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Reduction of heat flux losses through the use of thermal insulators

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1 Abstract

In this paper, we will present the application of the **steady-state heat transfer** equation, obtained from Fourier's Law, in the prediction of heat loss reduction in a system composed of several insulators arranged perpendicularly to the heat flow. For this purpose, we will become familiar with the general structure of the heat flow equation applied to a system with several elements arranged in series and in steady state:

$$q=UA\Delta T$$

Where q: heat transfer velocity (W); U: overall heat transfer coefficient A: area perpendicular to the transfer and ∆T: temperature difference between the considered points of a system.

2 Introduction

According to the zeroth law of thermodynamics, heat energy is transferred from high temperature to low temperature zones, in a process that is accompanied by a change of entropy until a state of thermal equilibrium is reached, if possible, characterized by a uniform distribution of temperatures. In a process of heat exchange between bodies at different temperatures, as long as a finite temperature difference is maintained between them, there will be an irreversible flow of heat between these bodies and equilibrium will not be reached. There can, however, be situations in which the macroscopic variables of the system do not change over time. This situation does not correspond to a real state of equilibrium but to a steady state because the temperatures of the different bodies involved and the heat flow between them remain constant over time (Tarrazó, 2002; Tarrazó and Sanjuan, 2005; Conesa 2015).

Heat transfer can take place by three basic mechanisms:

- **Conduction:** heat transfer phenomenon between molecules, i.e. by molecular transfer, where molecules with higher internal energy exchange heat only with adjacent molecules, either by vibration in solids or by vibration and translation in fluids.
- **Convection:** heat transfer phenomenon between groups of molecules with associative capacity and similar internal energy. It occurs only in fluids from the formation of vortexes or turbulences, which can be natural (density difference) or forced with the help of fans, pumps, etc.
- **Radiation:** heating phenomenon associated with the reception of photons in the thermal and microwave spectrum. Any body with a temperature greater than absolute zero emits photons with an energy level proportional to its temperature; these photons are transformed into heat when they reach other bodies depending on their capacity to absorb them. The oven grill, the microwave or the radiant stove are examples of this phenomenon. Another example of this phenomenon is the global warming of the planet by the sun's rays that pass through the atmosphere, are transformed into heat at the moment they come into contact with the Earth's surface and then the Earth is not able to radiate the excess heat due to the excess of carbon dioxide, causing the greenhouse effect.

In chemical, biochemical, biotechnological and microbiological processes, unit operations involving heat transfer phenomena between two points of the system at different temperatures are common. Examples include chemical polymerization reactions, fermentation, sterilization, freezing, drying or freeze-drying, among others. It is common to **use thermal insulators** to limit heat exchange in order to achieve this goal.

Are you ready to see how to design this type of system? *Well, in this document you will find the keys.*

3. Objectives

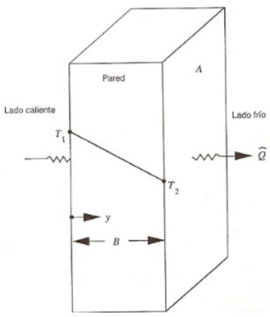
Once you have carefully read this document, you will be able to apply the equation to estimate the heat transfer between two points of a system. To do this, you will have to make a **graphical representation** of the **solid materials** involved in the case study, **including the characteristics** of both the **fluids** and the **solids** involved. Moreover, it will be necessary **to establish whether or not there is variation of the area perpendicular to the transfer** in order to be able to make an adequate prediction of the heat transfer rate.

4 Development

In this section, we will see how to handle the variables of the equations used in the estimation of heat transport by conduction and convection mechanisms from both a theoretical and practical point of view.

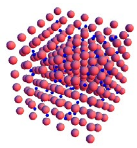
4.1 Fundamentals of steady-state heat transfer

When we are only considering heat transfer within a **solid**, we will apply **Fourier's First Law**. If we think of a surface whose ends are exposed to different temperatures, the heat flow (q/A, where q is the heat transfer rate) will be directly proportional to the thermal conductivity (k) and the temperature gradient between these points and inversely proportional to the distance separating them. It is said in this case, that the **thermal resistance by conduction** is defined as the quotient between the thickness of the material and its thermal conductivity and the area perpendicular to the transfer (A) (Figure 1).



CONDUCTION: Fourier's 1st Law

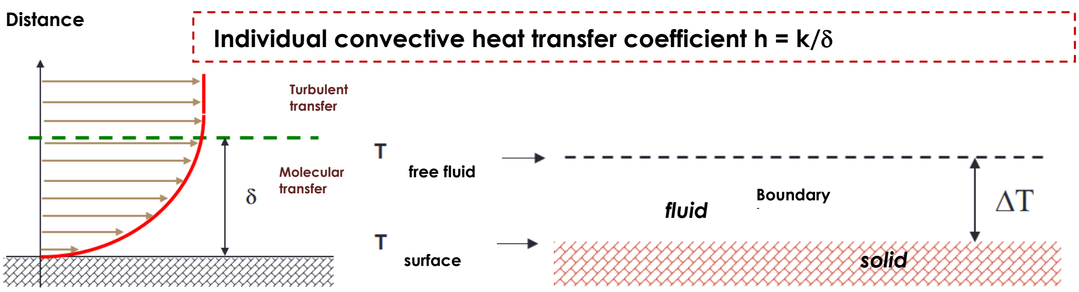
$$\frac{q}{A} = -k\frac{\partial T}{\partial x}$$



$$R_{conduction} = \frac{thickness}{k \cdot A}$$

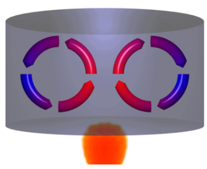
Figure 1. *Representation of heat transfer through a single solid material. Application of Fourier's first law*

In fluids, we have already mentioned that the predominant mechanism is convection. Well, since fluids must always be contained in solid containers (pipes, tanks, walls...), at the interface between the solid and the fluid there is a slowing down of the movement of the fluid molecules. This region is called the **boundary layer** (Bird et al., 2002; Ibarzt and Barbosa-Cánovas, 2005) and it is considered, from a theoretical point of view, the concentration of the resistance due to convection, following an expression similar to Fourier's 1st Law, in which δ is the thickness of the boundary layer and k would be the conductivity of the fluid. Thus, the theory of the equivalent boundary layer arises (Figure 2).



CONVECTION

$$q = -\frac{k}{\delta} \cdot A \cdot \Delta T = -h \cdot A \cdot \Delta T$$

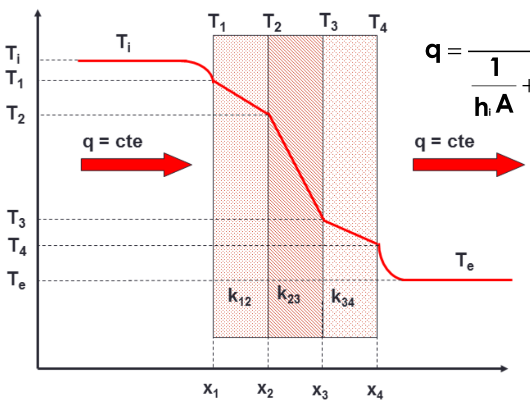


$$R_{convection} = \frac{1}{hA}$$

Figure 2 *Equivalent boundary layer theory*

What happens when conduction and convection occur in combination and we also have several insulating materials placed in series?

In these cases, the heat transferred through a single material is the same as that transferred between all the materials because, as it is in steady state, q=cte. In each section, however, we will have to take the resistance into account. In such cases, we will resort to the overall transmission coefficient (U) and the equation we will use is shown in Figure 3.



$$q = \frac{T_i - T_e}{\frac{1}{h_i A} + \frac{(x_2 - x_1)}{Ak_{12}} + \frac{(x_3 - x_2)}{Ak_{23}} + \frac{(x_4 - x_3)}{Ak_{34}} + \frac{1}{h_e A}} = \frac{T_i - T_e}{\frac{1}{U \cdot A}}$$

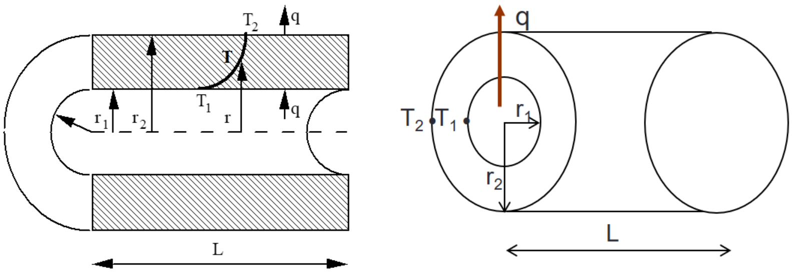
$$\frac{1}{UA_{ref}} = \sum_j \frac{1}{h_j A_j} + \sum_i \frac{e}{k_i A_i}$$

Figure 3*. Arrangement of several materials in series where there is conduction and convection. Overall heat transfer coefficient (U)*

In this case, the unit divided by the overall heat transfer coefficient and the reference area perpendicular to the transfer (A_{ref}) will be the sum of the resistances due to convection and the resistances due to conduction. In the example in Figure 3, the schematic represents a flat wall with several materials in series, but,

What is the treatment for the lining of a cylindrical pipe or a cylindrical tank with different insulators?

In these situations, the area perpendicular to the transfer will not be constant, but will depend on the distance between the layer under study and the centre of the cylinder. Therefore, the **mean logarithmic area (A_{ml})** is used to calculate the resistances due to conduction (Figure 4). For the resistance due to convection, we will use the lateral area of a cylinder (A=2πrL), using the corresponding radius in each case (inner or outer). Here, the overall transfer coefficient will have to be referred to the internal or external area (A_{ref}).



$$A_{ml} = \frac{2\pi L(r_2 - r_1)}{\ln \frac{r_2}{r_1}}$$

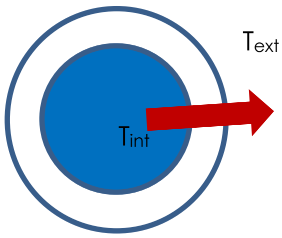
***Figure 4**. Representation of the variation of the area perpendicular to the heat transfer on cylindrical surfaces and adjustment by the logarithmic mean area (A_{ml}).*

4.2 Case study approach

As the best way to see how to work with the equation q=UAΔT is by means of a case study, **let's** assume that we have to **design a cylindrical tank that is going to be used to maintain a liquid at a constant temperature** by the application of a heat source at its base. The liquid will be perfectly agitated in order to avoid temperature profiles. There are 4 technical possibilities depending on the composition of the tank walls (Figure 5).

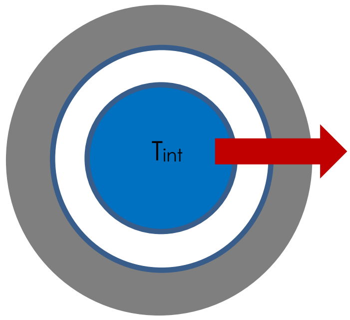
Possibility 1:

a single layer of glass (white layer)



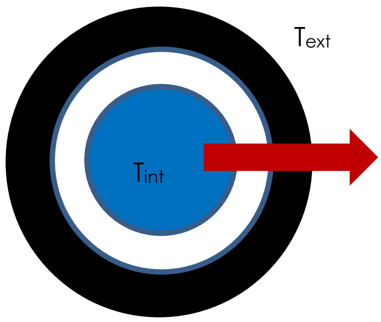
Possibility 2:

a layer of glass and a layer of type 1 insulator (grey layer)



Possibility 3:

a layer of glass and a layer of type 2 insulator (black layer)



Possibility 4:

Layer of glass and layer of type 1 or 2 insulator of double thickness (selecting the one that provides more insulation))

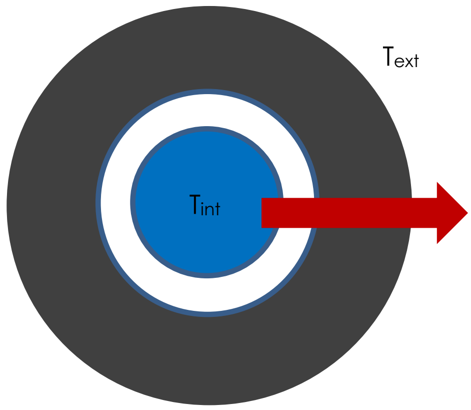


Figure 5. *Configuration of the 4 possible technical solutions for the design of a cylindrical tank*

4.2.1 Application of experimental data to evaluate heat loss effectiveness

Let's assign some values to the case. To do so, we will consider that the liquid maintained at 50°C is water and that the temperature of the environment where the tank is located at 25°C. The information we need to deal with this case is shown in Tables 1 and 2.

Table 1*. Dimensions of the tank and thickness of the materials (mm)*

Height	**110**
External diameter	**85**
Glass	**6.2**
Insulation 1. Cross linked polyethylene	**10**
Insulation 2. Polychloroprene	**10**

***Table 2.** Thermal conductivities (W/m°C) of materials and individual heat transfer coefficients (W/m²°C) of water and air*

$k_{polcrosslinked\ polyethylene}$	**0.04**
$k_{polychloroprene}$	**0.2**
k_{glass}	**0.8**
$h_{external}$ (ambient air)	**40**
$h_{internal}$ (water at 50°C)	**2000**

Do you feel up to calculating the heat loss rate (q) for each possibility?

Based on the results, we will be able to calculate the percentage reduction in heat loss compared to possibility 1 (no insulation) and decide which is the most efficient. In addition, we could also calculate the outside surface temperature of the tank.

1st) Obtain the value of the interface radii of the materials.

r_1 (inner radius of the glass tank) = r_2- glass thickness=0.0363 m

r_2 (outer radius of glass tank) =outer tank diameter/2= 0.0425 m

r_3 (outer radius of the tank with an insulator) = r_2+insulating thickness= 0.0525 m

r_4 (outer radius of the tank with two insulators) =r_3+insulating thickness=0.0625 m

2nd) Calculate the heat loss rate with the formula q=UAΔT

$$q_{possibility\ 1} = -\frac{(25-50)}{\frac{1}{2\pi\cdot 0.110\cdot 0.0363\cdot 2000}+\frac{ln\left(\frac{0.0425}{0.0363}\right)}{2\pi\cdot 0.110\cdot 0.8}+\frac{1}{2\pi\cdot 0.110\cdot 0.0425\cdot 40}}$$

$$q_{possibility\ 1} = -\frac{2\pi 0.110\cdot(25-50)}{\frac{1}{0.0363\cdot 2000}+\frac{ln\left(\frac{0.0425}{0.0363}\right)}{0.8}+\frac{1}{0.0425\cdot 40}} = \mathbf{21.6\ W}$$

$$q_{possibility\ 2} = -\frac{2\pi 0.110\cdot(25-50)}{\frac{1}{0.0363\cdot 2000}+\frac{ln\left(\frac{0.0425}{0.0363}\right)}{0.8}+\frac{ln\left(\frac{0.0525}{0.0425}\right)}{0.04}+\frac{1}{0.0525\cdot 40}} = \mathbf{2.9\ W}$$

$$q_{possibility\ 3} = -\frac{2\pi 0.110\cdot(25-50)}{\frac{1}{0.0363\cdot 2000}+\frac{ln\left(\frac{0.0425}{0.0363}\right)}{0.8}+\frac{ln\left(\frac{0.0525}{0.0425}\right)}{0.2}+\frac{1}{0.0525\cdot 40}} = \mathbf{9.9\ W}$$

As can be seen, when considering possibility 2 the heat losses are smaller than those of possibility 3, so we would select cross-linked polyethylene as the insulating material instead of polychloroprene. Thus, in possibility 4, we would consider a double layer of polyethylene to see if it would be convenient to incur a greater cost and take up more space in the tank lining to ensure it is thermally sealed.

$$q_{possibility\ 4} = -\frac{2\pi 0.110\cdot(25-50)}{\frac{1}{0.0363\cdot 2000}+\frac{ln\left(\frac{0.0425}{0.0363}\right)}{0.8}+\frac{ln\left(\frac{0.0625}{0.0425}\right)}{0.04}+\frac{1}{0.0625\cdot 40}} = \mathbf{1.7\ W}$$

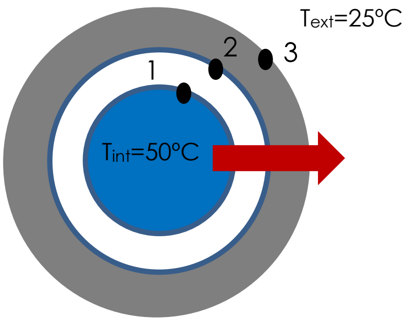
3rd) <u>Deduce the percentage of heat loss reduction, predict a temperature or the percentage of resistance due to conduction or convection</u>

For the former, we will apply the following formula:

$$\%\ Reduction = 100\cdot\frac{\left(q_{only\ glass} - q_{with\ insulator/s}\right)}{q_{only\ glass}}$$

Therefore, the percentage reduction of heat losses using a 1 cm thick cross-linked polyethylene layer would be 86.6%. If the thickness of this material were 2 cm, the reduction would be 92.2%. However, polychloroprene would only provide a reduction of 54.2%. The choice of material would obviously also depend on economic considerations, as well as other technical aspects (flame retardancy, stability, ease of cleaning, etc.).

Suppose we were to calculate the temperature in the outer layer of the tank. In this example, the fluid inside the tank is not very hot (50°C), but in another situation, we could be working at dangerous temperatures that would put the industrial operators at risk. Therefore, if we wanted to know the temperature in the outermost part of the tank (T_3) using the 1 cm polyethylene insulation and knowing that q=constant, we would proceed as shown in Figure 6.



$$q_{int\rightarrow ext} = q_{3\rightarrow ext} = \frac{-(T_{ext} - T_3)}{\frac{1}{h_{ext}A_{ext}}}$$

$$T_3 = q_{3\rightarrow ext}\cdot\frac{1}{h_{ext}A_{ext}} + T_{ext} = 27\ ℃$$

Figure 6. *Estimation of the temperature of the tank's outermost layer*

Another important aspect to take into account is the percentage of resistance that is considered to be due to conduction or convection. Thus, for example, in possibility 2 we would say that:

$$\%\ Resistance_{\ conduction} = 100\frac{\sum\frac{thicknesses}{K_i A_{ml}}}{\frac{1}{UA_{ref}}} = 100\frac{7.93}{7.93+0.71} = 91.8\%$$

$$\%\ Resistance_{\ convection} = 100\frac{\sum\frac{1}{h_j A_j}}{\frac{1}{UA_{ref}}} = 100\frac{0.71}{7.93+0.71} = 8.2\%$$

5 Closing statement

In summary, in this article we have seen how to predict the rate of heat transfer by conduction and convection when there are several materials in a system, analyzing the variation of the area perpendicular to the transfer in cylindrical systems. For this purpose, we have calculated the resistances due to conduction or convection. Finally, we have calculated how to predict the heat loss reduction according to the insulator and its thickness. In this way, we will be able to select the most suitable and efficient technical solution to avoid energy transfer.

6 Bibliography

Bird, R.B, Stewart, W.E. y Lightfoot, E.N. (2002). Transport Phenomena, Revised 2nd Edition, Editorial: Wiley & Sons Inc. New York (EEUU).

Conesa, J.A. (2015). Mecanismos de transferencia de calor. https://www.ingenieriaquimica.net/recursos/384-mecanismos-de-transferencia-de-calor

Ibarz, A. y Barbosa-Cánovas G.V. (2005). Operaciones unitarias en la ingeniería de alimentos. Editorial Mundi-Prensa

Tarrazó, J. (2002). Introducción a las operaciones básicas en la ingeniería de alimentos. Editorial UPV.

Tarrazó, J., Sanjuán N. (2005). Problemas de ingeniería de procesos en las industrias agroalimentarias. Editorial UPV.