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Parametric Study of Transient Heat Conduction on Common Geometrical Configurations Using a Graphical User Interface

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In general heat transfer, which is the science that studies the rate of energy transfer, has an extensive working area ranging from biological systems to common household appliances, industrial processes, electronic devices, among others. For engineers, it is necessary to have a complete understanding of this phenomena to design the best equipment that gives the highest efficiency and save the maximum energy possible. Most of the study about heat transfer is addressed to the steady state because systems remain in that state most of the time. However, there are always perturbations that cause variability on the systems producing complications that require immediate attention by the implementation of control of processes. For that reason, it is necessary to know the dynamic behavior of the systems by understanding their transient state. In heat transfer, these systems are designed with different shapes that can be sectioned and studied separately with the use of the common configurations such as walls, cylinder, and spheres. In this article, it is presented a parametric study of Transient heat transfer processes which often involve the use of partial differential equations that normally require rigorous computational tools, and their analytical solutions require severe mathematical methods. With the help of an easy to use Graphical User Interface (GUI) developed in Matlab, three case studies will be presented for common geometrical configurations typical of a heat transfer course. It was found the temperature profile in a transient state for cylinders, walls, and spheres using numerical methods of solutions, and the temperature as a function of the convective heat transfer coefficient for the same configurations. It will be shown the effect of the convection on the loss of heat of walls, cylinders, and spheres with the same volume as a function of time.

1. Introduction

Heat transfer covers a wide range of systems from biological to common household appliances, industrial processes, and electronic equipment. In most cases, unit operations in the chemical process industry require an exchange of a large amount of energy needed for different process requirements that need to work at a controlled temperature so that each process operates at high efficiency (Nagarani et al., 2014). To reach that goal it is necessary the use of different types of heat exchangers ranging from plate heat exchangers to fin heat exchangers.

There are many variables involved in the design of a heat exchanger such as the fluid velocities, the fluid temperature at the exits, number of tubes, diameter and length of tubes, number and geometrical configuration of deflectors, overall heat transfer coefficient, maximum pressure drop allowed, and thermal conductivity of the heat exchanger material. This number of variables and their interaction makes extremely necessary for engineers to have a broad knowledge of the fundamentals of heat exchangers. It is usually learned theoretically and experimentally in engineering colleges, but it takes too much time to run many experiments to understand the effect of all the variables in the performance of a heat exchanger in a short time. For that reason, it is necessary to include in the chemical and mechanical engineering undergraduate curriculum some easy to use programs such as STHEX-UA (Obregon et al., 2015), which is a software used to design shell and tube heat exchangers, or CTw-UA v1.0 (Obregon et al., 2017) that is used to design cooling towers. Both software let undergraduate students manipulate different variables that let to understand the phenomena happening internally inside both types of equipment. Engineers need to have a full understanding of all the phenomena

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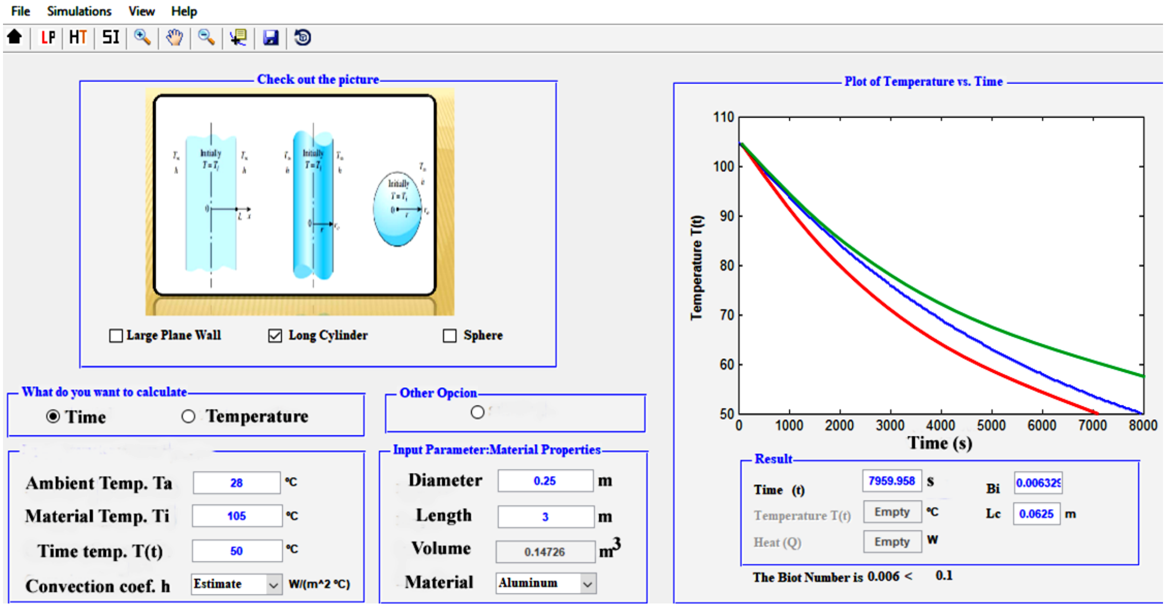
during the design of the best equipment to obtain high efficiency and to save the highest amount of energy possible. Most of the study about heat transfer is made in the steady state. However, there are always perturbations in operating variables that cause changes in the output variables of the equipment causing problems that require fast correction by the application of control of processes. It shows the necessity to study transient state behavior in these systems. Many interesting studies about simulation in this area has been done, for instance, simulation of transient responses of the U type plate heat exchanger (Dwivedi and Das, 2007), transient study on mini-channel regenerative heat exchangers (Alfarawi et al., 2017), A transient heat transfer study of a thermally enhanced solar absorber PV plate using simple thermal, optical and electrical models (Paradis et al., 2017), simulation of shell-and-tube heat exchangers in steady-state and transient state (Bonilla et al., 2017), numerical model to make transient simulation of borehole heat exchangers (Biglarian et al., 2017), and transient heat transfer study of an air-cooled condensing heat exchanger in a long-term passive cooling system (Kim et al., 2017) . However, those are advanced studies for specific systems difficult to understand for newly graduated engineers or senior engineering students.

The main contribution of this article is the simulation of transient heat transfer by conduction for the most common configurations with the development of a Matlab graphical user interface giving to engineers an easy computational tool to study the different patterns obtained. Three case studies are presented, the temperature profile in transient state as a function of the type of material for cylinders, walls and spheres, the temperature as a function of distance and time for the different configurations, and the total heat transferred at different times for different convective heat transfer of the fluid in contact with the surface of the system.

2. Material and method

2.1 Presentation of the GUI

It can be seen in Figure 1 the main view of the developed software. This computational tool was registered in the National Leadership Copyright. The graphical user interface shows some of the inputs that can be given by the user. It simulates the temperature on common geometrical configurations. The effect of thermal and convective conductivity on the temperature and heat transferred can be studied. This graphical user interface allows engineers and students to have a better comprehension of heat transfer in a transient state.



☐ Large Plane Wall ☑ Long Cylinder ☐ Sphere

What do you want to calculate
● Time ○ Temperature

Other Opcion
○

Ambient Temp. Ta 28 °C
Material Temp. Ti 105 °C
Time temp. T(t) 50 °C
Convection coef. h Estimate W/(m^2 °C)

Input Parameter:Material Properties
Diameter 0.25 m
Length 3 m
Volume 0.14726 m^3
Material Aluminum

Result
Time (t) 7959.958 s
Temperature T(t) Empty °C
Heat (Q) Empty W
Bi 0.00632
Lc 0.0625 m

The Biot Number is 0.006 < 0.1

Figure 1: Main graphical user interface of the program

2.2 Flowchart of the program

As can be seen, Figure 2 shows the sequence of actions of the program that let to perform the calculations of the transient heat transfer system chosen.

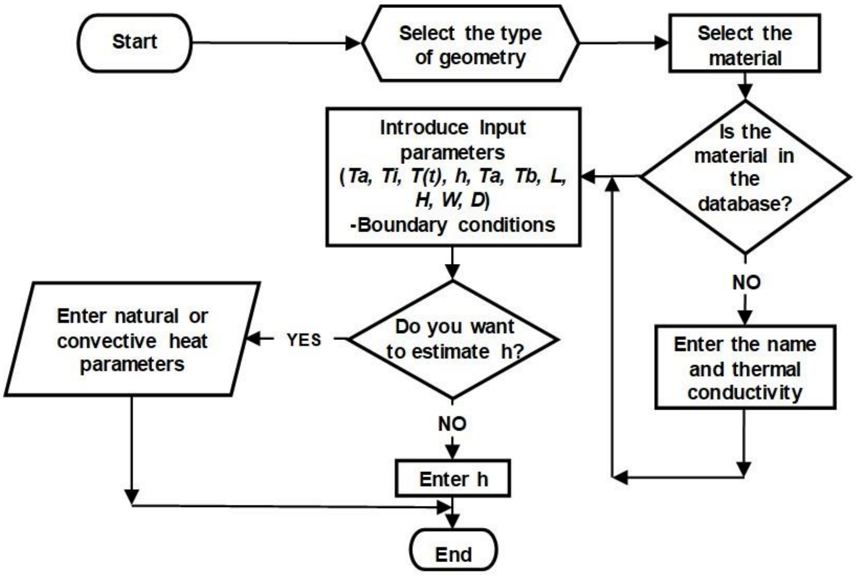


Figure 2: Schematic diagram of the software algorithm

2.3 Main relations used in the algorithm

The unidimensional transient heat conduction can be expressed as follow:

$$\frac{\partial^2 T}{\partial x^2} = \frac{1}{\alpha}\frac{\partial T}{\partial t} \tag{1}$$

where α is the thermal diffusivity of the solid. The solution of Eq(1) depends on the geometry as shown in Table 1.

Table 1: Solutions for equation 1 in a plane wall, a cylinder, and a sphere

Geometry	Solution	Roots
Plane wall	$\frac{T-T_\infty}{T_i-T_\infty}=\sum_{n=1}^{\infty}\frac{4 sen\lambda_n}{2\lambda_n+sen(2\lambda_n)}e^{-\lambda_n^2\alpha t/L^2}\cos(\lambda_n x/L)$	$\lambda_n \tan\lambda_n = hL/k$
Cylinder	$\frac{T-T_\infty}{T_i-T_\infty}=\sum_{n=1}^{\infty}\frac{J_1\lambda_n}{J_0^2(\lambda_n)+J_1^2(\lambda_n)}e^{-\lambda_n^2\alpha t/r_o^2}J_0(\lambda_n r/r_0)$	$\lambda_n\frac{J_1(\lambda_n)}{J_0(\lambda_n)}=hr_o/k$
Sphere	$\frac{T-T_\infty}{T_i-T_\infty}=\sum_{n=1}^{\infty}\frac{4(sen\lambda_n-\lambda_n\cos\lambda_n)}{2(\lambda_n)-sen(2\lambda_n)}e^{-\lambda_n^2\alpha t/r_o^2}\frac{sen(\lambda_n x/r_0)}{\lambda_n x/r_0}$	$1-\lambda_n\cot\lambda_n = hr_o/k$

Where T_i is the initial temperature of the solid, T_∞ is the fluid temperature, h is the convective coefficient of the fluid, k is the thermal conductive coefficient of the solid, J_0 and J_1 are the Bessel functions of the first kind. The solutions shown in Table 1 correspond to a plane wall of thickness $2L$, a cylinder of radius r_0 and a sphere of radius r_0 subjected to the convention from all surfaces.

3. Result and discussion

The study was done with different geometrical configurations, plane wall, cylinder, and sphere. The three geometries had the same volume (0.3 m^3). The right and left sides of the plane wall have heat transfer with symmetry.

3.1 Time dependence of the heat transfer rate

It was given the following parameters to study the heat transfer behavior: the ambient temperature (28 ^{o}C), the surface temperature of the solid (105 ^{o}C), and the convective heat transfer coefficients in W/(m^2 ^{o}C). The materials used are shown in Table 2.

Table 2: Properties of solid materials used in the simulations

Material	K, W/(m^{o}C)	ρ, Kg/m^3	Cp, J/(Kg^{o}C)
Pure Aluminum	236	2707	903
Pure Iron	76	7870	447
Stainless steels	55	7855	434

Figure 3 shows the total heat transferred (Q) to the air at a specific time. For the three geometries studied, the higher the time, the higher the total heat removed. However, the importance focusses in the effect of the convective heat transfer coefficient (h) on the total heat transfer. High values of h involve a high heat removal. In a plane wall, at low convective coefficients, the removed heat is almost linear with the time. It gets exponential when h increases, reaching a high heat removal in a short time. In cylinders and sphere, the pattern of Q is linear with the time for all the convective coefficients as seen in Figure 3. However, the increments in heat removal with increments in convective coefficient are almost linear as well. The best heat transfer removal results are found when h=40 W/m^{2o}C for plane walls. Cylinders present results similar to sphere due to their curvilinear shape, but cylinders have better behavior than spheres. These results are important when applying process control because of the fast response obtained at high fluid velocity (high values of h).

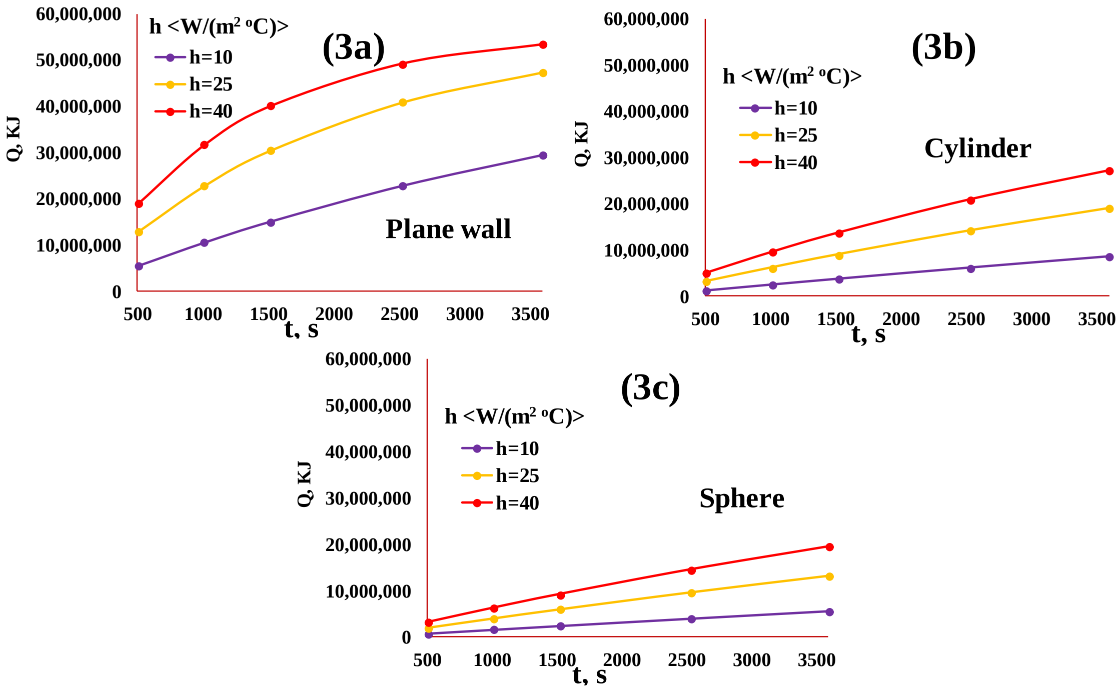


Figure 3: Behavior of the total heat transfer as a function of time, for different convective heat transfer coefficient in the geometries (a) plane wall, (b) cylinder, and (c) sphere. Material used: aluminium

In Figure 4a, b, and c, the heat removal follows the same pattern mentioned in Figure 3. They have the same behavior with a small difference when using aluminum. The best results are found in stainless steel and iron because of their similarities in their physical properties, see Table 2. If it is wanted to remove the heat the faster possible way, it is recommended to work with metal with properties similar to the properties of iron and stainless steel.

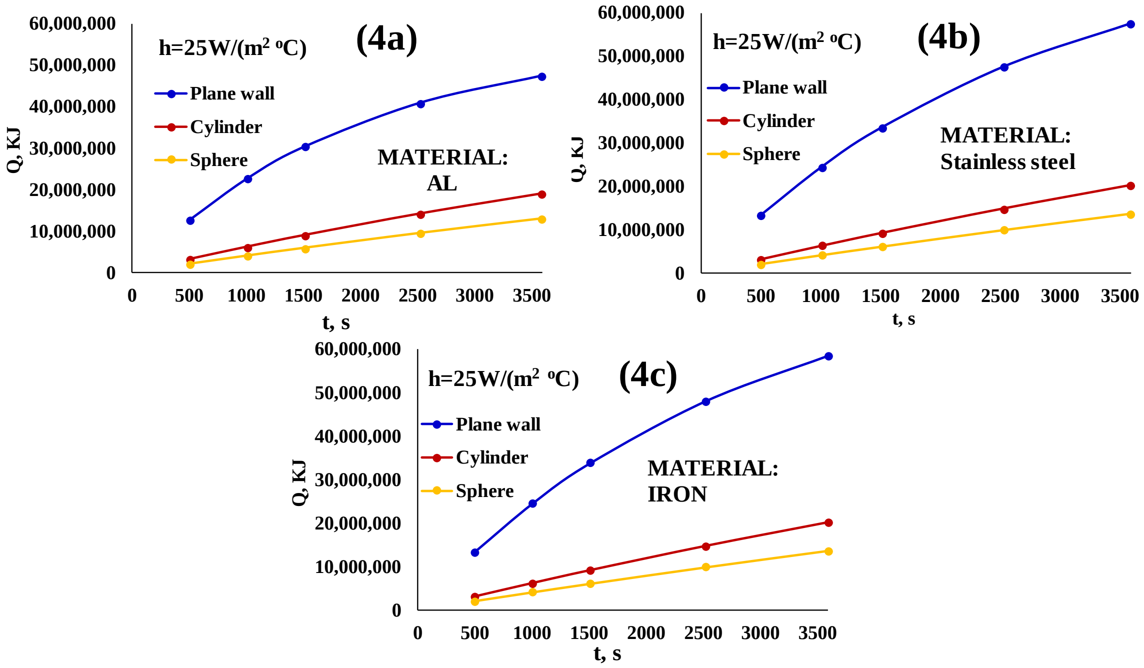


Figure 4: Behavior of the total heat transfer as a function of time for different geometries and the materials (a) Aluminum, (b) Stainless Steel, and (c) Iron

3.2 Effect of convection in the surface temperature profile for different geometries

As can be seen in Figures 5a, b, c, and d, the temperature decreases all the time trying to reach the steady state. Low values of convective coefficients make the decrease in temperature almost linear. However, when h increases the temperature decays exponentially. The pattern is linear when working with cylinders even working with different materials. The temperature profile of the sphere was not shown, but it was similar to the one of the cylinder. The profiles obtained in each plot help to decide on control parameters due to the temperature response for the different geometries shown.

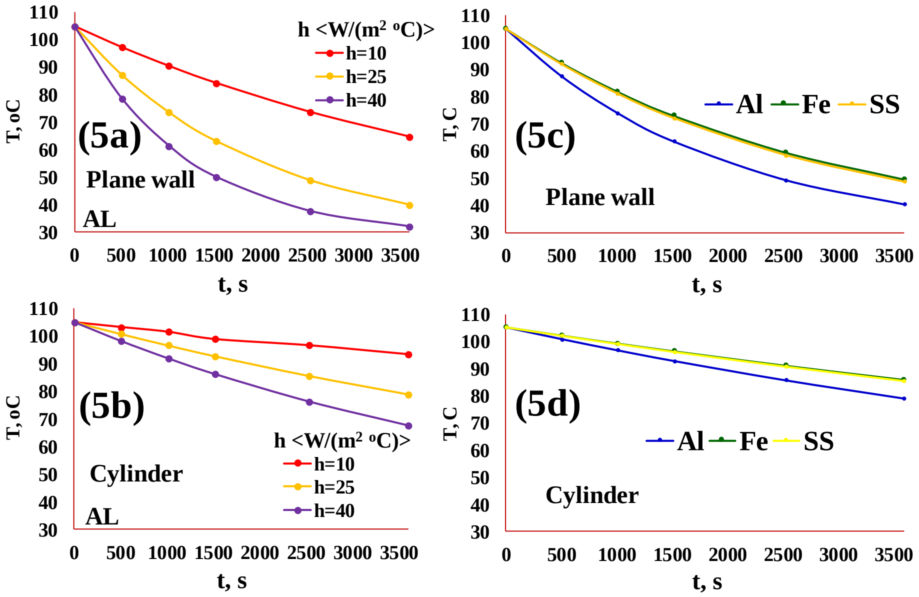


Figure 5: Temperature profile as a function of time for different convective coefficient (Left side) and materials (right side), for the geometries (a), (c) Plane wall, (b),(d) Cylinder.

One important consideration when working with any of the mentioned geometries is the convective heat transfer coefficient. It is necessary to work with fluids with high values of *h* to remove the highest amount of heat in the shortest time.

As can be seen in Figures 3, 4 and 5, with the choosing the geometry and some input parameters in the software it can be obtained the time-dependence heat rate as well as their dependence with the fluid velocity which is directly related to the convective heat transfer coefficient. The rate of decrease of temperature is of high importance in the heat treating for metal creation. For instance, steel has different layer formation depending on the rate of cooling and this process is called age hardening. Figure 5 help to choose the parameter of control of process needed to control the temperature depending on the final characteristics of the metal hardness. This friendly use of the software gives the student the possibility to understand the behavior of transient phenomena more easily and go beyond the limit of knowledge offered by a traditional curriculum of a chemical and mechanical engineering program.

4. Conclusions

It was designed a valuable computational tool that helps to increase in engineers and senior students their capacity to analyze the heat and temperature behavior in solids with common geometrical shapes. The geometries studies were a plane wall, a cylinder, and a sphere. High removal of heat is favored at high values of convective coefficients for any geometrical configuration. Different patterns of heat removal with time were obtained at different convective coefficient. It was linear at values of h near 10 W/(m^2 ^oC) and exponential at values near 40 W/(m^2 ^oC). It means that equilibrium is reached faster for high external fluid velocity. This is an important result to consider when applying process control because of the fast response obtained at high fluid velocity. In cylinders and spheres, the pattern of heat rate was linear during all the time for any value of the convective coefficient. Iron and stainless steel presented the best heat rate removal. The best heat removal was found with the highest value of h=40W/(m^2 ^oC) for the geometry plane walls. The temperature-time dependence is linear at low values of the convective coefficient for all the geometries. However, it had an exponential decay at high values of convective coefficient only for plane walls. The trend of decrease of temperature indicates that there is a limit of fluid velocity where the temperature behavior will remain with no variation. The results obtained help to decide about the values of the parameters of process control due to the time-temperature response for the different geometries shown. One example is during the control of temperature in the process of metal creation. The crystallization of the metal, as well as its hardness, depends on the rate of decrease of the temperature. Considering the importance of process control in the systems studied it will be created new subroutines in the software to determine the control parameter necessary to obtain the temperature response desired.

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