressed in this case as $R_T = R_i + R_1 + R_2 + R_o$ as there are two layers of material.

$$R_i = \frac{1}{h_i A} = \frac{1}{5000 \times (2\pi \times 0.035)} = R_i \quad \therefore R_i = 0.00090 \text{ k/w}$$

$$R_1 = \frac{\chi_1}{K_1 A_1} \quad (\text{Pipe thickness layer}) = \frac{0.01}{40 \times \left[\frac{2\pi \times 0.01 \times 1}{\ln \left[\frac{0.045}{0.035} \right]} \right]} \quad \therefore R_1 = 0.00099 \text{ k/w}$$

$$R_2 = \frac{\chi_2}{K_2 A_2} \quad (\text{Insulation layer}) = \frac{0.020}{0.025 \times \left[\frac{2\pi \times 0.020 \times 1}{\ln \left[\frac{0.065}{0.045} \right]} \right]} \quad \therefore R_2 = 2.34 \text{ k/w}$$

$$R_o = \frac{1}{h_o A_o} = \frac{1}{25 \times (2\pi \times 0.065 \times 1)} \quad \therefore R_o = 0.097 \text{ k/w}$$

Total resistance $R_T = 2.43 \text{ k/w}$

$$Q = \frac{190}{2.43} \quad \therefore Q = 77.90 \text{ W/m rate of heat loss}$$

Rate of heat loss with an additional layer of insulation 50mm thick,

$$R_T = R_i + R_1 + R_2 + R_3 + R_o$$

$$R_i = 0.00090 \text{ k/w}$$

$$R_1 = 0.00099 \text{ k/w}$$

$$R_2 = 2.34 \text{ k/w}$$

$$R_3 = \frac{\chi_3}{K_3 A_3} = \frac{0.050}{0.025 \times \left[\frac{2\pi \times 0.050 \times 1}{\ln \left[\frac{0.115}{0.065} \right]} \right]} \quad \therefore R_3 = 3.63 \text{ k/w}$$

$$R_0 = \frac{1}{h_0 A} = \frac{1}{25 \times (2\pi \times 0.115 \times 1)} \quad \therefore R_0 = \underline{0.055 \text{ k/w}}$$

$$R_T = \underline{6.02 \text{ k/w}}$$

$$Q = \frac{190}{6.02} \quad \therefore Q = \underline{31.56 \text{ W/m}}$$

10.2 Payback period

$$\text{Saving} = 77.90 - 31.56$$

$$= 46.34 \text{ W/m} \times \text{payback period}$$

$$= 46.34 \times (60 \times 60 \times 24 \times 7 \times 48)$$

$$= 1345.2 \text{ MJ}$$

The saving will be $0.02 \times 1345.2 = \text{£}26.90 \text{ m/year}$

$$\therefore \text{payback period} = \frac{125}{26.90} = 4.6 \text{ years}$$

10.3 Discussions and Evaluations of Results

An internal pipe diameter of 70mm, with a thickness of 10mm covered by a layer of insulation 20mm thick. Knowing the thermal conductivity of the material and insulation we can determine the rate of heat loss by calculating the resistance. Initially the rate of loss heat from the pipe to the air per metre length saw a heat loss of $Q = 77.90 \text{ W/m}$. With an additional 50mm thickness added $Q = 31.56 \text{ W/m}$ thus by adding an additional layer of insulation the heat loss reduced by 46.34 W/m .

The payback period of adding 50mm of insulation would take 4.6 years, a reasonably short amount of time taking into consideration the sum of heat loss reduced therefore making the investment of an additional insulating layer feasible.

11.1 Evaluation

There are three modes of heat transfer; conduction, the process that heat is transferred along a metallic surface, convection which depends on movement of the fluid, (this can be caused by a pump known as forced convection), and radiation, where energy is travelled through a vacuum and is transmitted as electromagnetic waves. Each capable of describing the flow of heat, determining the same result under different circumstances.

Using insulation materials can be used to reduce heat transfer such as low and high temperature insulation, an efficient way of maintaining or removing heat in a specific area.

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