

Thermo 3

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THERMOFLUIDS ELEMENT

Thermofluids and Applied Mechanics

BSc Mechanical Engineering – Year 3

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1.0 Introduction

This assignment will focus on underlying thermo fluid concepts consisting of heat transfer and fluid flow. It will consist of research performed on fundamental modes of heat transfer including background theory of boundary layer effects. The report will also detail insulation characteristics and the effect of temperature of temperature on thermal conductivity.

In addition to this research, a mathematical problem will be solved to enable analysis and evaluate the results.

2.0 Types of Heat Transfer

2.1 Conduction

Heat transfer through conduction occurs when an area that has greater kinetic energy transfers thermal energy onto another area that has lower kinetic energy. According to (www.machinedesign.com, 2015) this is down as "*direct molecular collision*".

Particles with slower speeds have an increase in kinetic energy through collision with particles of higher speeds. This is form of heat transfer I the most common and occurs through physical contact.

The rate of this process can depend on a number of variables such as;

- Cross section of material
- Temperature gradient
- Length of travel path
- Material properties

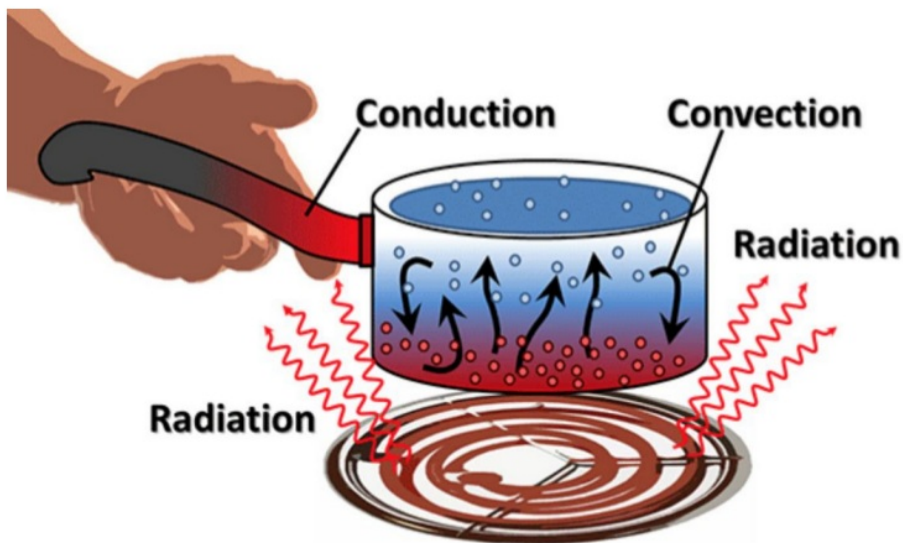
The flow of temperature will always occur from hot to cold and the heat transfer will stop once a thermal equilibrium occurs. An example of this would be heating up a section of metal with an open flame.

An important factor of this heat transfer is the cross sectional area. The size and length of the object can affect the amount of heat required to increase it's temperature. Equally, if the surface area is larger, it means that more heat will be lost. Therefore to decrease heat loss it would be beneficial to decrease the surface area and cross section.

The material properties of particular interest include the thermal conductivity coefficient. For example, a section of copper would conduct heat better than a block of wood.

2.2 Convection

Convection occurs though a liquid or a gas, such as air that is heated and travels away from the source of heat. It then carries some of this thermal energy with it. For example, fluid in a pan on a stove becomes hot. It gets less dense and rises. Molecules expand once thermal energy is introduced. As the temperature of the fluid in the pan increases the volume of the fluid also increases which causes displacement. As hot gases rise, colder, denser gases are forced down. This is the basis of convection currents. An example of this can be shown below:



2.3 Radiation

Electromagnetic waves generate thermal radiation. An object emits waves away, which carries this energy. Thermal radiation is a resultant due to movements of random molecules and atoms. The movement of charged electrons and protons causes the emissions of the electromagnetic radiation.

Dependent upon temperature, all objects radiate thermal energy. Simply, an object will radiate more the higher the temperature. The most obvious example of this being the Sun. The temperature also affects frequency and wavelength. When temperature rises, the frequency increases and the wavelength gets shorter. According to (www.mechinedesign.com, 2015)

"Thermal radiation is calculated by using the Stefan-Boltzmann law:"

$$P = e \sigma A (T_r^4 - T_c^4)$$

- P = net radiated power
- A = radiating area
- T_r = temperature of the radiator
- T_c = temperature of surroundings
- e = emissivity
- σ = Stefan's constant.

3.0 Insulation Materials

According to (www.nuclear-power.net, 2020) *“Thermal insulation is based on the use of substances with very low thermal conductivity and low surface emissivity.”*

In order to understand the performance of insulation materials, characteristics must be researched, these characteristics include;

Thermal Conductivity – This is the insulations materials ability to conduct heat. This is measure in W/mK. Although insulation in practise is typically a solid, Fourier’s Law applies to thermal conductivity therefore it is also relevant for liquids and gases. However these are very rarely used. One example may be gas between two panes of glass in double-glazing windows. This is the amount of heat transferred in Watts per meter squared (of a specified thickness).

According to (www.nuclear-power.net, 2020) *“The lower the thermal conductivity of the material the greater the material’s ability to resist heat transfer, and hence the greater the insulation’s effectiveness.”*

As an indication, gases tend to have lower thermal conductivity for example, air has 0.025 W/mK yet copper has 400 W/mK. For industry practise, insulation is commonly used with a thermal conductivity of approximately 0.019 – 0.046 W/mK.

R Value – The R Value is the measure thermal resistance. To achieve the most effective insulation the R number must be high. The units used for thermal insulance is m²K/W. Factors affecting the R-value consist of the density, thickness and type of insulation.

U Value – The inverse of the R Value (1/R). This is the thermal transmittance. It describes how well a meal can conduct heat. Therefore the lower the U Value, the better the insulation. (www.nuclear-power.net, 2020) claims *“The U-value is defined by an expression analogous to Newton’s law of cooling.”*

Surface Emissivity – The surface emissivity (ϵ) of a material surface is its overall effectiveness of emitting energy though heat transfer by thermal radiation. The scale is between 0 -1. Examples include a blackbody (black being 1), this typically emits radiation at 448 w/m² (at room temperature 298K). Aluminium foil has a surface emissivity of less than 1 of 0.07. Therefore;
 $448 \times 0.07 = 31.4 \text{ W/m}^2$

Fire Resistance – Insulation must be classified to have a fire resistance rating for health and safety reasons. Due to the application involving possible high temperatures this is an important factor to ensure safety and longevity of the material. The fire ratings are classified in minutes, displaying the amount of time the performance criteria of the material is fulfilled during a fire test. This ranges from 15 minutes – 360 minutes.

3.1 Insulation Materials

As stated above, insulation is based around a materials ability to have a low thermal conductivity. These materials must be good thermal insulators and poor thermal conductors. Such materials with these properties include;

- Rock wool
- Polystyrene
- Polyurethane

- Wool
- Fiberglass
- Goose Weathers

3.2 Effect of Porosity on Heat Transfer

Porosity is a percentage or fraction of the void in a material, or spaces in a material. It ranges between 0 – 1 and 0 – 100%. If porosity is decreased the rate of heat transfer increased. In turn this can also affect dimensionless factors such as the Reynolds, Prandtl and Nusselt numbers as the temperature of the fluid increases.

4.0 Effect of Temperature on Thermal Conductivity

4.1 Metals

When considering alloys and pure metals, predominantly the conductivity depends on electronic effect. When the temperature is increased the lattice vibrations and number of free electrons also increases. This would mean that that thermal conductivity of the metal would be expected to increase also. Having said this, the increase of lattice vibrations obstructs the flow of these free electrons.

Taking both factors into consideration (in most cases) with an increase of temperature the thermal conductivity decreases. Some exceptions to this include metals such as iron and platinum. Platinum's thermal conductivity increases when a temperature increase is introduced.

4.2 Gases

When it comes to gases, collisions between molecules increase when there is an increase of temperature. In turn, this will increase the thermal conductivity with an increase of temperature.

4.3 Liquids

As shown above, thermal conductivity can be dependant on the effect of molecular diffusion. The randomness of molecular movement increases as the temperature increases. This causes an obstruction of the heat through the liquid. Again, causing the thermal conductivity to decrease when temperature is increased. An exception to this is pure water. When considering pure water, thermal conductivity increases at first, but as the temperature increases, the thermal conductivity starts decreasing. This can be shown under the figure below;

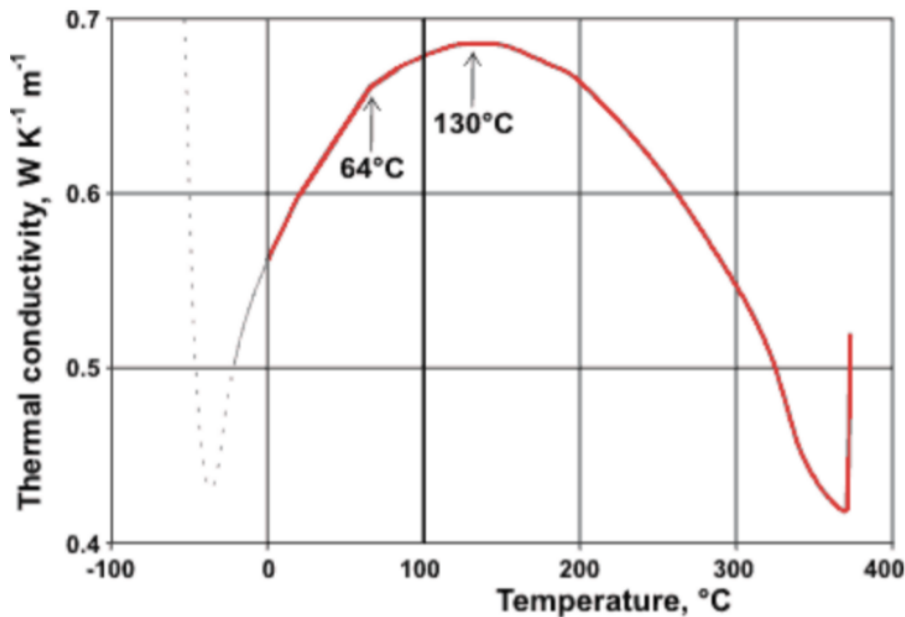


Figure 1: Thermal Conductivity of Pure Water (www.medium.com)

4.4 Pressure

Pressure must also be considered. According to (Ludic Learning, 2017) “most solids and liquids are incompressible in nature, thermal conductivity does not vary with pressure.”

Therefore we must look at the effect on gases. Continued from (Ludic Learning, 2017) “the thermal conductivity of gases is proportional to the square root of the temperature T , and inversely proportional to the square root of the molar mass M ”.

Although there is a relationship between pressure and temperature with regards to thermal conductivity, there are many examples in practise where thermal conductivity is independent of the pressure.

4.4 Thermal Diffusivity

Thermal diffusivity can be described as when a system gains heat, part of this heat is transported into another system and some is stored in the original system. As mentioned above, thermal conductivity is the ability of a material to transport heat. Here we must also consider the heat capacity of said material, this is represented as C_p .

Here we use both terms to calculate how fast heat is diffused through a system:

$$\alpha = \frac{(\text{heat conducted})}{(\text{heat stored})} = \frac{k}{\rho C_p}$$

From this formula, the thermal diffusivity can be shown as a ratio of the heat stored per unit against the heat conducted.

To conclude, material selection plays a large role in thermal conductivity. Properties must be considered. For example, a material with a low heat capacity or a high thermal conductivity will have a larger thermal diffusivity.

(Ludic Learning, 2017) *"The larger the thermal diffusivity, the faster the propagation of heat into the medium."*

Please refer to appendix for examples of this.

5.0 Dimensional Analysis

5.1 Reynolds Number

The Reynolds number (abbreviated to Re) is a dimensionless quantity used when predicating flow patterns in fluid mechanics.

The Reynolds number is used to determine if the flow of the fluid will be laminar. This means the the layers of the fluid are parallel and moving in the same direction. It also determines if a fluid is turbulent.

Transient flow is a mixture between both laminar and turbulent flow. Below the scales of these flows can be seen;

Laminar Flow = $Re < 2300$

Transient Flow = $2300 < Re < 4000$

Turbulent Flow = $4000 > Re$

5.2 Nusselt Number

The Nusselt number is used to describe the ratio between thermal energy convected to the thermal energy conducted within the fluid. It is equal to the dimensionless surface temperature gradient, this provides a measurement of the convection heat transfer on the material surface.

According to (www.nuclear-power.net, 2020) *"The Nusselt number is to the thermal boundary layer what the friction coefficient is to the velocity boundary layer. Thus, the Nusselt number is defined as:*

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

k_f is thermal conductivity of the fluid [W/m.K]

L is the characteristic length

h is the convective heat transfer coefficient [W/m².K]"

5.3 Prandtl Number

The Prandtl number can be defined as a ratio between the thermal diffusivity and momentum diffusivity. Momentum diffusivity is known as kinematic viscosity which describes the resistance the shear flows in relation to density. It can be defined as;

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

ν is momentum diffusivity (kinematic viscosity) [m^2/s]

α is thermal diffusivity [m^2/s]

μ is dynamic viscosity [N.s/m^2]

k is thermal conductivity [W/m.K]

c_p is specific heat [J/kg.K]

ρ is density [kg/m^3]

5.4 Grashof Number

This is defined as the ratio between the viscous to buoyant force acting on a fluid in the boundary layer. It can be related to the Reynolds number, as its role in natural convection is much the same as the Re in forced convection. If the mixing and motion is caused by density variations, which results in temperature differences in the fluid, then natural convection is used. Due to increased temperatures the density usually decreases which causes fluids to rise. Buoyant force causes this motion. Viscous force resists the motion.

(www.nuclear-power.net,2020) describes it as “The Grashof number is a way to quantify the opposing forces.”

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

- g is acceleration due to Earth's gravity
- β is the coefficient of thermal expansion
- T_{wall} is the wall temperature
- T_{∞} is the bulk temperature
- L is the vertical length
- ν is the kinematic viscosity.

6.0 Analysing Engineering Thermodynamic Problem

6.1 Rate of Heat Loss

Find the rate of heat loss from the pipe to air per meter

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

$$R_i = \frac{1}{H_i \times A_i} = \frac{1}{5000 \times (2\pi \times 0.035 \times 1)} = 0.0009 \text{ K/w}$$

$$R_o = \frac{1}{H_o \times A_o} = \frac{1}{25 \times (2\pi \times 0.065 \times 1)} = \mathbf{0.098 \text{ K/w}}$$

$$R_1 = \frac{X_1}{K_1 \times A_1} = \frac{0.01}{40 \times \left[\frac{2\pi \times 0.01}{\ln \frac{0.045}{0.035}} \times 1 \right]} = \mathbf{0.0011 \text{ K/w}}$$

$$R_2 = \frac{X_2}{K_2 \times A_2} = \frac{0.02}{0.025 \times \left[\frac{2\pi \times 0.02}{\ln \frac{0.065}{0.045}} \times 1 \right]} = \mathbf{2.34 \text{ K/w}}$$

$$\mathbf{RT = 0.0009 + 0.098 + 0.0011 + 2.34}$$

$$\mathbf{Q = \frac{200-10}{2.44}}$$

Therefore rate of loss = 77.86 W/m

6.2 Rate of heat loss with additional 50mm of insulation

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

$$R_{io} = \frac{1}{H_o \times A_o} = \frac{1}{25 \times (2\pi \times 0.115 \times 1)} = \mathbf{0.0009 \text{ K/w}}$$

$$R_3 = \frac{X_3}{K_3 \times A_3} = \frac{0.05}{0.025 \times \left[\frac{2\pi \times 0.05}{\ln \frac{0.115}{0.065}} \times 1 \right]} = \mathbf{0.0553 \text{ K/w}}$$

$$RT = 0.0009 + 0.0553 + 0.0011 + 2.34 + 3.63 = \mathbf{6.0273 \text{ K/W}}$$

$$\mathbf{Q = \frac{200-10}{6.0273}}$$

Therefore rate of loss = 31.52W/m

6.3 Payback Period

Find the payback period when the cost per meter of the extra 50mm insulation is £125. Operated over 48 weeks per year when the heat is generated at a cost of £0.02 per MJ.

$$Q = 77.9 - 31.5 = 46.4$$

$$\text{Yearly Loss} = 46.4 \times (60 \times 60 \times 24 \times 7 \times 48) = \mathbf{1347 \text{ MJ}}$$

$$\text{Therefore cost per meter per year} = 1347 \times 0.02 = \mathbf{£26.94 / \text{year}}$$

Based on £125 per meter, pay back period can be calculated as:

$$\mathbf{£125 / £26.94 = 4.7 \text{ years}}$$

When taking this pay back period into consideration the life expectancy of the insulation must be noted. If the expectancy is any less than 4.7 years would ultimately result in an overall loss. This also does not take into account the deterioration of the insulation and assumes optimum performance over the 4.7 years.

7.0 Conclusion

To conclude there is a wide range of factors that affect the efficiency of a thermo fluid system. The main factors being heat loss through the three modes of heat transfer. Conduction, convection and radiation. Once it is understood how the heat is being lost, it is then possible to mitigate this loss through the use of additional material to insulate the surface. Utilising insulation can decrease the heat loss therefore it is important to understand the factors impacting heat transfer and the characteristics of insulation. Not only can insulation be used to contain heat, it can also be used for protection against extremely cold weather conditions.

It is then possible to calculate the actual loss of energy and implement corrections to mitigate the loss. However this mitigation must be cost beneficial. By calculating the payback period a simple cost benefit analysis can be carried out to make an informed decision.

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9.0 Appendix

Material	diffusivity [m ² /s]
Building materials	
Aluminum	97.5 x 10 ⁻⁶
Iron	22.8 x 10 ⁻⁶
Marble	1.2 x 10 ⁻⁶
Ice	1.2 x 10 ⁻⁶
Concrete	0.75 x 10 ⁻⁶
Brick	0.52 x 10 ⁻⁶
Heavy soil (dry)	0.52 x 10 ⁻⁶
Glass	0.34 x 10 ⁻⁶
Wood (oak)	0.13 x 10 ⁻⁶
Thermal insulators	
Cork	0.038 x 10 ⁻⁶
Glass wool	0.023 x 10 ⁻⁶
Rock wool	0.022 x 10 ⁻⁶
Expanded polystyrene	0.035 x 10 ⁻⁶
Extruded polystyrene	0.026 x 10 ⁻⁶
Polyurethane foam	0.023 x 10 ⁻⁶
Phenolic foam	0.018 x 10 ⁻⁶