COMSOL as an Aid in the Teaching (Learning) of Heat Transfer

R. López[*], J. Morales, M. Vaca, A. Lizardi, H. Terres, A. Lara y G. Bautista.
Universidad Autónoma Metropolitana-Azcapotzalco
Departamento de Energía, Área de Termofluidos
México, C.P. 02200,
[*]E-mail: rlc@correo.azc.uam.mx

Abstract: Several undergraduate programs include the "Heat transfer" subject and, in our experience, it is hard for the students to grasp the concepts that are presented in the course. With this in mind, we designed and constructed an apparatus for the experimentation of heat transfer in a short bar. It was observed, however, that the time required to perform the experiment was so long, that the didactic aim was lost in time-consuming activities, such as the setting of the instrumentation, the data registration and processing, and the software calibration. The simulation using COMSOL was set for a short bar in an enclosure, to fix the boundary conditions required.
The results are presented in graphic format. The time taken to run the program is considerable smaller as compared to the physical experiment. Several crucial points are highlighted to the student such as the usefulness of the simulation, the easy introduction of the "what if…" scenario and the reduction of the associated costs as compared to the experimental facility.

Keywords: Heat transfer, short bar, heat conduction, heat convection.

1. Introduction

A topic that must be included in the "Heat transfer" course for undergraduate students is that referring to the heat flow through fins and bars of some solid material. In our experience, these concepts are not easy to understand for students, because they involve two types of transfer: conduction and convection; the first occurs in the bar and the second occurs both in the bar and the surrounding environment.

Heat transfer enhancement devices are usually used to increase the heat transfer rate from the source of heat to the ambient. Fins are employed to enhance the heat transfer between the primary surface and its convective, radiative, and convective–radiative environment. Since the weight and material costs are the primary design considerations in most of the applications, an optimal shape design became more and more important. An excellent comprehensive review of the existing extended surface heat transfer literature was given by Kraus et al. [1].

Free convection heat transfer from a horizontal, isothermal fin attached cylinder placed between two nearly adiabatic walls has various applications in industry. In many applications, electronic components can be cooled using a conductive fin. Understanding of the influence of conductive fin and placing component between two adiabatic walls is important for electronic devices design application.

All modes of free convention from a horizontal cylinder in a quiescent, infinite fluid have been studied extensively and well established correlations are available in the literature [2–6]. The effect of adiabatic confining walls on the heat transfer coefficient from a circular cylinder has been studied by some researchers [7–12]. But the available information on fluid flow and heat transfer from a heated fin attached cylinder between two adiabatic walls is very limited.

One of the most important aspects of electronic equipment management has always been recognized to be the dissipation of the heat produced in the electronic components, which is needed to avoid overheating of the apparatus.

During the years the electronic equipment cooling problem has become even more crucial, as a consequence of the continuous evolution reached by the electronics industry year by year, creating apparatus even more compact in their dimension. Consequently, the quantity of heat to be dispersed is high per unit area. With the above in mind it is clear the importance to be given to the optimization of cooling system of electronic equipment.

The heat transfer to the external ambient atmosphere by the electronic apparatus can be obtained mainly by using the mechanisms of the heat transfer by forced convection, natural convection and by radiation heat transfer.

Recently, performance and optimum design analysis of convective fin arrays attached to flat and curved primary surfaces has been carried out [13-16].

Aiming to facilitate the teaching-learning process, we constructed a lab prototype which allows the analysis of the thermal behavior of a small copper bar through which a constant flow of heat is supplied. The heat is supplied by an electric resistance, which allows a power supply of up to 1 000 W and is regulated by a rheostat. The bar is immersed in a fluid that absorbs heat. The physical dimensions of the bar are 0.15 m length, and 0.254 m diameter. The bar was instrumented with six thermo-pairs at regular distances, to measure temperature. The container with the fluid (water) that has a 0.10 m x 0.10 m transverse section and 0.20 m length was also instrumented with 12 thermocouple at regular distances to measure the liquid temperature. These temperatures are registered by means of a computer using Adam modules and the Labview software. The construction and evaluation details of the prototype are described in [17].

Although the experiment using this prototype fulfills the expected learning objectives, it has been observed; however, that the time required to perform it was so long, that the didactic aim was demerit by time consuming activities, such as the setting of the instrumentation, the data registration and processing, and the software calibration. We also noticed that we were constrained to a single experiment within a limited set of possible variations. Therefore, we decided to explore the virtual approach by means of multiphysics software. The experimental facility is aimed to study a short bar heated on one end, maintaining the bar itself in quiescent water.

The purpose of this work is to present the results obtained while using COMSOL Multiphysics software to describe the heat flow through a short bar immersed in a liquid, underlying the advantages over the actual experimentation.

2. **Model definition.**

A bar with A, crosses section, L, length and p, perimeter, immersed in a liquid at constant temperature t_0, is considered. The container is surrounded by air at t_∞, which is the environmental temperature. The bar is made of a material with a constant thermal conductivity, k, and the convective heat transfer coefficient between the bar and the surrounding liquid is h. The length of the bar is 0.15 m, the diameter is 0.0254 m, the material is copper and the surrounding fluid is water. The initial temperature of the bar and the fluid is 20 °C.

The physical properties of the copper bar are: thermal conductivity, $k = 400$ W/m K, density, $\rho = 8\,700$ kg/m^3 and thermal capacity, $C_p = 385$ J/kg K. It is interesting to note that the use of COMSOL Multiphysics offers an immediate advantage, allowing to change the type of material (iron, aluminum or any other) and to perform comparative analyses. Changes of the surrounding fluid (water, air, oil, etc.) can also be easily explored and included in sensitivity analyses. The geometry of the applied model is presented in fig. 1.

The heat flow through the bar, and between the bar and the surrounding environment, which occur by conduction and convection, respectively, are described in the program by means of the following equation:

$$\delta\, \rho\, C_p \frac{\partial T}{\partial t} + \Delta \cdot (-k \Delta T) = Q - \rho C_p u \cdot \Delta T$$

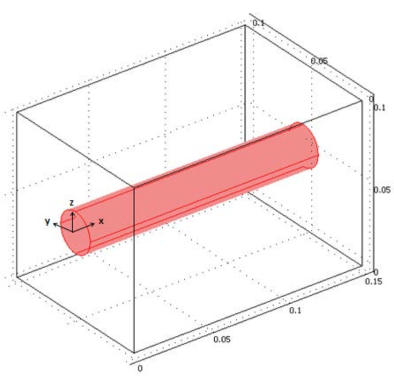
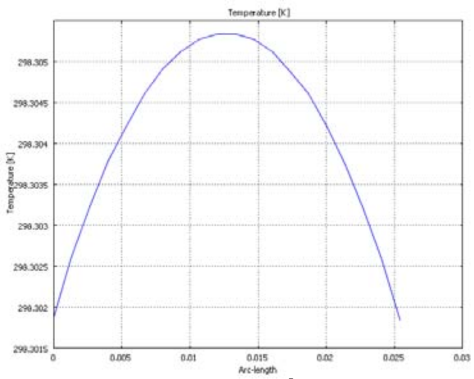


Fig. 1. Model geometry.

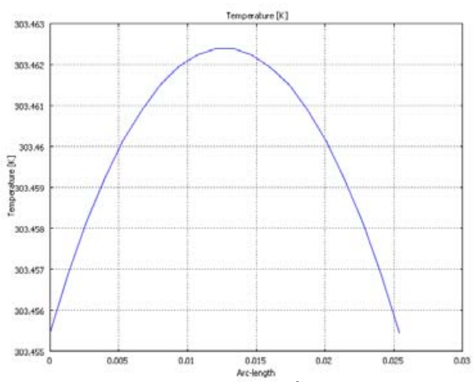
3. Results

Computer runnings were performed for energy supplies of 5 000 y 10 000 W/m^2 and for a maximal time of 3 600 s, since the program allows to change these two variables in order to complete the thermodynamic analysis of the short bar.

The temperature profile of the bar is presented in fig. 2. At the initial edge of the bar, for X = 0.00 m, comparing both values of supplied energy, the difference between the values of temperature in the central axis and the surface of the bar is minimal. The maximum temperatures that could be reached in the central line are 298.305 K, and 303.462 K respectively.



5 000 W/m^2

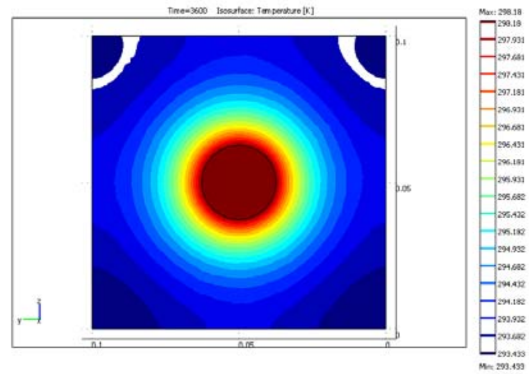


10 000 W/m^2

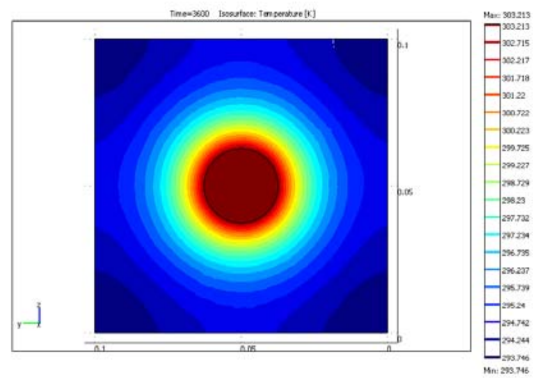
Fig. 2. Temperature profile in the bar, for 5 000 and 10 000W/m^2.

The temperature distribution in the bar observed from the cross section point of view and in the surrounding fluid at the initial edge of the bar, for X = 0.00 m, is presented in fig. 3. It can be clearly observed that the increment of the fluid temperature is proportional to the increment in the supplied energy. The pattern of the fluid temperature is also didactically produced.

The temperature profile of the fluid, observed from the upper part of the container is presented in fig.4. The highest temperature values occur at the beginning of the bar and they diminish towards its final edge. The minimal values are found near the corners of the container. This is an interesting scheme from the didactical point of view, since it allows the visualization of the patterns of temperature increments in the fluid, due to heat transfer. It is also possible to obtain this profile at any depth, which supports the understanding of the concept of heat transfer by means of convection.



5 000 W/m^2

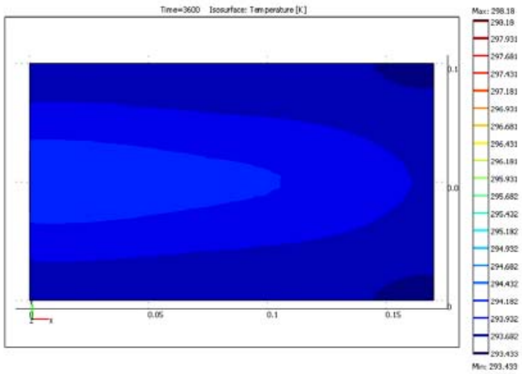


10 000 W/m^2

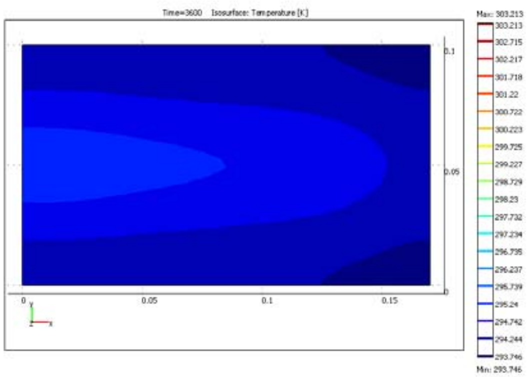
Fig. 3. Temperature patterns in the bar and the surrounding fluid, at the initial edge of the bar.

COMSOL Multiphysics is designed to produce different types of graphs. For instance, the wireframe is an option that allows to selectively eliminating "layers" of fluid, showing only areas where the analysis of temperature is of interest. An example of this feature is presented in fig. 5, where the results correspond to a selection of seven levels of temperature. In this case, the temperature distribution follows a parabolic pattern, thus the geometry can be clearly and easily presented to the students.

An experimental set that could support heat transfer concepts require great and sometimes unattainable investments in materials, equipment and time. The planning, execution of experiments, data acquisition and treatment could be easily overcome with optimal educational results through the application of the software advantages.



5 000 W/m^2



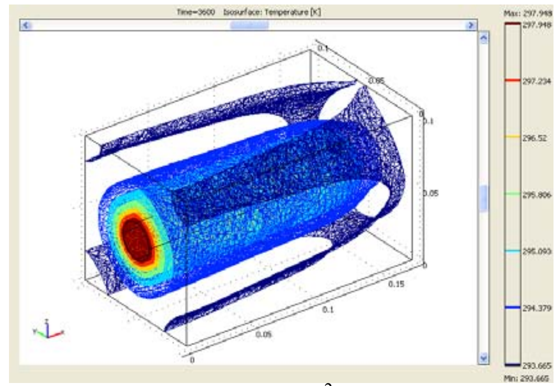
10 000 W/m^2

Fig. 4. Temperature distribution in the container fluid.

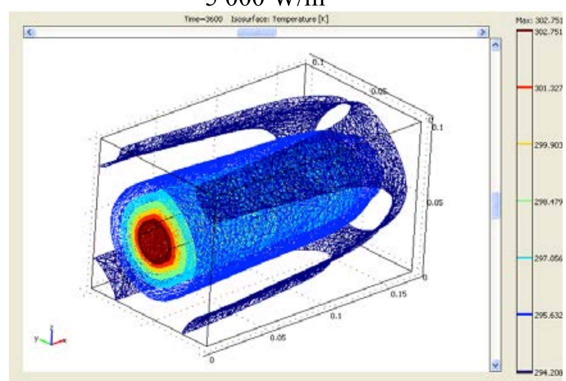
4. Conclusions

COMSOL Multiphysics software has been shown as a suitable tool for undergraduate engineering courses in Heat Transfer. It has been applied to solve and illustrate the analysis of heat transfer in a short metal bar with constant supply of heat, focusing on conditions of conduction and convection. The use of this software in the solution of this type of problems offers very attractive advantages over the actual experimentation, which requires an important economical investment and is time consuming with limited results.

The sensitivity analysis is an easy task that can be performed using the Comsol software, where the geometry, the power supply, the materials and fluid are freely exchanged and graphs produced are presented in an ample spectrum of presentations and views and focus. All this allows the student a better understanding of the phenomena studied and therefore better academic results.



5 000 W/m^2



10 000 W/m^2

Fig. 5. Wireframe type graphs of temperature distribution with seven levels.

5 References

1. A.D. Kraus, A. Aziz, J. Welty, Extended Surface Heat Transfer, John Wiley & Sons Inc, USA, (2001).
2. Vollaro AD, Grignaffini L, Gugliermetti F. Optimum design of vertical rectangular fin arrays. Int J Therm Sci, V 38, pp 525–9, (1999).
3. Bar-Cohen A. Fin thickness for an optimized natural convection array of rectangular fins. J Heat Transfer, V 101, pp 564–6, (1979).
4 Bar-Cohen A, Rohsenow WM. Thermally optimum spacing of vertical, naturally convection cooled, parallel plates. J Heat Transfer V 106, pp 116–23, (1984).
5 Bejan A. From heat transfer principles to shape and structure in nature: constructal theory. J Heat Transfer, V 122, pp 430–49, (2000).

6 Bejan A. Shape and structure, from engineering to nature. Cambridge University Press, (2000). UK.
7 Neagu M, Bejan A. Three-dimensional tree constructs of 'Constant' thermal resistance. J Appl Phys, V 86 (12), pp 7107–15, (1999).
8 Bejan A, Dan N. C onstructal trees of convective fins. J Heat Transfer, V 121, pp 675–82, (1999).
9 Silva AKD, Bej an A. Con structal muti-scale structure for maximal heat transfer density in natural convection. Int J Heat Fluid Flow, V 26, pp 26:34–44, (2005).
10 Bejan A, Lorente S. C onstructal theory of generation of configuration in nature and engineering. J Appl Phys Rev, V 100, (2006).
11 Bejan A. Simple method for convection in porous media: scale analysis and the intersection of asymptotes. Int J Energy Res, V 27, pp 859–74, (2003).
12 Holman JP. Heat trans fer. 9th ed. New York: McGraw-Hill, (1980).
13 Zhang X. and Liu D. Optimum geometric arrangement of vertical rectangular fin arrays in natural convection. Energy Conversion and Management, V 51, pp 2449–2456, (2010).
14 Rezaei A., Basharhagh M. and Yous efi T. Free convection heat transfer from a horizontal fin attached cylinder between confined nearly adiabatic walls. Experimental Thermal and Fluid Science, V 34, pp 177–182, (2010).
15 Elshafei E. Natural convection heat transfer from a heat sink with hollow/perforated circular pin fins. Energy, V 35, pp 2870-2877, (2010).
16 Kundua B. and Wongwises S. A decomposition analysis on convecting–radiating rectangular plate fins for variable th ermal conductivity and heat transfer coefficient. Journal of the Franklin Institute, V 349, pp 966–984, (2012).
17 López R., Vaca M., Liz ardi A., Terre s H., Morales J. a nd Lara A. 2012, Prototipo para el análisis de la transferencia de calor en convección natural en barras cortas. VI International Congress of Ph ysics Engineering. México. June (2012).