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# Development of an Educational Software in Matlab® for Transient Heat Transfer Analysis

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**Abstract**

Transient heat transfer processes often involve partial differential equations that normally require rigorous computational tools, and their analytical solutions require severe mathematical methods. This paper presents a user-friendly educational software developed in Matlab for the learning of the transient heat transfer phenomena addressed to undergraduate engineering students. The software is also supported by three case studies that contain the most useful information about theoretical, practical, and pedagogical aspects of a typical heat transfer course. A group of engineering students from Universidad del Atlántico were chosen to solve three case studies with and without the help of the software. A pretest and a posttest were made to evaluate statistically their performance for the two situations using a paired sample analysis, which allowed to determine, at a 95% level of confidence, the existence of a significant effect when implementing the software. The p-value obtained was lower than 0.05 indicating a positive effect in the use of the software becoming a support for teaching the concepts involved in transient heat transfer processes, promoting critical thinking in students, and meaningful learning.

**Keywords**: Matlab, Computational Tool, Learning, Transient Heat Transfer

## 1. Introduction

Most of the unit operations in the chemical process industry imply exchange of energy, arising the need to recover the available heat in different ways to save fuel and increase the profitability of the process. The electronics equipments, as well as, transformers, refrigerators and compressors, need to remove efficiently the heat in order to operate at its optimum temperature [1], and to achieve it, students of chemical, processes and mechanical engineering need to fully understand the basic concepts related to the heat transfer phenomena. Considering that the undergraduate courses of heat transfer tend to be extensive and are not completely covered in an academic period, it is necessary to find different ways to study all topics, mainly the fundamentals associated with the solution of the partial differential equations governing heat transfer in transient state. Some studies focused in solving numerically the equations that govern the phenomenon of heat transfer in transient state [2-4]. Some mathematical models have been developed to study different parameters of the transient heat transfer [5, 6] with analytical solutions that require the knowledge of advance mathematical concepts such as Fourier transform, Bessel, and infinite series, which are not usually studied in depth in heat transfer courses [7]. Alternatively, computational sciences play an increasingly important role in teaching processes in engineering undergraduate subjects, improving learning, developing cognitive and self-regulatory meta-skills [8-10]. Some computational tools have been developed to solve problems in heat transfer helping the understanding of physical problems by the students [11, 12]. Virtual learning environments and computational learning tools promote analytical thinking skills in students and offer a substantial change in traditional teaching methodologies [13]. Some researchers have developed computational tools to support the understanding of the heat transfer fundamentals, which include graphical visualization [14]. As mentioned above, it is evident that computational tools facilitate teaching-learning processes, and even more in subjects whose approach is theoretical-practical such as heat transfer.

The main contribution of this article is the development of a software called HT-Transient, which is a Matlab graphical user interface that simulate the transient heat transfer by conduction for common configurations, as well as, for semi-infinite solid and concentrated systems, providing to students and engineers a reliable tool to study, interpret and understand the fundamentals of the phenomenological process. In addition, the software promotes critical thinking on the user due to the rigorous case studies proposed to solve.

## 2. Methodology

The HT-Transient software, see Figure **1**, is a Matlab computational tool that can be used by undergraduate engineering students to improve their learning process on transient heat transfer. The learners access the information in a novel method, acquiring high levels of interactivity, becoming highly motivated in reaching their goals improving their own learning system. The software allows the professor to simulate laboratory experiments which let students to become more involved in the development of transient heat transfer concepts that help them to understand experiments so much easier supported in the HT-Transient graphical user interface. It let students to understand the processes of transient heat transfer by means of 3D plots and by solving some case studies to clarify the concepts related to this subject.

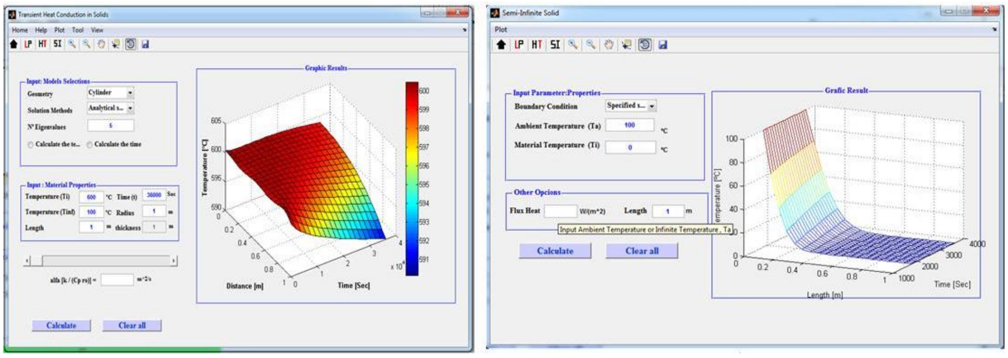

**Figure 1**. HT-Transient Software - input data

## 3. Fundamental Equations

The bodies whose temperature do not change with respect to their position are called Concentrated Systems [7], and the temperature T only depend on the time,

$$\frac{T_{(t)} - T_{\infty}}{T_i - T_{\infty}} = e^{-bt} \tag{1}$$

where $b = hAs/\rho VCp$ and the terms $b$, $h$, $As$, $\rho$, $V$, and $Cp$ represent the time constant, convective coefficient, surface area, density, volume and specific heat respectively. Solving the equation (1), it is possible to determine the temperature. The heat transfer by convection between the body and its surrounding fluid can be determined using the fundamental equation of the Newton's Law of Cooling,

$$Q_{(t)} = hA_S\left(T_{(t)} - T\right) \tag{2}$$

In the case of a plane wall, considering constant the physical properties, without generation of heat, and uniform initial temperature, the problem of unidimensional transient heat conduction can be expressed according to the governing equation (3).

$$\frac{\partial^2 T}{\partial x^2} = \frac{1}{\alpha}\frac{\partial T}{\partial t} \tag{3}$$

This differential equation can be solved applying several analytical techniques. Table 1 shows the analytical solutions [7] coded in the software.

**Table 1**. Summary of the solutions for one-dimensional transient conduction

| Geometry | Solution | Roots |
|---|---|---|
| Wall | $\theta = \sum_{n=1}^{\infty} \frac{4 sen\lambda_n}{2\lambda_n + sen(2\lambda_n)} e^{-\lambda_n^2 \tau} \cos(\lambda_n x / L)$, | $\lambda_n \tan\lambda_n = Bi$ |
| Cylinder | $\theta = \sum_{n=1}^{\infty} \frac{J_1 \lambda_n}{J_0^2(\lambda_n) + J_1^2(\lambda_n)} e^{-\lambda_n^2 \tau} J_0(\lambda_n r / r_0)$ | $\lambda_n \frac{J_1(\lambda_n)}{J_0(\lambda_n)} = Bi$ |
| Sphere | $\theta = \sum_{n=1}^{\infty} \frac{4(sen\lambda_n - \lambda_n \cos\lambda_n)}{2(\lambda_n) - sen(2\lambda_n)} e^{-\lambda_n^2 \tau} \frac{sen(\lambda_n x / r_0)}{\lambda_n x / r_0}$ | 1- $\lambda_n \cot\lambda_n = Bi$ |

In the solutions presented previously $\alpha$, $t$, $L$ and $Bi$ represents the thermal diffusivity of the material, time, length and Biot number respectively. The solutions of equation (3), allow to obtain the heat transfer fraction from the calculated heat using equation (4) for each of the configurations presented in Table 1

$$\frac{Q}{Q_{\max}} = \frac{\int \rho C_P \left[T_{(x,t)} - T_i\right] dV}{\rho C_P \left[T_\infty - T_i\right] V} = \frac{1}{V}\int_V (1-\theta) dV \tag{4}$$

In the case of idealized bodies extended infinitely in all directions, the temperature variation in the body depend on the thermal conditions of a single surface [7], and is calculated by equation (3). For large bodies, some mathematical solution tools have limitations, and considering the boundary conditions, they are expressed in terms of the complementary function error $(h)$as shown below:

$$\frac{T_{(x,t)} - T_i}{T_S - T_\infty} = erfc\left(\frac{x}{2\sqrt{\alpha t}}\right) \tag{5}$$

## 4. Results and discussion

In order to study the effect of the software on the teaching process, a survey of 56 undergraduate mechanical engineering students were evaluated based in a quasi-experimental design. A pre-measurement of the groups was made by a theoretical-practical guide of heat transfer before the presentation of the software and a subsequent test with the help of the software. The aim of the case studies was to determine the temperature at a specified position and time, according to the approximate exact solution, and to determine the effect of diffusivity on the temperature profiles and heat transfer of the different geometries studied.

### 4.1. Case Study: Transient Heat Transfer

In this case, the student analyzed the heat transfer for different geometries, obtaining the temperature profile using the software. Figure 2, illustrate the result of the cooling of a cylindrical shaft according to the parameters shown in Table 2.

**Table 2**. Parameters for the analysis of a long cylindrical shaft

| $a$ ($m^2/s$) | h($W/m^{2o}C$) | D(m) | Ti(ºC) | Ta( ºC) | t(s) |
|---|---|---|---|---|---|
| $3.47x10^{-6}$ | 215 | 0.35 | 1000 | 200 | 2700 |

The analytical solution was obtained using 9 terms of the series given in Table 1. Figure **2** shows the decrease of the temperature with the time and distance, given the initial condition at a temperature of 1000ºC. There is also a variation of temperature inside the body, thus the number of Biot obtained was much higher than 0.1, so the resistance to the heat conduction is high in relation to the heat convective resistance between the surface and the fluid.

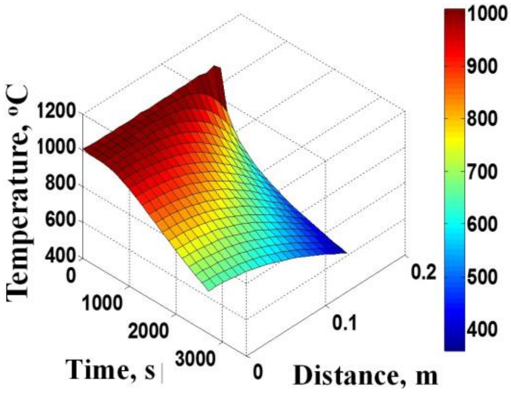


**Figure 2.** Temperature profile for a cylinder using the analytical solution

### 4.2. Case Study: Analysis of Concentrated Systems

In this section, it is shown the temperature profile of a solid sphere as a function of time given the operating conditions and properties shown in Table 3.

Figure 3 shows the temperature profile as a function of time and the convective coefficient for different fluids obtained by the students with the use of the software where the sphere was in contact with a fluid at 25ºC. It shows the high difference in temperature between the solid and the fluid at the beginning, and a subsequent decrease in temperature with the time tending to reach the fluid temperature.

**Table 3**. Properties for analysis of concentrated systems of a sphere

| $\alpha$ ($m^2/s$) | D(m) | Ti(ºC) | Ta( ºC) | T(ºC) |
|---|---|---|---|---|
| $173.8x10^{-6}$ | 0.5 | 600 | 25 | 40 |

The decrease in temperature was faster when the sphere was in contact with fluid with high convective heat transfer coefficients, as seen in figure 3.

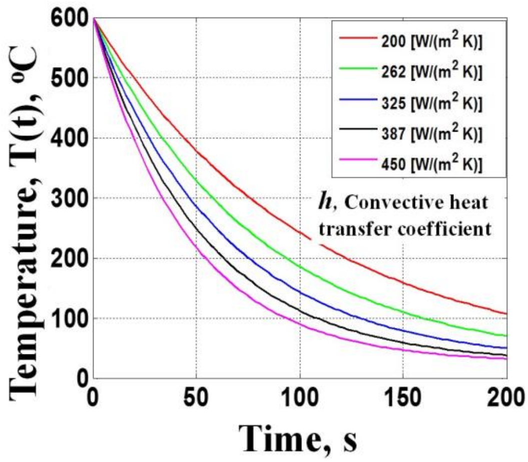


**Figure 3** .Temperature profile for a sphere as a function of time

### 4.3. Case Study: Heat Transfer in Semi-Infinite Solids

Given the parameters shown in Table 4, the students were able to study the effect the temperature profile in a Semi-Infinite Solid.

**Table 4**. Input parameters Semi-Infinite Solid

| $\alpha$ ($m^2/s$) | h(W/($m^2$ ºC) | K(W/mºC) | Ti(ºC) | Ts( ºC) | t (hours) |
|---|---|---|---|---|---|
| $2.31\times 10^{-5}$ | 220 | 80.2 | 0 | 100 | 10 h |

Figure **4** shows the temperature profile as a function of time and position, and it is observed that the temperature on the surface remains constant at every distance at time zero and increases gradually when the heat penetrates in the solid, where initially a small part near the surface is affected by heat transfer.

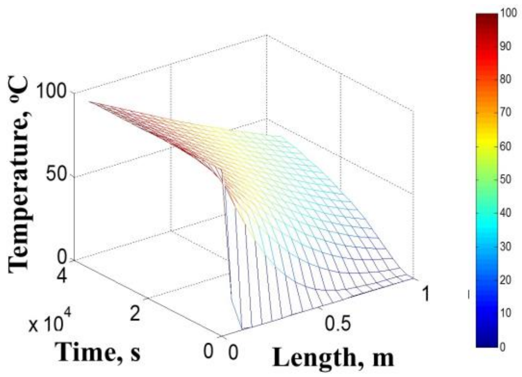


**Figure 4**. Semi-infinite solid temperature profile

**4.4. Student Performance Through HT-Transient Software**

The results of the student performance were evaluated using a t-test for paired samples. A pretest and a posttest were made to the students solving the case studies without the help of the software and with the software respectively. Then, a statistical analysis was performed at a 95% confidence level as shown in Table 5

**Table 5**. Statistical analysis results before and After the test

| Mean | Std. Desviation | Confidence Interval | | t | p | Standardized biasp | Standardized kurtosis |
|---|---|---|---|---|---|---|---|
| | | Lower | Upper | | | | |
| -3,7 | 0,5088 | -4,0078 | 3,5445 | -34 | 0 | 0.5067 | 0.9565 |

Table 5 shows the main data obtained from the paired analysis, where it can be seen that the kurtosis and standardized bias are within the range of -2 to 2, indicating the data come from a normal distribution. The results of the analysis also indicate that there is a significant difference between the pretest and the posttest, based on $t=-34$, $P=0$. The $P$-value lower than 0.05 shows that there is a significant effect when implementing the software as support in the teaching of the theoretical concepts involved in heat transfer processes promoting critical thinking in students, and meaningful learning.

## 5. Conclusion

An educational software was designed in Matlab for engineering purposes, to get a better comprehension of transient heat transfer. The tool was presented and validated with the assistance of engineering students from Universidad del Atlántico, contributing significantly in the learning process of the fundamental concepts of the transient heat transfer process. Three case studies were used to evaluate the performance of the students with and without the help of the software. These cases were Transient Heat Transfer in a Long Cylindrical Shaft, Analysis of Concentrated Systems in a Sphere in Contact with a Fluid, and Heat Transfer in Semi-Infinite Solids. A t-test for paired samples was used to evaluate statistically the use of the software by the students with a pretest and a posttest. A 95% level of confidence was used and a $P$-value lower than 0.05 was obtained indicating a significant positive effect in the use of the software becoming a support for teaching the concepts involved in transient heat transfer processes, promoting critical thinking in students, and meaningful learning. Other advantage was the reduction of test execution time due to the stimulation of a more active, dynamic and participatory learning, promoting a better understanding of the concepts involved.

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