

Thermofluids Assignment

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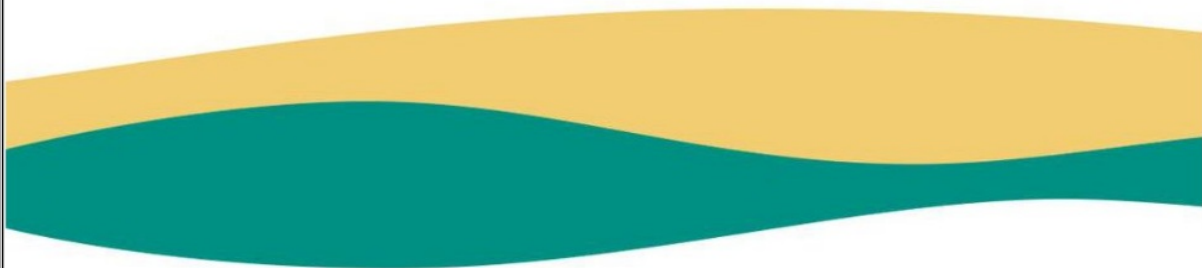


VALE

Thermofluids

Lee Wellington – LW094662

Assignment 1 – Heat Transfer



Summary

In this assignment thermal conduction, convection and radiation are discussed and evaluated to determine the mechanism for each mode. As a result conduction is proven to be dependent on thermal conductivity (k), convection is reliant on the heat transfer co-efficient (h) and radiation is based on emissivity (ϵ).

The discussion then moves onto insulation materials and their characteristics. Porosity is found to have a negative effect on the amount of thermal conductivity a material possesses, and temperature can have a varied effect on heat transfer characteristics depending on the material state and composition.

The report will also consider the use of dimensional analysis and give explanation as to why dimensionless numbers such as Reynolds, Prandtl, Grashof and Nusselt are important for determining the heat transfer co-efficient.

Finally, a mathematical scenario will be solved to determine the heat loss of a steel pipe with varied thicknesses of insulation.

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Introduction

For the module 'Thermofluids and Applied Mechanics' (Thermofluids element), an assignment has been issued whereby the fundamental modes of heat transfer and fluid flow are to be discussed and evaluated. Tasks a,b,c and d will examine phenomena such as;

- Conduction, convection, and radiation.
- Characteristics of insulating materials and the effects of porosity.
- The effects of temperature on thermal conductivity.
- How dimensional analysis can be used to analyse factors affecting heat transfer and the significance of dimensionless quantities such as;
 - Reynolds Number
 - Nusselt Number
 - Prandtl Number
 - Grashof Number

Finally, task e will involve the application of heat transfer theory to calculate the (heat) loss of a mathematically modelled system. The scenario will then examine the effects of adding additional insulation and evaluate if such an investment is cost effective.

Aim

The aim of this report is to develop the writers understanding of thermodynamic processes and evaluate the significance of factors that can affect heat transfer. From analysing the concepts and mechanisms involved the writer will be able to demonstrate how mathematical theory can be used to calculate the heat loss for a typical system that has two insulation proposals. The results of the exercise will then be discussed to form a recommendation on whether it is financially beneficial to further invest in the system or not.

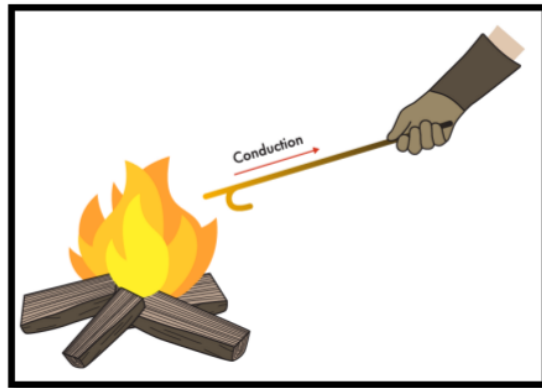
Task A

Heat can be defined as a 'form of energy that is transferred between two materials of different temperature' (Sciencing, 2019). Thermal energy flows continuously through objects often taking the easiest path with least resistance. There are three modes in which heat transfer can occur; conduction, convection and radiation.

Conduction

As shown in figure 1 conduction is a process whereby heat is transferred through a heated solid.

Figure 1 - Example of Thermal Conduction



(Duke Education, 2020)

In the example shown above heat transfer is achieved by the vibration of molecules. Across the length of the bar, each row of molecules is at a marginally lower temperature than its predecessor therefore, at the hottest end the molecules vibrate with the most energy and at the coolest end the molecules vibrate with the least energy. As the more active molecules vibrate, they transfer some of their energy onto adjacent molecules. Over time a balance is reached which is also referred to as thermal equilibrium whereby 'the hot end of the bar loses energy and the cool end of the bar gains energy, until the entire bar is the same temperature' (ThoughtCo., 2018). Through experimentation it has been found that if there is a temperature gradient along a bar (of thickness 'x' and area 'a'), the amount of heat (Q) transferred is directly proportional to the time and temperature difference (T₁-T₂) between the ends and inversely proportional to the thickness (x) when their faces are kept at uniform temperatures. Hence;

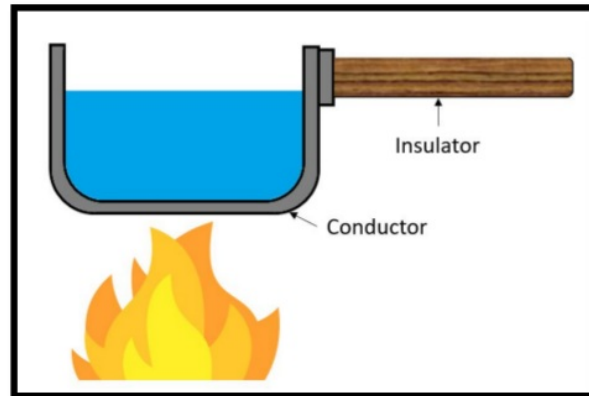
$$Q \propto \frac{A(T_1 - T_2)t}{x}$$

Or;

$$Q = \frac{kA(T_1 - T_2)t}{x}$$

Where 'k' (constant) is the thermal conductivity of the material. If a material has high 'k' value it is deemed a good conductor of heat and consequently a low value denotes a poor conductor. Metals such as silver, copper and aluminium are deemed the best conductors of heat whereas cork, wood and fibre glass are considered the poorest. As a result, these materials are identified as insulators as they do not allow heat to easily flow through them. Understanding the mechanics of thermal conduction has influenced many designs that consider heat. For example, to ensure cooking utensils such as frying pans or saucepans conduct enough heat to cook food, they are typically made from steel whilst the handles are made from wood (insulator) to protect the user.

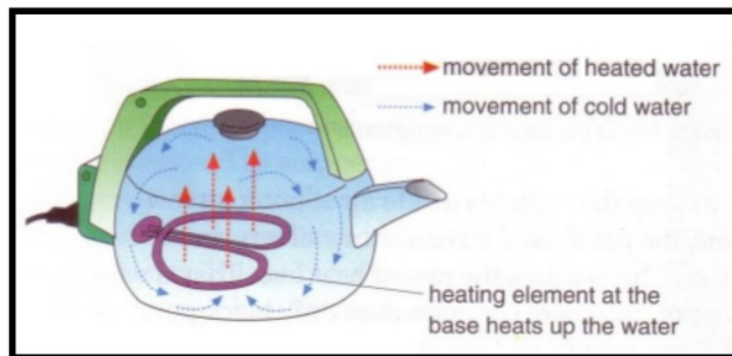
Figure 2 – Use of Conducting and Insulating Materials in Design of Saucepan



Convection

'Convection is the transfer of heat by the movement of a fluid (liquid or gas) between areas of different temperature' (ScienceDirect, 2015). When fluid molecules are heated, they expand, become less dense and therefore rise. The rising molecules are then replaced by cooler (denser) ones which are in turn heated and made to expand. For the example shown in figure 3 this process would be repeated until the water temperature triggers the kettle's thermostat switching it off.

Figure 3 - Example of Convection



(Slideshare, 2012)

To determine the amount of heat (Q) transfer due to convection Newton's Law of Cooling can be applied, whereby;

$$Q = hA(T_A - T_1)$$

($T_A - T_1$) = Temperature Difference

A = Area (m^2)

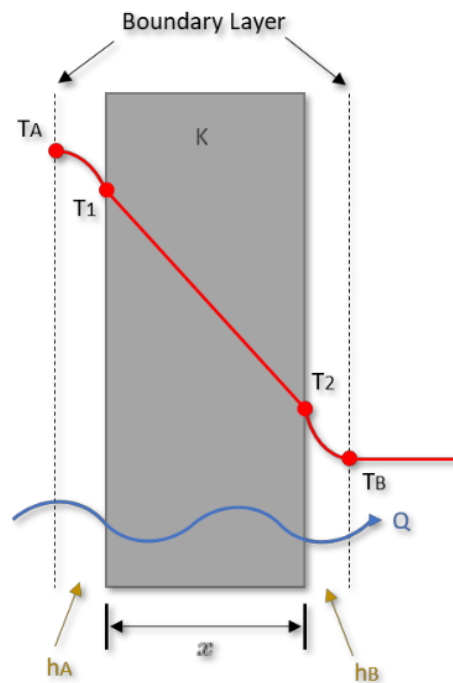
H = Heat Transfer Co-efficient ($W/m^2.K$)

'The convective heat transfer co-efficient (h) is dependent upon the physical properties of the fluid and the physical situation' (Engineers Edge, 2020). As a rule of thumb, the heat transfer co-efficient of laminar flow is relatively low in comparison with turbulent flow due to their differing boundary layers.

Combined Conduction and Convection

When considering combined conduction and convection through a slab as shown in figure 4.

Figure 4 – Diagram of Slab with Combined Conduction and Convection



The thermal conductivity (k) and convective heat transfer co-efficient elements (h_A & h_B) can be combined to produce an overall heat transfer co-efficient (U).

$$U = \frac{1}{\frac{1}{h_A} + \frac{x}{k} + \frac{1}{h_B}}$$

(When Area = 1m)

Therefore, the following equation can be used to calculate the heat transfer across the whole slab.

$$Q = UA\Delta T$$

(ΔT) = Difference in Bulk Temperature
 A = Area (m^2)
 U = Overall Heat Transfer Co-efficient ($W/m^2.K$)

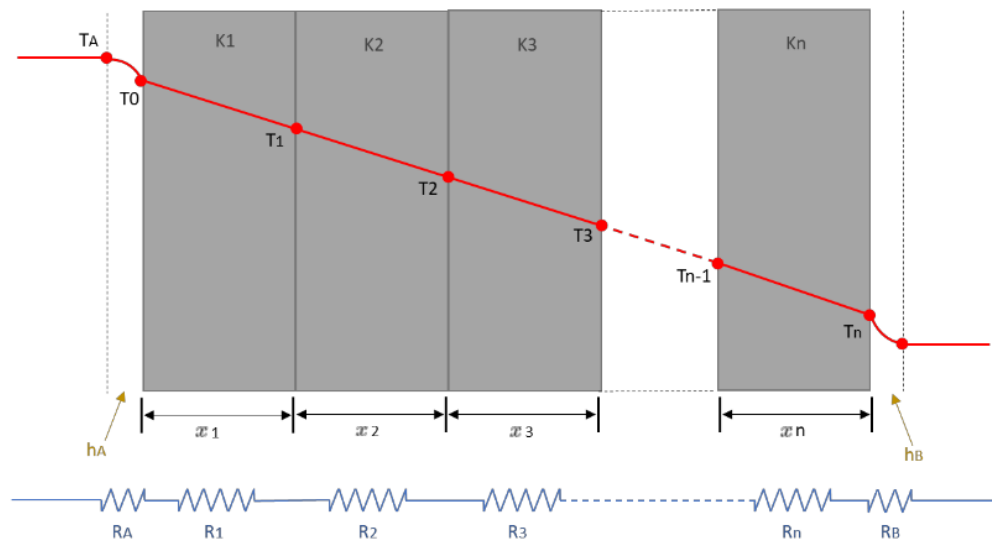
It is more convenient however to solve combined conduction and convection problems using the electrical analogy whereby the flow of heat can be considered analogous to an electrical current using Ohms Law.

$$I = \frac{V}{R} \rightarrow Q = \frac{T_A - T_B}{R_T}$$

Where

$$R_T = R_A + R_1 + R_2 + R_3 + R_n + R_B$$

Figure 5 – Electrical Analogy Applied to Composite Wall Diagram



Convection resistors R_A and R_B are calculated using;

$$Q = hA \Delta T \rightarrow \text{In Terms of } I = \frac{V}{R} \quad \boxed{R = \frac{1}{hA}}$$

(I) (R) (V)

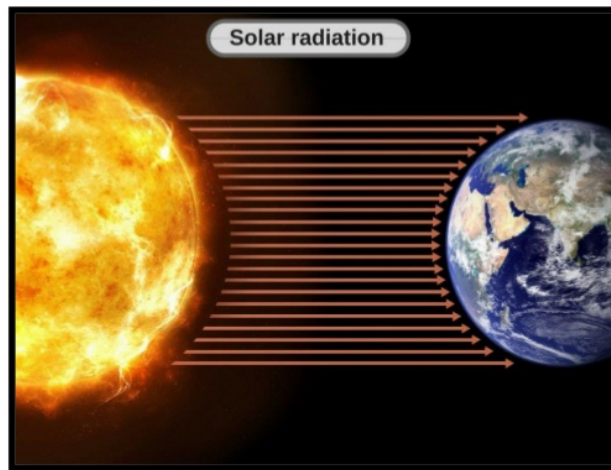
Conduction resistors R_1, R_2, R_3 and R_n are calculated using;

$$Q = \frac{kA}{x} (T_2 - T_1) \rightarrow \text{In Terms of } I = \frac{V}{R} \quad \boxed{R = \frac{x}{kA}}$$

Radiation

'Heat transfer through radiation takes place in form of electromagnetic waves mainly in the infrared region' (Engineering Toolbox, 2020). It is a method of heat transfer that does not require any contact between the source of the heat and the heated object and can even travel through a vacuum as shown in figure 6. The process involves the absorption of radiation to impart heat energy.

Figure 6 – Solar Radiation



(Science ABC, 2016)

The amount of heat (Q) transfer achieved from radiation is proportional to an objects surface area (A) and its absolute temperature to the fourth power (T^4).

$$Q \propto AT^4$$

T = Absolute Temperature (K)
 A = Area (m^2)

According to Stefan–Boltzmann law, to calculate the amount of heat transfer, two constants are required;

$$Q = \varepsilon \sigma AT^4$$

ε = Emissivity
 $\sigma = 5.67 \times 10^{-8}$ (W/M^2K^4)

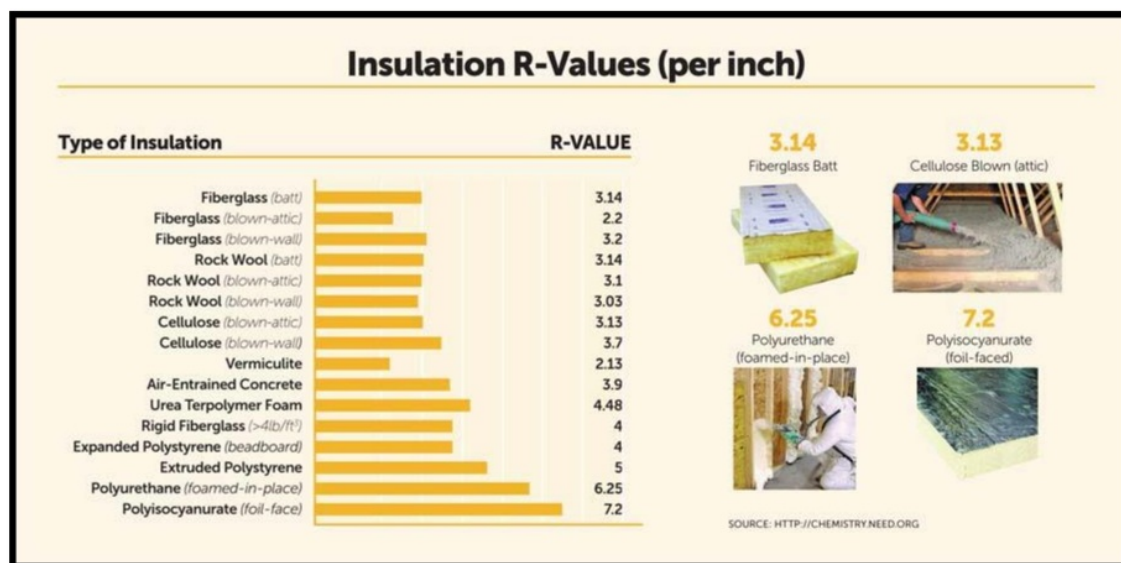
Emissivity is a material constant value that determines how readily an object can radiate out energy. Its value is based upon the 'black body ideal' which ranges from zero to one. Objects that are given emissivity values close to one can absorb and emit radiation readily whereas objects closer to the value of zero cannot. The second constant (σ), is referred to as the Stefan-Boltzmann constant which is a constant of proportionality and given the value of 5.67×10^{-8} (W/M^2K^4).

Task B

Characteristics of Insulation Materials.

As the name suggests, thermal insulating materials are very good at preventing the transmission of heat. A materials ability to inhibit heat can be quantified using thermal resistivity (R) which is the inverse of thermal conductivity. In industry, insulating materials are typically used to lag pipework, line vessels, and insulate buildings. Their primary function is to prevent the loss of heat which can be costly to consumers and processes. There are various types of insulating materials available with differing resistivity (R) values as shown in figure 7.

Figure 7– Insulation R Values Chart (per inch)



(Green Builder, 2015)

Such thermal insulating materials typically have the following characteristics;

- Low Density
- Low Thermal Conductivity (k)
- Low Thermal Transmittance (U)
- Low Surface Emissivity (ε)
- High Specific Heat Capacity
- Fire Resistance

How Do Insulation Materials Work?

The mechanics of thermal insulation involves slowing the transfer of heat that can occur through conduction, convection, and radiation. *'Materials, which have a low thermal conductivity, are those, which have a high proportion of small voids containing air or gas'* (TIASA, 2001).

Figure 8 – Fibreglass Insulation with Foil



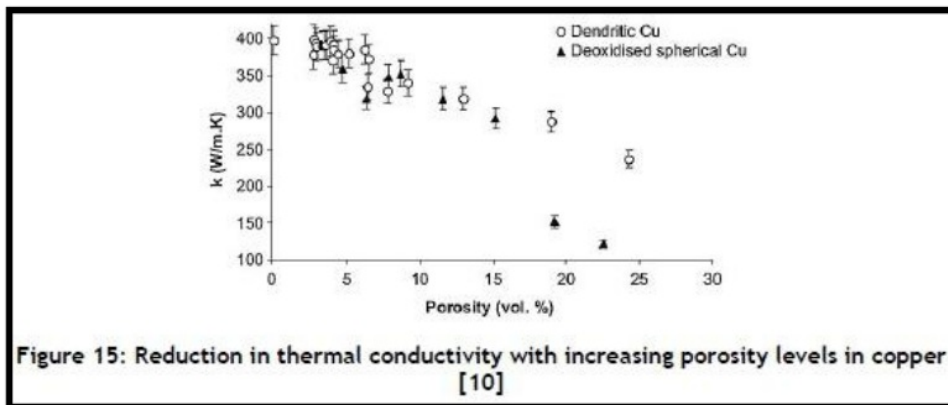
(The Insulation Shop, 2020)

When considering typical household insulation (figure 8) its construction involves layers and layers of fibreglass backed with Aluminium foil. Fibreglass is a composite material that has low thermal conductivity (approx. 0.04 W/mK) properties for restricting heat loss via conduction. Additionally, the fibrous structure of the material further inhibits thermal conduction as heat can only travel through the small fibres that are in contact with each other. Also, its fibres trap small pockets of air which can limit the transfer of heat via convection. The aluminium foil provides strength but more importantly reflects any radiant heat back into the home.

What Effect Does Porosity Have on Heat Transfer Characteristics?

Porosity is a term used to measure the amount of pores or voids a material has in relation to its total bulk volume. To determine its effect on heat transfer characteristics, a journal produced by J.M. Benson and E. Snyders was reviewed. The data displayed in graph 1 demonstrates the effect differing porosity has on the thermal conductivity of copper.

Graph 1 – Thermal Conductivity of Copper with Increasing Porosity



(SCI-ELO, 2015)

As the porosity is increased, the copper's ability to conduct heat is reduced due to the gas filled pores having a considerably lower thermal conductivity value than the bulk material. For very high temperature applications, refractory bricks constructed from highly porous clay are used to line and insulate furnaces. This is an example where porosity has been purposely applied to the design of a component to reduce its thermal conductivity.

Figure 9 – Porous Refractory Brick



Task C

Evaluate the Effect of Temperature on the Thermal Conductivity

The effect of temperature on thermal conductivity is dependent on the state (solid, liquid or gas) and composition of the object in question. As previously mentioned in 'Task A' the method of imparting (conductive) energy on a molecular level involves the vibration of particles or molecules. When considering a typical gas at a low temperature, molecules are often spread apart and non-energetic so interaction is minimal and as a result the amount of thermal conductivity is low. However, when the temperature is increased the gas molecules become more energetic and collisions are more frequent increasing their ability to impart heat. Therefore, in this instance thermal conductivity is increased by increasing the temperature.

Table 1 – Example of Effects of Temperature on Thermal Conductivity of Gases

TABLE 2.13 Thermophysical Properties of Selected Gases

Substance	Data	Property (at low pressure)	T (°C)											
			-150	-100	-50	0	25	100	200	300	400	600	800	1 000
			123.15	173.15	223.15	273.15	298.15	373.15	473.15	573.15	673.15	873.15	1 073.15	1 273.15
Acetone	Chemical formula: C ₃ H ₆ O Molecular weight: 58.08 Normal density (at 0°C, 101.3 kPa): 2.59 kg/m ³ Boiling point: 56.1°C Critical temperature: 235.0°C Critical pressure: 4.761 MPa	Specific heat capacity c _{ps} (kJ/kg K)	S	S	L	L	L	1.557	1.838	2.093	2.311	2.659	2.906	3.098
		Thermal conductivity λ _g [(W/m ²)/(K/m)]	S	S	L	L	L	0.018	(0.027)	(0.038)	(0.051)	(0.076)	—	—
		Dynamic viscosity η _g (10 ⁻³ Ns/m ²)	S	S	L	L	L	0.931	1.21	1.46	1.72	2.20	2.64	3.05
Acetylene	Chemical formula: C ₂ H ₂ Molecular weight: 26.04 Normal density (at 0°C, 101.3 kPa): 1.17 kg/m ³ Boiling point: -83.95°C Critical temperature: 35.55°C Critical pressure: 6.24 MPa	Specific heat capacity c _{ps} (kJ/kg K)	S	S	1.503	1.616	1.687	1.871	2.047	2.177	2.286	2.462	2.613	2.734
		Thermal conductivity λ _g [(W/m ²)/(K/m)]	S	S	0.013	0.018	0.021	0.030	0.042	0.053	0.066	0.087	0.107	0.125
		Dynamic viscosity η _g (10 ⁻³ Ns/m ²)	S	S	0.785	0.960	1.04	1.28	1.55	1.83	2.08	2.53	2.93	3.30

(Rohsenow, et al., 1998a)

The effect of temperature on liquids and solids is more varied but in general a liquid will see reduced thermal conductivity with increasing temperature as molecules expand (become less dense) and move apart from each other. For most metallic solids, thermal conductivity will also reduce with increasing temperatures however the most significant variances are seen at extremely high temperature as shown in table 2.

Table 2 – Example of Effects of Temperature on Thermal Conductivity of Solids

TABLE 2.32 Thermal Conductivity and Density of Selected Elements

Substance	Chemical formula	T (°C)	T (°K)	Density ρ (kg/m ³)	Thermal conductivity λ (W/m K)
Aluminum, 99.75%	Al	-190	83.15	2,700	255.860
		0	273.15		229.111
		200	473.15		229.111
		300	573.15		222.133
		800	1073.15		125.604
99%		-100	173.15	—	209.340
		0	273.15		209.340
		100	373.15		207.014
		300	573.15		222.133

(Rohsenow, et al., 1998b)

As well as vibrating molecules, the process of heat transfer for a metallic object is heavily dependent on the motion of free electrons. When a metal is subjected to extreme temperatures their molecules vibrate as such a high frequency they obstruct the flow of free electrons and therefore hinder heat transfer process. For non-metallic materials where there are no free electrons the process of heat transfer is solely reliant on vibrating molecules, so in this instance the thermal conductivity will increase with increased temperature.

Task D

Dimensional analysis 'is a mathematical technique, which deals with the dimensions of physical quantities. It is an important tool for establishing relationship between physical quantities involved in a fluid phenomenon' (Civil Engineering Terms, 2012). As shown below its application can be used to establish relationships that can be used to help calculate the heat transfer co-efficient for convection.

$$\frac{hL}{k} = \phi\left(\frac{\mu C_p}{k}\right) \left(\frac{\rho V L}{\mu}\right)$$

(Nusselt) (Prandtl) (Reynolds)

Some of the dimensionless factors that are considered in heat transfer are;

Reynolds Number

'The Reynolds number is the ratio of inertial forces to viscous forces and is a convenient parameter for predicting if a flow condition will be laminar or turbulent' (Thermal Engineering, 2019). The following equation can be used to determine the flow condition of a fluid.

$$Re = \frac{\rho V L}{\mu}$$

P = Density of the fluid
V = Velocity of the fluid
L = Characteristic length
 μ = Dynamic viscosity of the fluid

A Reynolds number less than 2000 typically denotes laminar flow and a value of more than 4000 indicates turbulent flow. As the Nusselt number is some function of the Reynolds and the Prandtl numbers, the Re number is also an important element when calculating the heat transfer co-efficient.

Prandtl Number

'The Prandtl number is defined as the ratio of momentum diffusivity to thermal diffusivity' (Nuclear Power, 2020). The relationship was first identified by German Engineer Ludwig Prandtl who also discovered the boundary layer. The number can be expressed using;

$$Pr = \frac{\mu C_p}{k} \rightarrow Pr = \frac{\text{Viscous Diffusion Rate}}{\text{Thermal Diffusion Rate}}$$

μ = Dynamic viscosity of the fluid
 C_p = Specific heat capacity of fluid
k = Thermal conductivity of fluid

A small Prandtl number (significantly less than 1) indicates that thermal diffusion is the prominent behaviour whereas a large value (significantly more than 1) indicates momentum is more dominant. This is significant when determining the dominant mode of heat transfer (conduction or convection) that will occur for a fluid. High thermal diffusion indicates that conduction is more prominent whereas high viscous diffusion signifies convection is the most effective energy transferring mode. Similarly, to the Reynolds number the Pr number is an

important factor for calculating the Nusselt number which in turn can derive the heat transfer co-efficient.

Nusselt Number

The Nusselt number is the ratio of heat transfer by convection to the heat transfer by conduction. The Nu number can be calculated using;

$$Nu = \frac{hL}{k}$$

h = Heat transfer Co-efficient
L = Characteristic length
k = Thermal conductivity

The Nu number is typically the most desired value as it contains the convective heat transfer co-efficient value which is needed to theoretically calculate the heat transfer (Q) of a given system. For forced convection applications the Nusselt number can also be obtained using Dittus-Boelter correlation equations which are used to quantify the relationship between the Prandtl number and the Reynolds number for given situations. For example *'a liquid flowing in a straight circular pipe with a Reynolds number between 10 000 and 120 000 (in the turbulent pipe flow range), when the liquid's Prandtl number is between 0.7 and 120, for a location far from the pipe entrance or other flow disturbances, and when the pipe surface is hydraulically smooth, it can be expressed as'*

$$0.023 \cdot Re^{0.8} \cdot Pr^n$$

(CHEMEUROPE.COM, 2020)

Grashof Number

The Grashof number is used in thermofluids to determine the ratio of buoyancy to viscous forces acting on the fluid. The Gr is usually considered for natural convection scenarios and it can be expressed using;

$$Gr = \frac{g\beta\Delta TL^3}{\nu^2} \rightarrow Gr = \frac{\text{Bouyancy Force}}{\text{Viscous Force}}$$

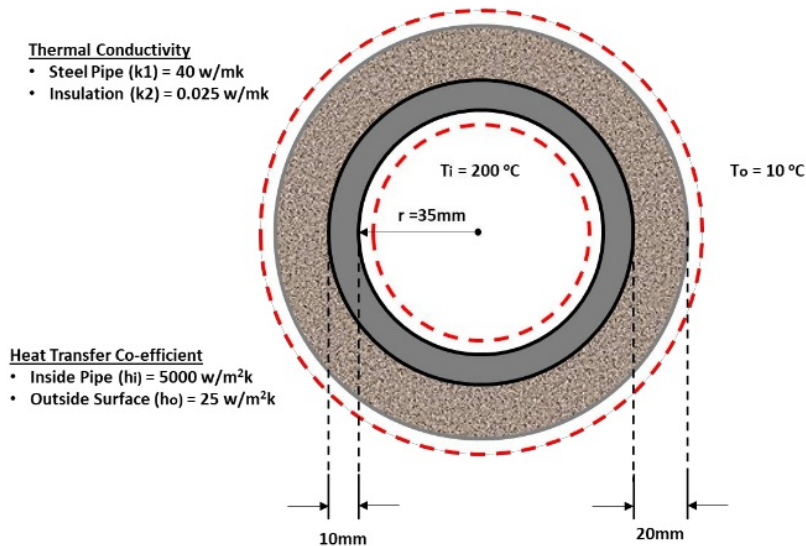
P = Gravitational constant
β = Co-efficient of thermal expansion (fluid)
ΔT = Temperature Difference
L = Characteristic length
ν = Kinematic viscosity of the fluid

Heat transfer via convection requires circulation *'therefore, the Grashof number (and heat transfer coefficient) will rise as the buoyancy forces increase and the viscous forces decrease'* (ME Mechancial, 2016). Similarly to the Reynolds number, the Grashof number can be used in correlation with the Prandtl number to calculate the Nusselt number when natural convection circumstances are concerned.

Task E

The following calculations were performed to find the rate of loss of heat from of a pipe for the scenario modelled in figure 10.

Figure 10 - Diagram of Steel Pipe (Task E)



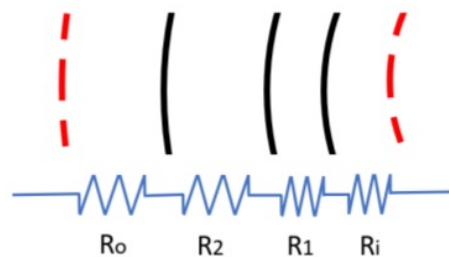
From using the electrical analogy, the heat loss (rate) of combined conduction and convection can be calculated using;

$$Q = \frac{T_i - T_o}{R_T}$$

Internal Temperature (T_i) = 200 °C
 Outside Temperature (T_o) = 10
 R_T = Total Resistance = ?

To calculate the resistance of the conduction (R_1 & R_2) and convection (R_i & R_o) elements the following calculations were performed;

Figure 11 – Arrangement of Resistors



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

$$R_I = \frac{1}{h_i A_i} = \frac{1}{5000 * (2\pi * 0.035 * 1)} = 0.000909 \text{ k/w (6dp)}$$

$$R_1 = \frac{x_1}{k_1 A_1} = \frac{0.01}{40 * (\frac{2\pi * 0.01}{\ln(\frac{0.045}{0.035})} * 1)} = 0.0010 \text{ k/w (4dp)}$$

$$R_2 = \frac{x_2}{k_2 A_2} = \frac{0.02}{0.025 * (\frac{2\pi * 0.02}{\ln(\frac{0.065}{0.045})} * 1)} = 2.34 \text{ k/w (2dp)}$$

$$R_o = \frac{1}{h_o A_o} = \frac{1}{25 * (2\pi * 0.065 * 1)} = 0.0979 \text{ k/w (4dp)}$$

$$\therefore R_T = 2.34 + 0.001 + 0.0979 + 0.000909$$

$$R_T = 2.439809 \text{ k/w}$$

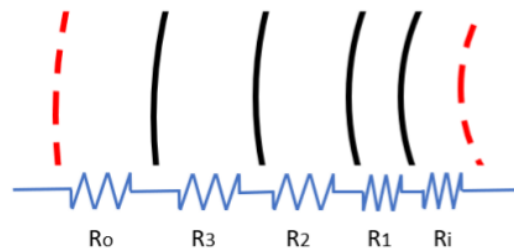
Therefore, the rate of heat loss from the pipe to the air is;

$$Q = \frac{200 - 10}{2.439809}$$

$$Q = 77.87 \text{ w/m (2dp)}$$

Part 2 of the question involves calculating the rate of heat loss if an additional 50mm thickness of insulation is added to the pipe.

Figure 12 – Arrangement of Resistors with Additional Layer of Insulation



The values obtained for resistors R_i , R_1 and R_2 will remain the same as they are unaffected by the additional layer (R_3). R_o however will require re-calculating due to its positional change.

$$R_3 = \frac{x_3}{k_2 A_3} = \frac{0.05}{0.025 * (\frac{2\pi * 0.05}{\ln(\frac{0.115}{0.065})} * 1)} = 3.63 \text{ k/w (2dp)}$$

$$R_o = \frac{1}{h_o A_o} = \frac{1}{25 * (2\pi * 0.115 * 1)} = 0.0554 \text{ k/w (4dp)}$$

$$\therefore R_T = 0.0554 + 3.63 + 2.34 + 0.001 + 0.000909$$

$$R_T = 6.027309 \text{ k/w}$$

Therefore, the rate of heat loss from the pipe to the air is;

$$Q = \frac{200 - 10}{6.027309}$$

$$Q = 31.52 \text{ w/m (2dp)}$$

The final part of the question involves calculating the payback period if the extra layer of 50mm insulation costs £125 per metre of length to install. The pipe will operate continuously for 48 weeks per year and the heat is generated at a cost of 2p per MJ.

$$\text{Saving} = 77.87 - 31.52$$

$$\text{Saving} = 46.35 \text{ w/m } \left(\frac{\text{J}}{\text{s}}/\text{m}\right)$$

$$\text{Scale Up Value for 48 weeks} = 46.35 * (60 * 60 * 24 * 7 * 48)$$

$$\text{Scale Up Value for 48 weeks} = 1346 \text{ MJ}$$

Therefore, the saving will be;

$$0.02 * 1346 = £26.92 \text{ /m/yr}$$

$$\therefore \text{Payback Period} = \frac{125}{26.92}$$

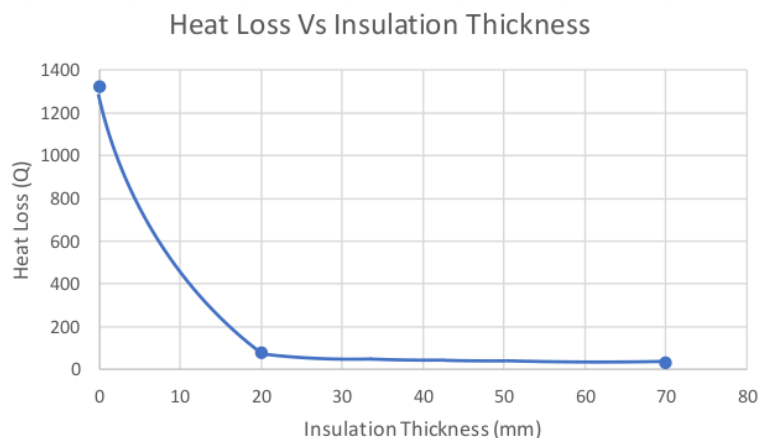
$$\text{Payback Period} = 4.64 \text{ Years (2dp)}$$

Discuss and Evaluate the Results

The calculations performed in 'Task E' have demonstrated how the electrical analogy can be applied to a typical industrial scenario to determine the heat loss of a system through combined conduction and convection. From converting each layer into a theoretical resistor, a series can be created to find the overall resistance. From analysing each resistor element, it is clear to see that R2 (insulation = 2.34 k/w) is the most effective heat resistant layer across the system. In total it accounts for almost 96% of the overall resistance ($R_T = 2.439809 \text{ k/w}$). Therefore, if the pipe had no insulation layer the heat loss would be significantly higher (1324.89 k/w).

In part two of the scenario a proposal is made to add an additional 50mm of insulation to the pipe. From re-applying the electrical analogy (considering the additional layer) the heat loss rate is reduced from 77.87 w/m to 31.52 w/m.

Graph 2 – Heat Loss Vs Insulation Thickness



From plotting the heat loss values for all three scenarios (no insulation, 20mm and 70mm), it can be seen that the effectiveness of the insulation reduces as more is added. In this context the additional 50mm of insulation prevents very little heat loss when compared to the initial heat loss recovered by 20mm insulation. Despite this a payback period of only 4.64 years was calculated for the investment of adding an extra 50mm of insulation. Typically, in industry an improvement proposal requires a payback period of less than 3 years however with ever increasing energy costs, companies are more proactively looking at ways to save energy and reduce their carbon footprint.

Conclusion

In this report the three modes of transferring thermal energy (conduction, convection, and radiation) have been discussed and evaluated. From doing so the significance of parameters such as the heat transfer co-efficient (h) and thermal conductance (k) have been highlighted when trying to theoretically calculate the heat transfer (Q). Additionally, from understanding the intricacies of each method on a molecular level it has given explanation as to why certain materials are used for certain applications. The characteristics of what promotes thermal conductivity or thermal resistivity have been utilised in many industries to improve the efficiency or effectiveness of heat transfer or insulation.

Research into other factors that influence thermal conductivity revealed a number of interesting findings however the most fascinating was the effects of porosity. When purposely introduced into material which is regarded as a good thermal conductor it reduced its ability to transfer heat. This was due to gas filled pores within the material slowing down the transmission of energy. As a result, this characteristic has been incorporated into many designs to improve the thermal resistivity of insulating products.

Finally, the application of dimensional analysis on convection has proven very useful as it has enabled various correlations to be determined between the Reynolds, Prandtl and Grashof numbers. These relationships can be used in conjunction to calculate the Nusselt number and the much sought-after 'heat transfer co-efficient'.

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