

# RH186462 Thermofluids Assignment

*by* Richard Hall

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# Thermofluids Element

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Heat Transfer

Hall, Richard

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## **Summary**

The assignment critically examines the significance of thermofluid theory, through the evaluation and investigation of the concepts of heat transfer, the application and practical effectiveness of insulation, as well as the significance of dimensionless groups.

A calculation is completed as to the rate of heat loss through a pipe and insulation, allowing for a payback analysis to be completed and concluding recommendations to be presented.

Closing conclusions are made as to the significance of heat transfer application in industry, emphasising that information gained through calculation of theoretical performance can have a valuable influence on the design and installation of equipment and systems.

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### **1.0 Task (a)**

The existence of heat transfer across a system can be explained as a measure of heat flow transitioning between boundaries of differing temperatures. In order to quantify the process of heat flow Krieth (2016) comments *"heat flow is governed not by a unique relationship, but rather by a combination of various independent laws of physics."*

Accepted academic literature identifies three distinct modes of heat transfer; that of conduction, heat transfer by convection and radiation.

#### **1.1 Conduction**

The process of conduction can be categorised as the transfer of heat on a molecular level from a density of higher temperature to a density at lower temperature. Wells (1863) defines this process writing *"heat is said to be communicated by conduction when it is transmitted from particle to particle of a substance...some substances oppose very little resistance to its passage, while through others it is transmitted slowly, or with great difficulty"*.

Calculating the rate of heat transfer through a conductive body is achieved using Fourier's law (Bergman & al, 2011) which states that *"heat transfer is proportional to the negative gradient in temperature and to the area, at right angles to that gradient, through which the heat flows"*.

Heat transfer through conduction can be expressed as an integrated equation between two points of a homogenous material (Figure 1):

$$Q = K A \frac{dT}{dX}$$

Where:

Q = Heat transfer (W)

K = Thermal conductivity constant of material (w/m<sup>2</sup>K)

A = Area of cross section (m<sup>2</sup>)

$\frac{dT}{dX}$  = Change in temperature across cross section of material (K)

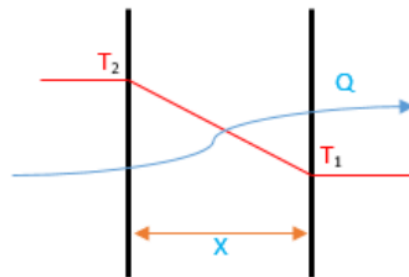


**Figure 1:** Diagram showing heat transfer due to conduction through a material.

## 1.2 Heat transfer by convection

The nature of convection can be expressed as the transference of heat through the movement of a liquid or gas in relation to thermodynamics of a material, this process occurs in the boundary layers of a material. Reynolds (1971) defines convection writing *"it is the transfer of energy by macroscopic fluid motions, depending on the intrinsic energy and its velocity"*. The process that Reynolds describes is the interaction of particles that are in close proximity to an elevated temperature source absorbing heat energy, thus increasing their relative movement and causing alteration in density and diffusion to a wider area (i.e. hot air rising). The area left by the diffusion of affected particles is then populated by slower moving colder particles due to their difference in density for the cycle of convection to repeat.

To quantify the heat transfer through the boundary layer of a material Newton's law of cooling is utilised. Logan (2013) comments on the use of the law writing *"the rate of change of temperature is proportional to the difference between the temperature of the object and the surrounding ambient temperature"*.

Expressing this relationship mathematically:

$$Q = h A (T_2 - T_1)$$

Where:

Q = Heat transfer due to convection (W)

h = The boundary layer heat transfer coefficient (W/m<sup>2</sup>K)

A = Cross section surface area (m<sup>2</sup>)

T<sub>2</sub>-T<sub>1</sub> = Temperature difference (K)

Figure 2 demonstrates the heat transfer due to convection and the application of Newton's law of cooling across a material.

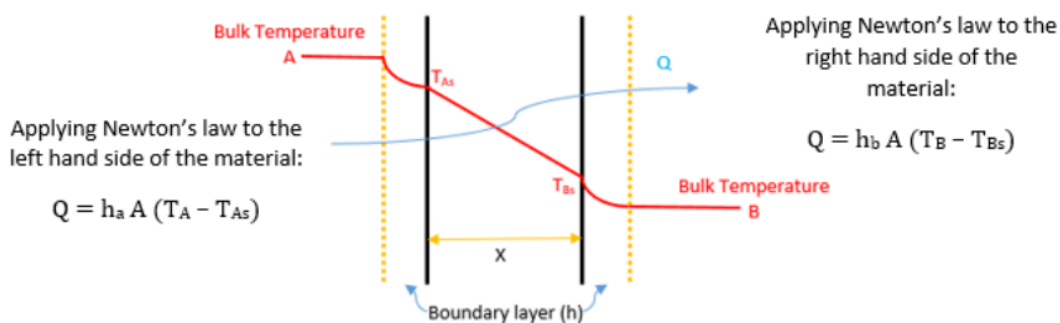


**Figure 2:** Diagram illustrating heat transfer due to convection within the boundary layers of a material.

### 1.3 Radiation

Heat transfer by radiation differs from the modes of conduction and convection, as it does not require direct contact or a medium in which to travel. The transfer of thermal energy occurs through the absorption, reflection and transmission of electro-magnetic waves. Wells (1863) writes of radiation as a heat transfer mode stating *“The radiation of heat goes on at all times, and from all surfaces, whether their temperature be the same as or different from that of surrounding objects”*.

Rates of absorption and emission between materials and surfaces of radiation differ greatly, an example of this can be seen in *figure 3* below. Radiation in the form of wavelengths have been identified across the ultra violet, infrared, microwave and radio frequency spectrums. Scientific studies such as Kirchhoff's law (Kirchhoff, 1860) has established that *“for an arbitrary body emitting and absorbing thermal radiation in thermodynamic equilibrium, the emissivity is equal to the absorptivity”*.

There are however additional laws founded in physics providing the necessary tools in which to identify and quantify the amount of heat flow transferred and lost through the mode of radiation. In the infrared spectrum alone, three fundamental laws govern:

Planck law (Passon, 2017)– The curve mapping of emissivity against temperature and radiant energy.

Stefan – Boltzmann law (Hobbs, 2006) – Establishing the total potential power radiated at a specific temperature through black body heat transfer using the constant  $\sigma = 5.67 \times 10^{-8} \text{ J/s} \cdot \text{m}^2 \cdot \text{K}^4$  through the equation:

$$\frac{Q}{t} = \sigma e A T^4$$

Wein's law (Riedl, 2001) – The sizing of varying wavelengths that differ at the point of maximum energy emission.

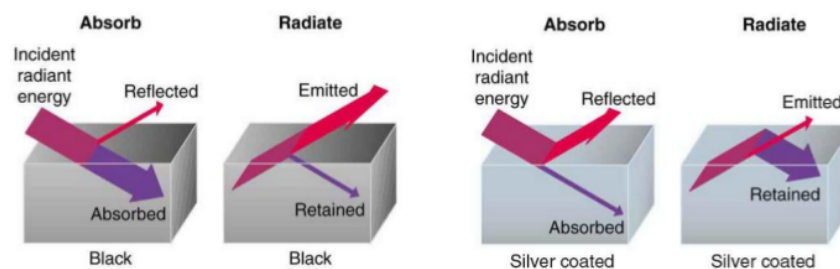


**Figure 3:** Radiation differences between black and silver bodies. (OpenStax College, 2019)

#### 1.4 The combination effect of modes across a boundary layer.

The resulting effects and compound nature of transient energy across an object, is best described through consideration of how heat transfer travels through a homogenous material. Negating radiation heat transfer, it can be witnessed that the energy passing into and out of a cross-sectional area, undergoes three distinctive stages of transmission:

- Stage 1: Convection - as it enters the boundary layer of the material.
- Stage 2: Conduction - as it passes through the body of the material
- Stage 3: Convection - again as it passes through the final boundary layer

In order to equate the complete heat transfer of the system, an overall heat transfer coefficient ( $\mu$ ) must be established, the heat transfer equation therefore becomes:

$$Q(w) = \mu(w/m^2k) A(m) \Delta T(k)$$

Where:  $\frac{1}{\mu} = \frac{1}{h_a} + \frac{X}{K} + \frac{1}{h_b}$

The resulting overall heat transfer coefficient can also be established through the process of an electrical analogy. In this instance the heat can be equated for current and heat transfer coefficient to electrical resistance. Ohms law can be paralleled to the requirements of the heat transfer equation:  $Q = \frac{T_A - T_B}{RT}$  where:  $RT = R_A + R_1 + R_B$  (Figure 4)

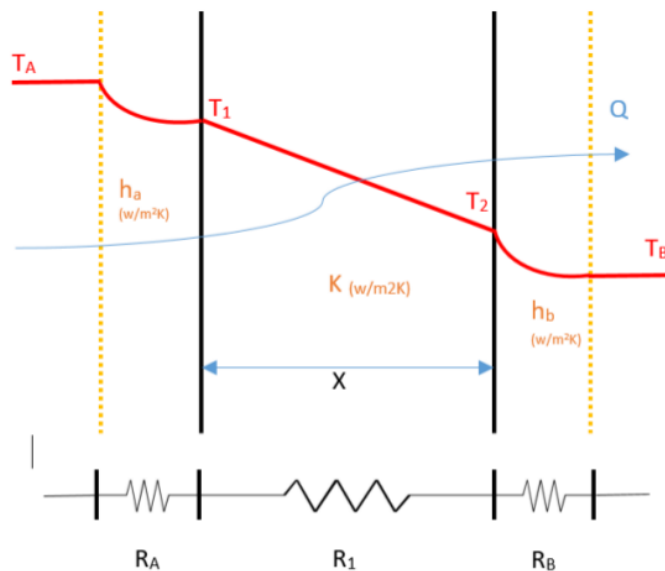


Figure 4: Electrical analogy of heat transfer.

## 2.0 Task (b)

In considering the characteristics of insulation, a material is termed a good insulator if it possesses a natural capacity to reduce and prevent the transmission of heat or electricity energy. Dunlop (2003) writes of the use of insulation materials stating, *“Insulation is something that slows the rate of heat flow. Nothing can stop heat flow, but some materials slow it down more than others”*.

For an insulator to be effective, a material needs to exhibit a low thermal conductivity and provide a high resistance to heat. Air permeability is an essential factor on the selection of insulation whilst ease of installation, thermal resistance and safety features also desirable qualities. Typical examples of desired features include; the structure of material to be generally porous, passage of steam or moisture through a material to be limited, material that is durable in operation and resistant to water, fire and chemical degradation.

Insulating materials whether electrical or thermal work by limiting the effects of conduction, convection and radiation. A good insulating material impedes the transference of energy through its construction of multiple layers or pores, creating miniature cells and forcing energy to undergo multiple transitions between conduction and convection. The action of energy crossing multiple boundary layers within the material encumbers the conveyance of heat or electrical flow.

On an atomic level a good insulator’s electrons are tightly bound, enhancing transmission resistance by restricting movement. However the structure exhibited by good insulators have a low density to promote a porous arrangement, increasing the amount of closed cells of gas or air within the body of a material (*figure 5*).

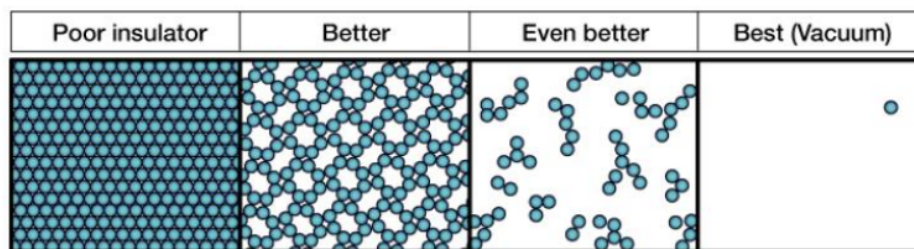


**Figure 5:** *Insulation material properties.* (Cruzan, 2012)

The type of insulation used depends on its suitability for the task intended, Shawyer (2003) writes *“a wide range of insulation materials is available, selection of insulation should be based on a multitude of factors from cost, form, shape and durability”*.

Interpreting this statement, it is not solely about choosing a material with the least thermal conductivity, but one that will be economically cost effective to the needs of its environment, process and installation.

### **3.0 Task (c)**

Different types of insulators can be graded for effectiveness by measurement of their conductance or conveyance of heat flow. Shawyer (2003) defines thermal conductivity commenting *"this is a measure of the capacity of a material to conduct heat through its mass...it is defined as the amount of heat/energy (expressed in Kcal, Btu or J) that can be conducted in unit time through unit area of unit thickness of material"*.

To generalise the relationship; the lower the thermal conductivity of a material the more resilient the material becomes to the transference of heat energy. To quantify the measure of conductivity the inverse concept of thermal resistance (R) is used, the higher the R number the more effective the material as an insulator.

When evaluating the effects of temperature on thermal conductivity, the effects of changes in temperature results in differences in gases, liquids and solids. Muthaiah's (2018) study of molecular dynamics in amorphous polyethylene summarises, *"in gases the thermal conductivity increases with temperature, for liquid and solids it depends on the particular substance dependant on the material atomic structure of free electrons"*.

Analysing the findings of Muthaiah's (2018) study as with sources other literary review such as Khachan (2018) and Yaws (1995) it can be witnessed that in solids, the resulting variance due to temperature depends upon the amount of vibration and free flow of electrons within a materials lattice structure. Yaws (1995) presents that at higher temperatures, thermal conductivity decreases at an inversely proportional relationship due to vibrations in the lattice impeding the free movement of electrons. For metallic liquids, conductivity decreases as temperature rises, resulting from the altered distance between molecules from expansion of the liquid. An exception to this is water which demonstrates an increase to the point of 130 °C before decreasing. As with liquids, molecular diffusion plays an important factor in the transference of heat energy within gases, Khachan (2018) states *"that thermal conductivity is directly proportional to the square root of temperature"*.

Considering the molecular activity of gases in relation to temperature increase, the effect forms increased kinetic collisions of energy, subsequently raising the thermal conductivity properties.

Knowing how a given material reacts conductively to variance in temperature, has far reaching impacts on many engineering disciplines across mechanical, civil and chemical disciplines, altering intended designs and the effectiveness of proposed solutions. As an example of the different results, Cengal (2011) graphically presents a range of material and the effects of thermal conductivity (*appendix 8.1*).

#### 4.0 Task (d)

The use and development of dimensionless groups in fluid mechanics became a necessity, as a result of the need for applying universal scaling terms to experimental fluid calculations.

Dimensionless groups are considered the formulation of force ratios within fluids, Graebel (2001) writes of the utility within the discipline stating *"they provide a means of consolidating experimental, analytical and computational results into a compact form... they play a central role in fluid mechanics because of the large number of parameters and highly complex behaviour of fluid flows"*.

There are many collections of dimensionless variables that provide recognisable orders of magnitudes into the behavioural characteristics of fluids, i.e. inertia, viscosity, pressure, gravity etc. A selection of most prominent ratios and their importance are critically assessed below;

#### 4.1 Reynolds Number

The Reynolds number can be defined as the ratio of inertia forces to the viscous forces within a fluid system and is used for the classification of a fluid state. The formula is expressed:

$$Re = \frac{\rho v D}{\mu}$$

Where:  $\rho$  = density of fluid ( $\text{kg/m}^3$ )    $v$  = Velocity ( $\text{m/s}$ )    $D$  = Diameter of the pipe ( $\text{m}$ )

$\mu$  = Dynamic viscosity ( $\text{kg/ms}$ )

Relative to the nature of the flow system a low Re number ( $<2000$ ) indicates a laminar flow within the pipe whilst a high Re number ( $>4000$ ) results in a turbulent flow (figure 6), resulting numbers found in between these two parameters undergo a phase of transition. The calculation of the Reynolds number is important in establishing a velocity profile of the fluid within different diameters of pipe and for formulation frictional losses found in the boundary layers.



Figure 6: Examples of laminar and turbulent flow. (Nuclear-power, 2019)

## 4.2 Nusselt Number

The Nusselt number is the ratio of the convection of relative to the amount of heat conducted.

The formula for calculation of the Nusselt ratio is expressed:

$$Nu = \frac{h L}{K}$$

Where:  $h$  = Convective heat transfer coefficient ( $W/m^2k$ )     $L$  = Characteristic length (m)

$K$  = Thermal conductivity ( $W/mk$ )

Generally speaking the resulting Nusselt number is found to be greater than 1 due to the physical convection of energy being greater than that of conduction energy. If the Nusselt number is found to be one heat transfer within the fluid can be seen to be by conduction only with no apparent effect from convection. The significance of using this ratio becomes apparent when comparing the Nusselt number of two fluids indicating the levels of convection and conduction properties across a boundary within a system.

## 4.3 Prandtl Number

The Prandtl number can be defined as the ratio of viscous diffusion in relation to thermal diffusion, and is expressed in the formula:

$$Pr = \frac{\mu C_p}{K}$$

Where:  $\mu$  = Viscosity coefficient (PaS)     $C_p$  = Specific heat ( $J/KgK$ )     $K$  = Thermal conductivity ( $W/mk$ )

The molecular chemical properties of a fluid dictate the composition and structure within the free movement of the fluid, when considered with a capacity for heat storage and transference (thermal conductivity) the outcome results in a relative thickness of momentum. A fluid with a high Prandtl number demonstrates that effects of viscosity are stronger when compared to thermal diffusion limiting thermal diffusion. Inversely a fluid with a low Prandtl number exhibits low viscosity and a high thermal diffusion. The ratio is significant within fluid mechanics as the Prandtl number will denote the thickness of the boundary layer of the fluid. *Figure 7* shows the effects of Prandtl number ratio on the thermal boundary of a fluid.

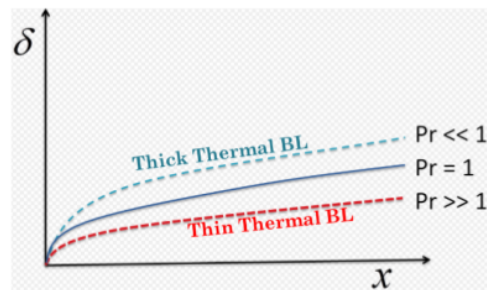


**Figure 7:** Effects of Prandtl ration on thermal boundaries (CFD, 2020)

#### 4.4 Grashof number

The Grashof number can be defined as the ratio of buoyancy force in relation to viscous force. The formula for the ratio applied to pipes is expressed:

$$Gr = \frac{g\beta(T_s - T_\infty) D^3}{\nu^2}$$

Where:  $g$  = Gravitational acceleration (m/s<sup>2</sup>)       $\beta$  = coefficient of thermal expansion (1/K)

$T_s$  = surface temperature (K)       $T_\infty$  = Bulk temperature (K)       $D$  = Diameter of pipe (m)

$\nu$  = Kinematic viscosity (Dynamic viscosity / density)

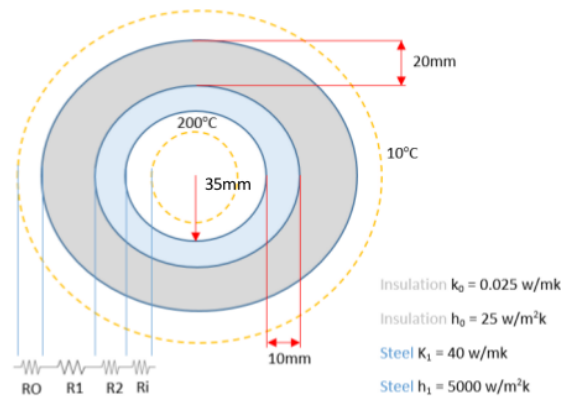
(Shenoy, 2018)

The purpose of the ratio is comparable to that of the Reynolds number in the prediction of laminar and turbulent transition of flow, however is used in circumstance of free or natural convection when differences in temperature, effect the density of fluid. Grashof (1826-1893) found using this method that the critical number for the transition phase from laminar to turbulent flow began at  $> 4 \times 10^8$  (Shenoy, 2018). The significance of the ratio is demonstrated through its calculated factors of the force of inertia multiplied by the force of buoyancy, this divided by the square of viscosity. The relationship dictates the type of flow within the boundary layer of the fluid, if the viscosity is high and the dominant variable in the relationship the resulting Grashof number is small indicating laminar flow, inversely if the buoyancy attribute is high so too is the Grashof number resulting in turbulence within the fluid structure.

### 5.0 Task (e)

"A steel pipe carries steam at 200°C the internal diameter of the pipe is 70mm and its thickness is 10mm. it is covered with a layer of insulation 20mm thick. The thermal conductivity of the steel and insulation are 40 W/Mk and 0,025 W/mk respectively. The ambient air temperature is 10°C. The heat transfer coefficient between the steam and the inside surface of the pipe is 5000 W/m²K and that between the outside surface of the insulation and the air is 25 W/m²K. Neglecting radiation heat transfer."

5.1 "Find the rate of loss of heat from the pipe to the air per metre of length."



Convection layers:

$$R_i = \frac{1}{h_1 A} \therefore \frac{1}{5000 \times (2\pi \times 0.035 \times 1)} = 0.0009 \text{ K/W}$$

$$R_o = \frac{1}{h_0 A} \therefore \frac{1}{25 \times (2\pi \times 0.065 \times 1)} = 0.098 \text{ K/W}$$

Conduction layers

$$R_1 = \frac{x_1}{K_0 A_1} \therefore \frac{0.02}{0.025 \times \left( \frac{2\pi \times 0.02}{\ln \left( \frac{0.065}{0.045} \right)} \times 1 \right)} = 2.34 \text{ K/W}$$

$$R_2 = \frac{x_2}{K_1 A_2} \therefore \frac{0.01}{40 \times \left( \frac{2\pi \times 0.01}{\ln \left( \frac{0.045}{0.035} \right)} \times 1 \right)} = 0.00011 \text{ K/W}$$

$$R_{total} = R_i + R_o + R_1 + R_2 \therefore 0.0009 + 0.098 + 2.34 + 0.00011 = 2.44 \text{ K/W}$$

$$\text{Where: } Q = \frac{T_{Total}}{R_{Total}} \therefore \frac{(200-10)}{2.44} = 77.8 \text{ w/m}$$

The rate of heat loss from the pipe to the air per metre = 77.8 w/m

**5.2 “Find the rate of heat loss if an additional 50mm thickness of the insulation is added to the pipe.”**

To find the heat loss the additional layer (R3) must be calculated, additionally RO must be altered to include the new thickness:

$$R3 = \frac{x_3}{K_0 A_3} \therefore \frac{0.05}{0.025 \times \left( \frac{2\pi \times 0.05}{\ln\left(\frac{0.115}{0.065}\right)} \times 1 \right)} = 3.63 \text{ K/W}$$

$$RO = \frac{1}{h_0 A} \therefore \frac{1}{25 \times (2\pi \times 0.115 \times 1)} = 0.055 \text{ K/W}$$

$$R_{new} = Ri + RO + R1 + R2 + R3 \therefore 0.0009 + 0.055 + 2.34 + 0.00011 + 3.63 = 6.02 \text{ K/W}$$

$$\text{Where: } Q = \frac{T_{Total}}{R_{new}} \therefore \frac{(200-10)}{6.02} = 31.5 \text{ w/m}$$

The rate of heat loss after adding an extra layer of insulation is from the pipe to the air per metre = 31.5 w/m

**5.3 “Find the payback period if the extra 50mm of insulation costs £125 per metre of length to install, the pipe operates continuously for 48 weeks per year, and the heat is generated at a cost of 2p per MJ.”**

Calculating the saving difference = Q1 – Q2 = 77.8 – 31.5 = 46.3 J/s/m

Extrapolated to 48 weeks per year = 46.3 x (60 x 60 x 24 x 7 x 48) = 1344 MJ

Total cost = 0.02 x 1344 = £26.88 per metre per year

Therefore the payback period will be:  $\frac{\text{Installation costs}}{\text{saving per metre}} \therefore \frac{125}{26.88} = 4.65 \text{ Years}$

**5.4 Recommendations**

At a payback period of 4.65 years, the extra costs of installing the additional insulation falls beyond the normal acceptable return on investment of ~2-3 years. It would be advisable to consider options of insulation with a higher thermal resistance to increase the savings difference and reduce overall payback period. However the benefits that a change in insulation type may offer must be considered against the potential installation costs and suitability for the intended environment and process.

## **6.0 Conclusions**

Investigating the effects of heat transfer through material as well as the properties of fluid flow and boundary layer friction is paramount when considering practical industry applications. Taking as an example a heat exchanger in hydrocarbon service, the assessment for the potential heat transfer and fluid flow can be greatly beneficial to both the processing efficiency and operational costs of equipment design.

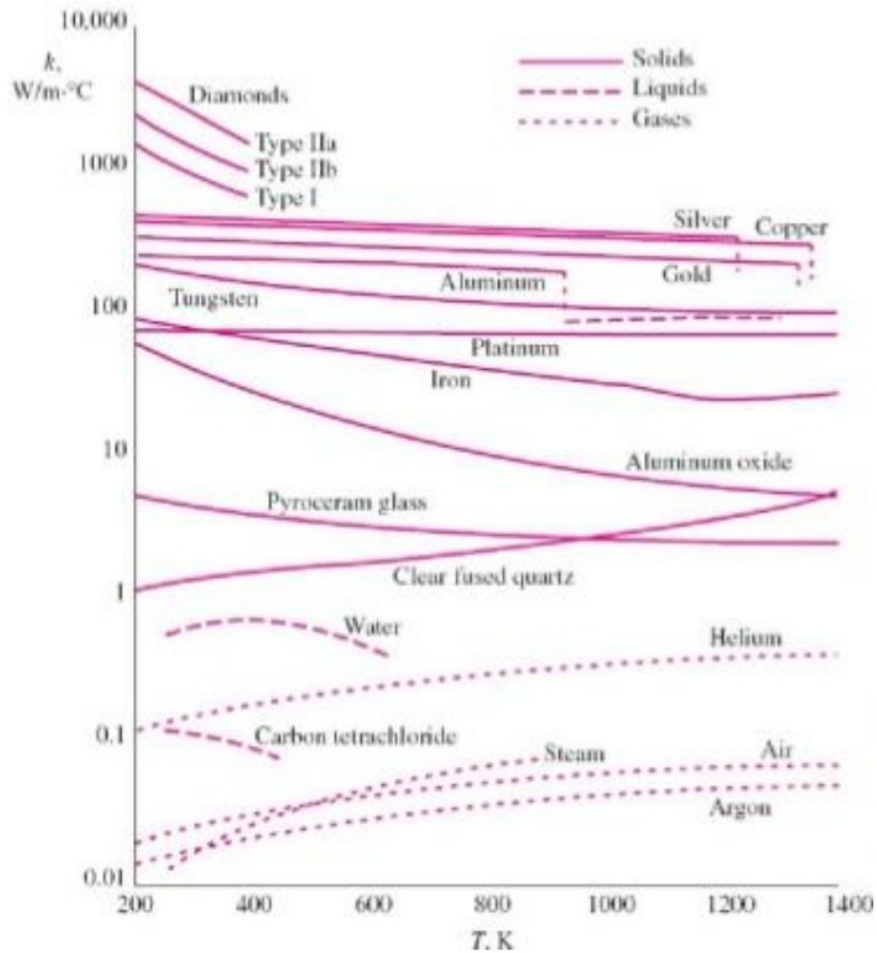
Gaining understanding into the fundamental aspects of thermodynamic relationships and the laws of physics that govern the properties of fluids, allows the engineer the ability to perform theoretical calculations based upon known parameters and established material properties. The resulting indicators informs and justifies decisions when specifying the correct materials for fabrication, dimensions and configuration of design. Furthermore the calculation of heat transfer has the advantages of not only predicting the expected performance of a given material and its associated thermal conductivity, but also providing the capacity for a return on investment analysis through controlled operation and specification of the equipment or system.

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## 8.0 Appendix

### 8.1 Effects of thermal conductivity in relation to temperature



(Cengel, 2011)