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Thermofluids

Assignment 1 – Heat Transfer

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Nomenclature

Symbol	Description	Unit
$\dot{Q}$	Heat loss	J/s
ε	Emissivity	
A	Area	m^2
h	Heat transfer coefficient	W/m^2K
$\dot{E}$	Rate which energy is radiated	Rad
C_p	Specific capacity of fluid	J/m^3K
K	Thermal conductivity	W/m^2K
L	Characteristic length	m
g	Acceleration due to gravity	m/s^2
ξ	Coefficient of expansion	K^{-1}
ΔT	Difference in temperature	$^{\circ}C$ or K
μ	Dynamic viscosity of fluid	$Kg/m/s$
Gr	Grashof number	
Pr	Prandtl number	
Nu	Nusselt number	
Re	Reynolds number	
ρ	Density	Kg/m^3
r_m	Arithmetic mean area	m^2
R	Resistance	K/w

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a)

To begin the topic of heat transfer it is first worth considering the three laws of thermodynamics (Basaran, 2017):

1. Energy is not lost, it gets transferred.
2. As entropy increases so does the amount of disarray between atoms. Entropy is a quantity given to the amount of disorder in an atom.
3. If heat is caused by the motion of particles then there must come a point when all heat is lost and particles completely stop.

Conduction

Heat is a term given to the total *potential* and *kinetic energy* in atoms. Atoms consist of protons, neutrons and electrons. When a material experiences a rise in temperature which is the average kinetic energy within atoms, the electrons move to neighbouring atoms. The atoms without electrons become positively charged. The protons do not transfer to neighbouring atoms, instead they vibrate and create energy which ripples throughout the **material** and raises the overall heat.

Figure 1 shows that heat is lost through material i.e. walls. This is why houses with less insulation are unable to retain their heat. Another example could be the thickness of a duvet. Thicker duvets are better suited for cold winter months whereas thin duvets with less tog values are for the warmer summer months. This is because the thicker duvets *retain* more of the temperature produced by the human body compared to a thinner duvet.

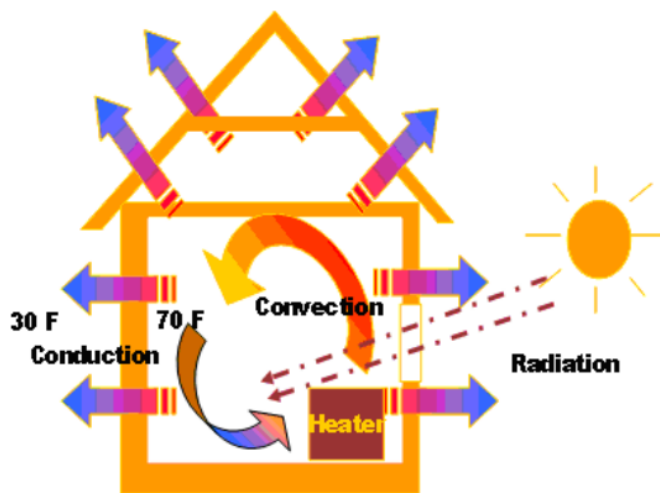


Figure 1 – heat transfer at a household

Convection

Similar to conduction, convection is the movement of heat through fluids. But whereas conduction transfers heat through direct contact between two bodies, convection is the process of cold, dense fluid falling downwards and pushing the warmer and less dense fluid upwards. As seen in Figure 1. This is example of why the ocean breeze tends to be cold, because the hot air has risen and evaporated (Cronin, et al., 2019).

The theory used to define convection is given by Newton's law of cooling:

$$Q = hA (T_2 - T_1)$$

Conduction and convection through the boundary layer of an object

There are instances where conduction and convection are present and acting on the same cross-section of material. For example, consider a pipe with layers of insulation. To calculate the heat lost from the system we would first need to consider the conduction acting on the outside surface of the insulation.

Each layer acts protects the pipe from heat loss, so the majority of ambient temperature will not reach the pipe.

Instead, it will seep into the insulation and settle.

The heat loss is calculated using an electrical analogy similar to Ohm's law.

Where Ohm's law uses Voltage = Current x Resistance, the thermodynamic equivalent uses one of Fourier's law equations, $Q = kA/x (t_1 - t_2)$.

Resistance is equal to x/kA .

Current is equal to Q and $(t_1 - t_2)$ is equal to voltage.

By comparing Newton's law of cooling to Ohm's law we can calculate the resistance within the boundary layer. Using the equation $Q = hA (t_w - t)$. The thermal resistance is given by $R = 1/hA$. From this h is equal to the heat transfer coefficient of the boundary layer.

The value of A can be calculated using either:

The logarithmic mean area (1) or the arithmetic mean area (2):

$$(1) \quad \frac{2\pi (r_2 - r_1)}{\ln \left(\frac{r_2}{r_1} \right)}$$

$$(2) \quad r_m = \frac{r_2 + r_1}{2} \quad \text{where } A = 2\pi r_m$$

Therefore, the total resistance through the boundary layers can be calculated by:

$$R_T = R_1 + R_2 + R_3 + \dots + R_n$$

The overall heat loss is given by:

$$Q = (t_a - t_b) / R_T$$

Figure 2 shows the effect of conductivity and convection through the boundary layer of a wall. The direction of flow is given by Q , the conductivity of heat through the wall. For the first layer where the value of k is equal to one, Figure 2 shows a progressive decline in heat loss. In comparison, when the value for k is equal to two, in the second layer, the illustration demonstrates a rapid decline in heat loss.

The heat transfer through conductivity occurs on either side of the layer, and convection occurs in between where the heat is able to move in air pockets.

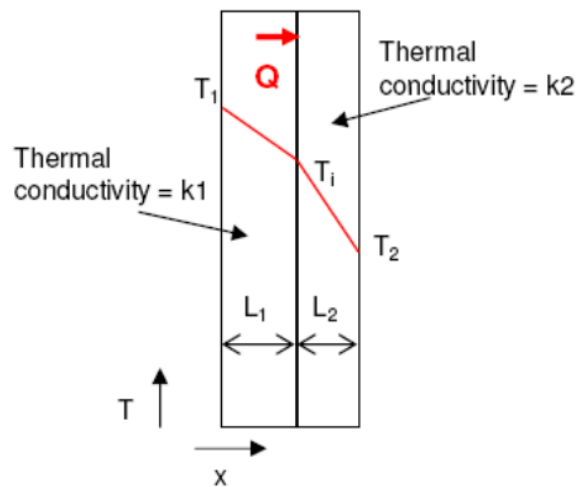


Figure 2 – Heat transfer through boundary layers (EnggCyclopedia, 2020)

(Electromagnetic) Radiation

Radiation is the heat transfer of high temperature to low temperature through regions where perfect vacuum exists. At an atomic level radiation is the imbalance of neutrons and protons within the nucleus. The unstable atom releases energy waves in the form of alpha, beta and gamma waves until it becomes stable again. This is known as radioactive decay. The waves emit heat energy and it is considered that any temperature greater than absolute zero will radiate heat. This is because at *absolute zero* all particles cease to have any energy and no longer move around (National Physical Laboratory, 2020). This definition represents the *third law of thermodynamics*, discovered by Walter Nernst (Masanes & Oppenheim, 2017) .

A "black body" is an object that is able to absorb all radiation it comes into contact with. Therefore a black body material would be suitable as a radiator. For a black body the rate which energy is radiated ($\dot{E}$) can be calculated using the formula:

$$\dot{E} = \alpha \cdot A \cdot T^4$$

For a black body surrounded by a black surface at absolute zero, the equation becomes:

$$\dot{Q} = \sigma \cdot A \cdot (T_1^4 - T_2^4)$$

If the body is not black then as a result of less energy being radiated, the equation used is:

$$\dot{E} = \varepsilon \cdot \alpha \cdot A \cdot T^4$$

Where, ε is the *emissivity* of an object which is the tendency for it to reflect radiation (Björn & Nilsson, 2018). To put the value in perspective a shiny mirror will rank lowest at zero and a black body object will rank highest at one. The value emissivity value can be manipulated by covering an object in black paint or spraying a fluid such as oil on it so that it becomes reflective.

b)

Insulation materials work by resisting the rate of heat loss through heat transfer. As discussed in the previous section conduction is the direct contact between two bodies. Similar to how materials conduct and insulate against electricity, materials react in the same manner to heat. Materials that prevent the roaming of electrons are better insulators because they can keep their balanced charge. Whereas, poor insulating materials lose electrons and become positively charged which creates vibrations which create energy and increases heat, thus conduction takes place. Metals are good conductors of heat and are why the heating element used in many products such as a toaster or radiator is metal. A toaster will quickly glow red suggesting it is very hot, and the material can repeat the conduction process without failure. This is only the case if the heat is within the materials conductive capability range.

Similarly, materials such as plastic and wood make good insulators hence why saucepans either have plastic or wooden handles rather than metal. Fibreglass is another example of a good thermal insulator. The common characteristic between these materials, particularly with wood and fibreglass, is that they restrict the movement of air in pockets of space. That is why houses use a dense fibrous material in the attic (loft insulation) and foam cavity wall insulation on the outside walls. Doors and windows have insulating properties too and they prevent heat loss through convection. Instead they lose heat through conduction but at a lower rate.

A porous material has air pockets known as voids within its microstructure. When heat is transferred through a porous material the atoms become free to move around. The movement of atoms creates vibrations which allows the transfer of heat through conduction; allowing it to continue its path through the material.

c)

Temperature is the average quantity of heat energy amongst atoms measured in degrees Celsius. Temperature and heat can be compared by considering a spark versus a warm bath. A spark is a spontaneous measure of insignificant heat but it has a high temperature and is very hot. In comparison, a warm bath has a lower temperature but has a lot of heat. This is because the water holds pockets of hot fluid which rises to the surface, forcing the colder fluid downwards (Young, 2010). The difference between the two is that a spark is unlikely to change the temperature of the bath, whereas the water would extinguish the spark immediately.

A thermometer is an instrument used to measure the temperature of its surroundings. This is achieved when the mercury within the thermometer has heat energy that is equal to the energy being transferred through conduction by its surroundings. As the heat energy of the mercury increases, the fluid rises. The fluid level is measured on a scale of degrees Celsius or Fahrenheit.

In summary, in order for the temperature of a fluid to change, the thermal conductivity being applied must be constant to show the gradual change. Consider the time it takes to boil a kettle. As the heat energy increases so does the temperature. The increasing movement of molecules in a fluid is known as entropy.

d)

Below are the definitions and expressions given to four dimensionless groups.

Reynolds Number

The Reynolds Number is used to determine the type of flow present in a pipe i.e. laminar, transient or turbulent. Typically the ranges are:

- Laminar = <1000
- Transient = 1000-2500
- Turbulent = >4000

The difference between the types of flow is that a laminar flow has individual boundary layers which flow parallel to each other but do not mix. In contrast, a turbulent flow has no order and the layers mix causing chaos amongst the flow.

The benefit of a laminar flow is that it is predictable and requires less energy to create. Assuming that in testing conditions the same fluid is used so that the viscosity, density and length remain the same, the only remaining factor to determine the type of flow is the velocity. Where time is important i.e. in the production industry, turbulent flow is more beneficial as it reduces time which the fluid travels for.

The Reynolds number can be calculated using the equation:

$$\frac{\rho VL}{\mu}$$

The equation shows the relationship between the type of flow depending on its density, velocity, length of travel and viscosity. If the viscosity increases the Reynold's value decreases. Whereas increasing the density, volume or length will increase the Reynold's value.

Nusselt Number

The Nusselt number provides a ratio between the heat transfer by convection and conduction. The expression given is as follows:

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

As the equation above suggests, an increase in either the Prandtl number or the Reynolds number is proportional to the change of the Nusselt number. Therefore, a laminar flow will be in the low range and a turbulent flow will be in the higher range. Since convection is the movement of fluid in all directions, a greater Nusselt number will indicate a convection system. In contrast, a low Nusselt number will suggest a laminar, conductive flow. Therefore, typical ranges for a conductive system are 1-10 and ranges of greater than 100 are convection (Chordiya & Sharma, 2019).

Prandtl Number

The Prandtl number provides a ratio between heat storage to heat conducted and determines the thickness of the boundary layer. The equation to calculate the Prandtl number is:

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

The equation given from the dimensional analysis shows the relationship between the three groups above. Whilst each of them represent a ratio between certain properties, they link together to state the type of flow, boundary layer and heat transfer.

Typically a laminar flow will have a Reynold's number less than 2000, a thick boundary layer and a Nusselt number of approximately 1. Whereas, a turbulent flow will have a thin boundary layer, a Reynolds number of above 4000 and a Nusselt number of between 100 and 1000.

Grashof Number

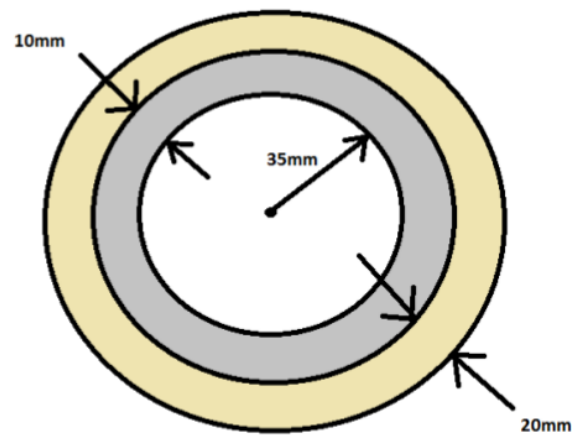
The Grashof number provides a ratio between the buoyancy force due to density and the restraining force due to the viscosity of the fluid.

$$Gr = \frac{gl^3\xi\Delta T}{\nu^2}$$

The Grashof number shows the resisting viscous force that is present when the temperature of a fluid increases, reducing the density thus causing the fluid level to rise. This is known as the buoyancy force. This is important because it is the buoyancy force that controls the flow of natural convection allowing hot fluid to rise and cold fluid to fall. The viscous force acting on the fluid prevents the flow, keeping the fluid hot at the top and cold at the bottom. The Grashof number tells us whether the flow of convection is natural or forced (Al-Afghani, 2017).

e)

i)



$$h_i = 40 \text{ W/mK}$$

$$h_o = 15 \text{ W/mK}$$

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

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

$$R_l = \frac{1}{h_l \cdot A}$$

$$R_l = \frac{1}{40 \times 2\pi \times 0.035 \times 1}$$

$$R_l = 0.11368 \text{ K/w}$$

$$R_o = \frac{1}{15 \times 2\pi \times 0.065 \times 1}$$

$$R_o = 0.1632 \text{ K/w}$$

$$R_1 = \frac{0.02}{0.01 \times \left(\frac{2\pi \times 0.02}{\ln\left(\frac{0.065}{0.02}\right)} \right)}$$

$$R_1 = 18.76 \text{ K/w}$$

$$R_2 = \frac{0.01}{35 \times \left(\frac{2\pi \times 0.01}{\ln\left(\frac{0.045}{0.01}\right)} \right)}$$

$$R_2 = 0.006839 \text{ K/w}$$

Therefore,

$$R_T = 18.93 \text{ K/w}$$

Since,

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

$$Q = \frac{200 - 10}{18.93}$$

$$Q = 10.04 \text{ W/m}$$

ii)

When the insulation is 70mm thick:

$$R_1 = \frac{0.07}{0.01 \left(\frac{2\pi \times 0.07}{\ln \left(\frac{0.115}{0.045} \right)} \right)}$$

$$R_1 = 14.93 \text{ K/w}$$

Therefore,

$$R_T = 14.93 + 0.00114 + 0.1632 + 0.11368$$

$$R_T = 15.2 \text{ w/m (J/J) /m}$$

iii)

$$\text{Payback period} = 15.2 - 6.12802$$

$$\text{Payback period} = 9.07198 \text{ w/m}$$

$$\text{Payback period} = 9.07 (48 \times 24 \times 7 \times 2)$$

$$\text{Payback period} = 146286.96 \quad (-0.146\text{mJ})$$

$$\text{Saving} = 0.02 \times 0.146$$

$$\text{Saving} = 2.92\text{p m/yr}$$

$$\text{Payback period} = \frac{125}{2.92}$$

$$\text{Payback period} = 42.8 \text{ years}$$

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