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by Robert Thomas

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Heat Transfer

PSDM6022

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BSC MECHANICAL ENGINEERING | CHRIS DAVIES

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2 Introduction

a) Aim

To develop and understanding of the underlying thermofluid concepts involved in heat transfer and fluid flow thus enabling the analysis of more complex phenomena.

b) Objective

To meet the aim above the report will research the three fundamental modes of heat transfer and also insulation materials and thermal conductivity.

The final part of this report is related to the application of appropriate mathematical based methods for modelling and engineering thermodynamic problems.

3 Question a)

c) Conduction

When there is seen to be a temperature gradient in a solid or stationary fluid medium, there is an energy transfer between the high temperature region to the low temperature region. This heat transfer is referred to as conduction.

Heat transfer can be seen to flow in the direction of the decreasing temperature since the higher temperature have reflect higher molecular energy. The conduction heat flow equation can be seen below:

$$Q \cong -kA \frac{\partial T}{\partial X}$$

Where:

Q = Heat transfer rate (W, J/s, Btu/Hr)

K = Thermal conductivity of material (W/Mk, W/m°C)

$\frac{\partial T}{\partial X}$ = Temperature gradient in the heat flow direction

d) Convection

Heat that is transferred between a surface and moving fluid with varying temperature is known as convection. Convection heat transfer can be either forced convection or natural.

Forced convection is created when a fluid is has an external force applied such of that from a fan or pump.

Natural convection is created by buoyancy forces due to differences in density. This is caused by temperature variation in the fluid. At heating the density change will cause the fluid to rise and be replaced by cooler fluid that will continue to heat and rise.

The heat transfer per unit surface through convection was first described by Newton, the relationship is referred to as Newton's Law of Cooling.

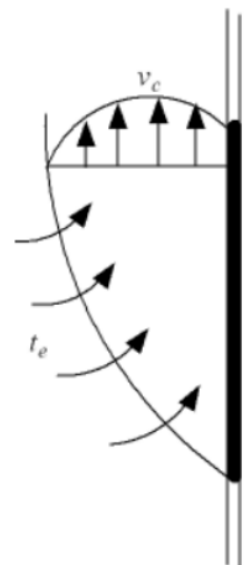


Figure 1 - Convective heat transfer

Newton's Law of Cooling is the following equation:

$$q = h A (dT)$$

Q = Heat transferred per unit time (W, Btu/Hr)

h = Convection heat transfer coefficient of the process (W/m²°C,)

A = Heat transfer area of the surface (m²)

dT = Temperature difference between the surface and the bulk fluid (°C, F)

e) Radiation

Heat transferred in the form of radiation take the form of electromagnetic waves. Radiation that is emitted by a body is a consequence of thermal agitation of its composing molecules. Radiation heat transfer is best show by reference to the "Black Body".

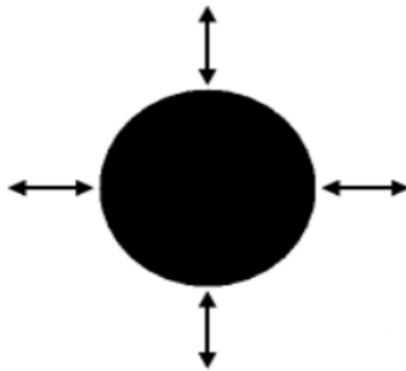


Figure 2 Heat transfer due to radiation "Black Body"

According to Dr.Gehleer "The black body is defined as a body that absorbs all radiation that falls on its surface. Actual black bodies don't exist in nature - though its characteristics are approximated by a hole in a box filled with highly absorptive material. The emission spectrum of such a black body was first fully described by Max Planck." (Dr.Gehleer, 2015)

A black body is a hypothetical body that is able to completely absorb all wavelengths of thermal radiation. As these bodies do not reflect light they therefore appear black if they are of a low temperature. All black bodies heated to a specific temperature emit thermal radiation.

The radiation energy per unit time for a black body is proportional to the fourth power of the absolute temperature and can be expressed with Stefan-Boltzmann Law as:

$$q = \sigma T^4 A$$

Where:

q = Heat transfer per unit time (W)

$\sigma = 5.6703 \times 10^{-8} \text{ (W/m}^2\text{K}^4\text{)} - \text{Stefan Boltzmann Constant}$

T = Absolute temperature (K)

A = Area of the emitting body (m^2)

If the surface temperature of the sun is 5800 Kelvin and if we were to assume that the sun is regarded as a black body the radiation energy per unit area can be expressed by modifying the equation above to the following:

$$q/A = \sigma T^4$$

For objects other than ideal black bodies which are referred to as Gray Bodies the Stefan Boltzmann Law can be expressed as:

$$q = \varepsilon \sigma T^4 A$$

Where:

ε = Emissivity coefficient of the object.

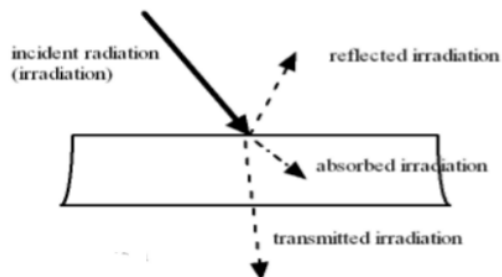


Figure 3 - Partly reflected radiation

For gray bodies the radiation is partly either reflected, absorbed or transmitted. As show above in figure 3. The emissivity coefficient is in the range $0 < \varepsilon < 1$, depending on the type of material and the temperature on the surface.

Convection and Conduction across a Boundary Layer

Conduction and convection is a combination of Fourier's Law of Conduction and Newton's Law of cooling. Combined, they can be re-arranged into the form:

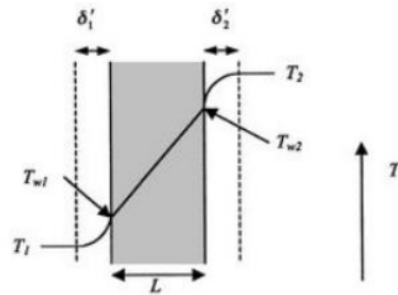


Figure 4 - Combined conduction and convection

By applying Fourier's Law.

$$q = -kA \frac{dT}{dX}$$

$$\frac{dT}{dX} = \frac{T_1 - T_2}{X_2 - X_1}$$

$$\frac{q}{A} = k \frac{T_1 - T_2}{X_2 - X_1} = \frac{K(T_1 - T_2)}{\Delta X}$$

Where q/A is the heat flow per unit area.

By combining the two equations the thermal resistance can be identified. The heat transfer through an object in series or parallel is calculated using a process called the electrical analogy.

4 Question b)

Thermal Conductivity

Thermal conductivity is determined by the physical property which specifies the amount a material or substance can transmit energy. The thermal conductivity of a material is dependent on the chemical composition. It is also dependent on the phase of the substance i.e. gas, liquid or solid. If the substance is a solid material then then it is dependent on its crystalline structure. Other factors include temperature and pressure and if the material is homogenous. Non homogenous materials are of important for engineering applications as they are used for insulation purposes. They are found to be described by the general principles established for homogenous materials.

Insulating Materials

Insulation materials are used to obstruct the flow of heat between an enclosure and its surroundings. Where the temperature is lower than ambient temperatures low temperature insulation is used to prevent the enclosure from gaining heat. High temperature insulation is used for the reversed effect, where the prevention of temperature loss due to ambient surrounding temperature is required.

Typical low temperature insulation materials include:

- Rock wool
- Cork
- Glass wool

Typical high temperature materials include:

- Asbestos
- Magnesia
- Diatomaceous earth

When a material has a strong dependence on the thermal conductivity with density and temperature it is referred to as the bulk density. To define bulk density "it is the mass of the substance divided by its volume. Which is inclusive of the number of pores should the material be porous".

Insulation materials with low conductivity is as a result of the air that is contained within the pores rather than the low conductivity of the solid substance itself. The thermal conductivity of the insulation material is directly relative to its bulk density. Although it can be seen that at a

temperature limit the convection and radiation within the pore may will increase the transfer of heat through the material and therefore reversing the effect of bulk density.

5 Question c)

f) What effect does temperature have on thermal conductivity?

In regards to pure metals and alloys, thermal conductivity is heavily dependent on electronic effect. As the temperature increases, both number of free electrons and lattice vibrations increase. Thus the thermal conductivity is expected to increase respectively. However this is not the case, increased vibrations in the lattice structure obstructs the flow of free electrons through the medium. As a result of this phenomena, most cases result in a decreased thermal conductivity as a result of the increase in temperature for metals and alloys.

Some exceptions to this include iron, where the thermal conductivity initially decreases and then reverses and increases slightly due to the temperature increase. Whereas platinum, the thermal conductivity increases with temperature.

In the case of gases, molecular collisions increase with the increase in temperature. Therefore, thermal conductivity increases with temperature.

In liquids, thermal conductivity depends on predominantly on molecular effect. As temperature increase, the randomness of molecular movements increase. As a result the transport of heat through liquid is obstructed. Therefore, the thermal conductivity if the liquid decreased with the increase of temperature.

The exception to this being pure water, initially thermal conductivity increases with temperature but then starts to decrease. (J.Lucid, 2017)

6 Question d)

a) Reynolds Number

The Reynolds number is the ratio of inertial forces to viscous forces and is a parameter for predicting if a flow condition will be laminar or turbulent. It can be interpreted that when the viscous forces are dominant (slow flow i.e. low Re number) they are sufficient enough to keep all the fluid particles in line which therefore creates the laminar flow. Very low Reynolds numbers indicate viscous creeping motion, where inertia effect are negligible. When the inertial forces dominate over the viscous forces the flow then becomes turbulent. $Re < \text{Laminar}$, $Re > 4000$ Turbulent. (D.Cheias, 2018). See below for Reynolds number diagram:

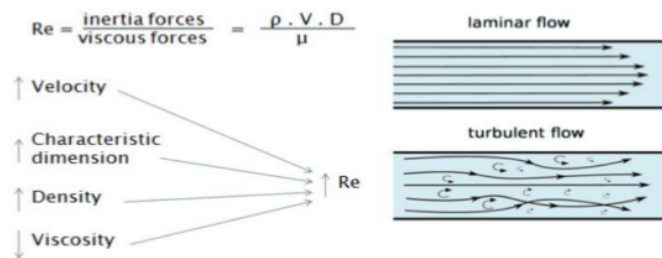


Figure 5 - Reynolds number diagram

As the Re number is comprised of the physical characteristics of the flow. And increasing Reynolds number indicates an increasing turbulent flow. Defined below:

$$Re_D = \frac{\rho V D}{\mu} = \frac{V D}{\nu}$$

Figure 6 Reynolds number definition

Where:

V = Flow velocity

D = Characteristic linear dimension

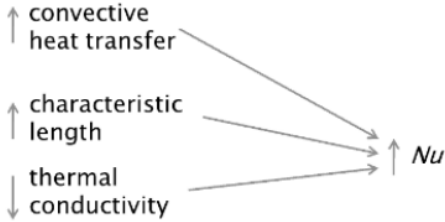
ρ = Fluid density (kg/m^3)

μ = Dynamic viscosity (N.s/M^2)

ν = Kinematic viscosity (m^2/s), $\nu = \frac{\mu}{\rho}$

g) Nusselt Number

The Nusselt number is used to describe the ration of thermal energy convected to a fluid to the thermal energy conducted within the fluid. The Nusselt number is equal to the dimensionless temperature gradient at the surface, it provides a measure of the convection heat transfer occurring at the surface. The conductive component is measured under the same conditions as the heat convection albeit but with stagnant fluid. Therefore, the Nusselt number is to the boundary layer what the friction coefficient is to the velocity boundary layer. (N.Connor, 2018). The Nusselt number is defined as below:

$$Nu_L = \frac{\text{convective heat transfer}}{\text{conductive heat transfer}} = \frac{hL}{k_f}$$


$$Nu_L = f(Re_L, Pr)$$

Figure 7 - Nusselt number definition

k_f = Thermal conductivity of the fluid (W/mk)

L = The characteristic length (m)

H = The convective heat transfer coefficient (W/m²K)

The Nusselt number represents the enhancement of heat transfer through a fluid as a result of convection relative to conduction across the same fluid layer. A Nusselt number equalling 1 for a fluid layer represents heat transfer across the layer by only pure conduction. The larger the Nusselt number, the more effective the convection, with turbulent flow typically in the 100-1000 range. For turbulent flow, the Nusselt number is a function of the Reynolds and Prandtl number.

h) Prandlt Number

The Prandlt number is defined by the ration of momentum diffusivity to thermal diffusivity. The momentum diffusivity or kinematic viscosity as it is also referred, defined the materials resistance to shear-flows in relation to density. (E.Rapp, 2017). The Prandlt number is given as below:

$$Pr = \frac{\text{viscous diffusion rate}}{\text{thermal diffusion rate}} = \frac{\nu}{\alpha} = \frac{\mu/\rho}{k / (c_p / \rho)} = \frac{\mu \cdot c_p}{k}$$

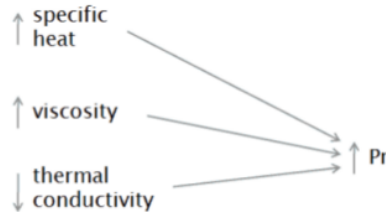


Figure 8 - Prandlt number definition

ν = Momentum diffusivity (kinematic viscosity) (M^2/s)

α = Thermal diffusivity (M^2/s)

μ = Dynamic viscosity ($N.s/M^2$)

K = Thermal conductivity ($W/M.K$)

C_p = Specific heat ($J/KG.K$)

Small values of the Prandlt number $Pr \ll 1$, means the thermal diffusivity dominates. Whereas, with larger PR number > 1 , the momentum diffusivity dominates the behaviour. For example, the typical value for liquid mercury which is 0.025 indicated the heat conduction is more significant compared to convection therefore thermal conductivity is dominant. When the Pr number is small, it shows that heat diffuses quickly compared to the velocity.

Unlike the Reynolds number, the Prandlt number is not dependant on geometry of an object but dependant solely on the fluid and the fluid state. The Prandtl number is often found in property tables alongside viscosity and conductivity,

i) Grashof Number

The Grashof number is another dimensionless number defined as the ration of the buyant force acting on a fluid in the velocity boundary layer. Its role in natural convection is much the same as that of the Reynolds number in forced convection. Natural convection is used if this motion and mixing is caused by density variation resulting from temperature differences within the fluid.

Normally the density variation decreased due to an increase in temperature and causes the fluid to rise. This motion is caused by the buoyant force. The major force that resists the motion is the viscous force. The Grashof number is means to quantify the opposing forces. (Monteith, 2010).

Grashof number defined below:

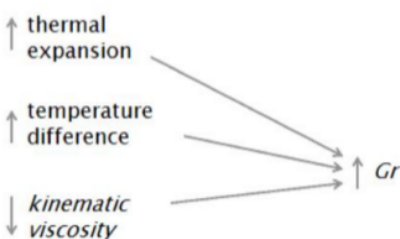
$$Gr = \frac{\text{buoyant forces}}{\text{viscous forces}} = \frac{g\beta(T_{\text{wall}} - T_{\infty})L^3}{\nu^2}$$


Figure 9 Grashof number defined

Where:

g = Acceleration due to gravity

B = Coefficient of thermal expansion

T = Wall temperature

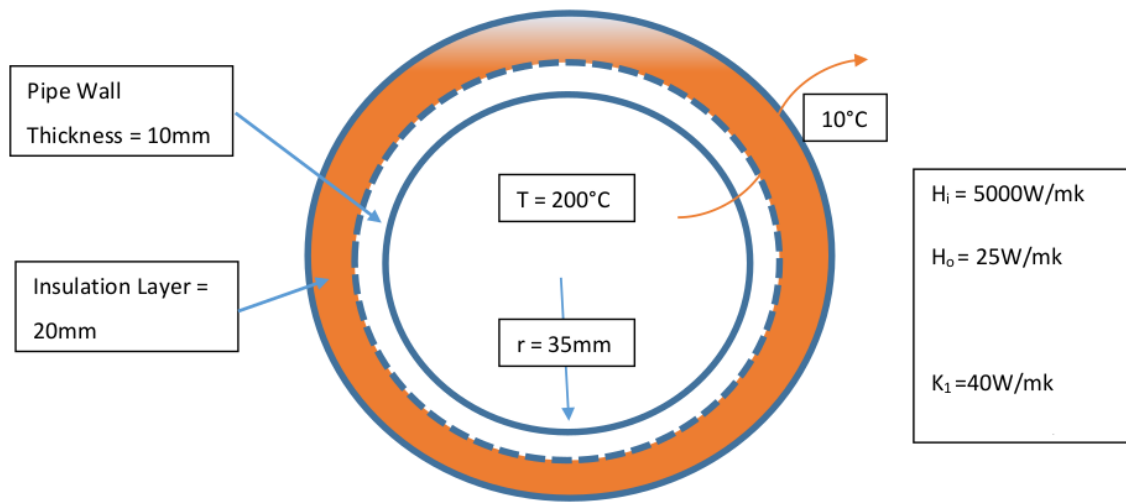
T = Bulk temperature

L = Vertical length

V = kinematic viscosity

For liquids (B) can be calculated if variation of density with temperature at constant pressure is known. For a vertical flat plate, the flow turns turbulent for value of $Gr.Pr > 10$. As in forced convection the microscopic nature of flow and convection correlations are distinctly different in the laminar and turbulent regions. The Grashof is closely related to the Prandtl number which describes the relationship between momentum diffusivity and thermal diffusivity.

7 Question e)



a)

$$R_i = \frac{1}{H_i A} = \frac{1}{(5000 \times (2\pi \times 0.035 \times 1))}$$

$$= 9.09 \times 10^{-4} \text{K/w}$$

$$R_o = \frac{1}{H_o A} = \frac{1}{(25 \times (2\pi \times 0.065 \times 1))}$$

$$= 0.097 \text{K/w}$$

$$R_1 = \frac{x}{K_1 A_1} = \frac{0.01}{(40 \times (\frac{2\pi \times 0.01}{\ln(\frac{0.45}{0.35})} \times 1))}$$

$$= 0.0009 \text{K/w}$$

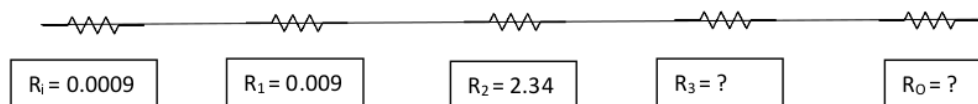
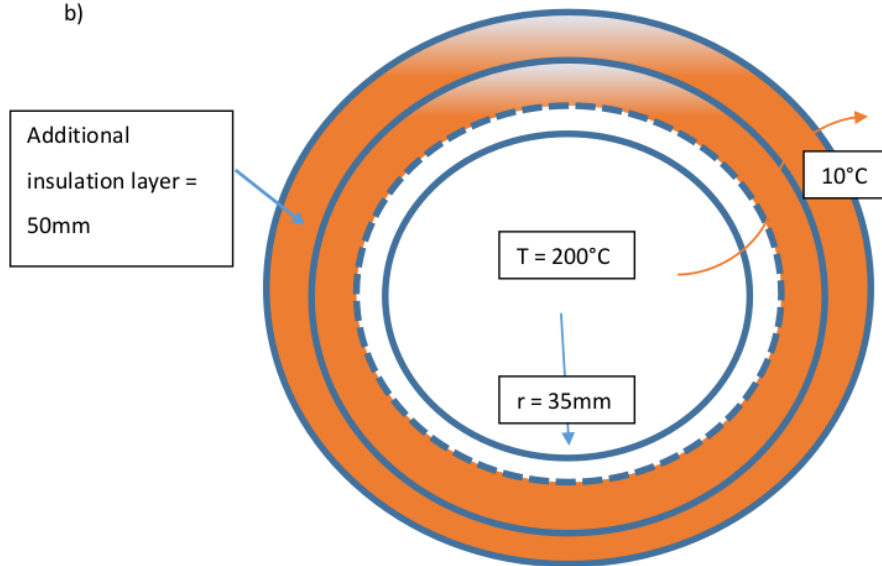
$$R_2 = \frac{x}{K_2 A_2} = \frac{0.02}{(0.025 \times (\frac{2\pi \times 0.02}{\ln(\frac{0.65}{0.45})} \times 1))}$$

$$= 2.34 K/w$$

$$R_{Total} = (0.000909) + (0.0009) + (0.0009) + (2.34) = 2.43 K/w$$

$$Q = \frac{190}{2.43} = 78.18 \text{ Watts per meter.}$$

b)



$$R_3 = \frac{x}{K_3 A_3} = \frac{0.05}{(0.025 \times (\frac{2\pi \times 0.05}{\ln(\frac{0.115}{0.65})} \times 1))}$$

$$= 3.63 K/w$$

$$R_o = \frac{1}{h_o A} = \frac{1}{(25 \times (2\pi \times 0.115 \times 1))}$$

$$= 0.055K/w$$

$$R_{Total} = (0.000909) + (0.009) + (2.34) + (3.63) + (0.055) = 6.0268 Kw$$

$$Q = \frac{190}{6.0262} = 31.52 \text{ Watts per meter.}$$

c) Total Payback Period Calculation

$$= 78.5 - 31.52 = 46.98 w/m$$

$$= 46.98 \times (60 \times 60 \times 24 \times 7 \times 48) = 1363.84 MJ$$

$$Saving = 0.02 \times 1363.84 = £27.28$$

$$Payback Period = \frac{125}{27.28} = 4.6 \text{ Years}$$

Evaluation of Results

From the calculation above it can therefore be calculated that the payback period for an extra 50mm of insulation would be 4.6 years. The mathematical calculation above shows that the insulation should be used to reduce the heat transfer on the system. By having a relatively short payback period any upfront costs would be justified should they be practical. The efficiency of the system would also be improved as well as the work to maintain the temperature be reduced.

8 Conclusion

To conclude this paper it can be seen that heat transfer through an object is apparent in three different modes convection, conduction and radiation. The reason for this is due to the nature of heat and its natural ability to find an equilibrium between mediums.

On the contrary to heat transfer principles, insulators reduce the heat transfer for all three methods. Insulators are a viable way of maintaining or removing heat when and were required in engineering practise.

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