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Introduction to Heat Transfer in a First-year Mechanical Engineering Course

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Abstract

An activity is designed and deployed in a first-year mechanical engineering class to expose students to heat transfer. This educational activity is part of an introductory course given during the first year to introduce students to mechanical engineering and give them tools to use while pursuing their Bachelors of Science degree. The activity is scalable and can be easily deployed in first-year engineering classes at other educational institutes. Its rigor is planned for first-year students who have not yet taken the prerequisites required for heat transfer. It is presented with its goals, goal attainment measures and feedback representing the student perception. Analysis of the student's work and feedback give evidence that using this activity is appropriate as an instructional tool at the first-year level where a heat transfer introduction is desired.

1. Introduction

Mechanical Engineering Freshman II is an introductory class offered to first-year students who have declared a mechanical engineering major. The goal of the introductory course (as a whole) is to help students learn concepts in mechanical design, forces and stresses, engineering materials, motion and power transmission, and thermal and energy systems. The course has several different activities, one of which is described in this paper. The goal of this particular activity is to cover the heat transfer portion of the introductory class.

Activities are often used to help clarify concepts of heat transfer that are difficult to explain in a lecture style course. The activities can include rigorous learning experiments [1, 2], or the use of low cost desktop-scale apparatus [3], or design and build prototypes [4], or studying the cooling effects of crushed or solid ice [5], or other experiments. Numerical assignments using Excel are used [6]. Numerical and experimental projects are also presented [7] where ANSYS was used for the numerical simulations. The benefit of these activities are in enhancing the student's understanding [8] or in repairing misconceptions in heat transfer. They can be highly effective at the junior level [9] and improve the student's interest in heat transfer [10].

The activity presented here is unique in that it utilizes a simple physical problem with an existing analytical solution. Engineering software that is widely used in mechanical engineering practice is used for performing three-dimensional simulations. Students learn to use such software to make design decisions throughout their coursework and future career. At this stage, first-year students learn to generate engineering plots, create three-dimensional models, and run simulations during the activity.

The activity is implemented in classes of 48 students and other classes of over 200 students. The activity is scalable and can be easily applied in any mechanical engineering first-year class. It is found to have no limitations based on the class size as long as computers are available with the SolidWorks or equivalent software as the students work in teams of two [11].

2. Goals

The goal is for students to learn, during their first-year, that there are governing equations used by engineers to model a physical process. The students are expected to:

- Remember the meaning of different terms in the heat transfer differential equation. These terms are complicated and include thermal conductivity, specific heat, density, convection coefficients, ambient temperature, and physical geometry of the sphere.

- Comprehend how physical properties and numerical solutions can affect the results of the heat transfer equation. With certain assumptions (lumped parameter model), the heat transfer equation can be solved analytically. The analytical solution is provided to the students and can be plotted as an X-Y plot of temperature versus time with different materials. Engineering software is also used to solve the governing equations numerically. Sensors are added in the numerical simulations to yield an X-Y plot similar to that obtained with the analytical solutions. The plot obtained analytically matches that obtained numerically only if the assumptions are applied correctly, the analytical solution is obtained appropriately, and the simulations are performed properly. Many students use the wrong physical properties in the analytical solution or the simulation at first. During the activity, they comprehend the value of using the correct inputs in order for their plots to match.

3. Problem Definition

An initial value problem is selected for this activity. A sphere is specified to have a given diameter and initial temperature (Fig. 1). It is subjected to constant convection cooling and cools to room temperature over time following a temperature versus time chart similar to the one shown in Fig. 2. Conduction heat transfer occurs inside the sphere while convection heat transfer occurs at the outside surface of the sphere.

A 50-minute lecture is given to explain the conduction and convection modes of heat transfer. Since cooling a sphere due to convection has an analytical solution for $Bi < 1$, the lumped parameter analysis can be used and the governing equations and their analytical solution are provided to the students. Bi is defined as follows:

$$\boldsymbol{Bi = \frac{h}{\left(\frac{k}{L}\right)}}$$

Where h is the convection heat transfer coefficient, k is the thermal conductivity of the solid material, and L is a representative length scale (Volume / Surface Area of the sphere). The units of h, k, and L must be properly selected so that Bi will be dimensionless.

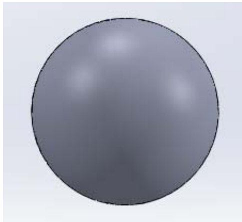

Fig. 1, Sphere in an
Initial Value Problem

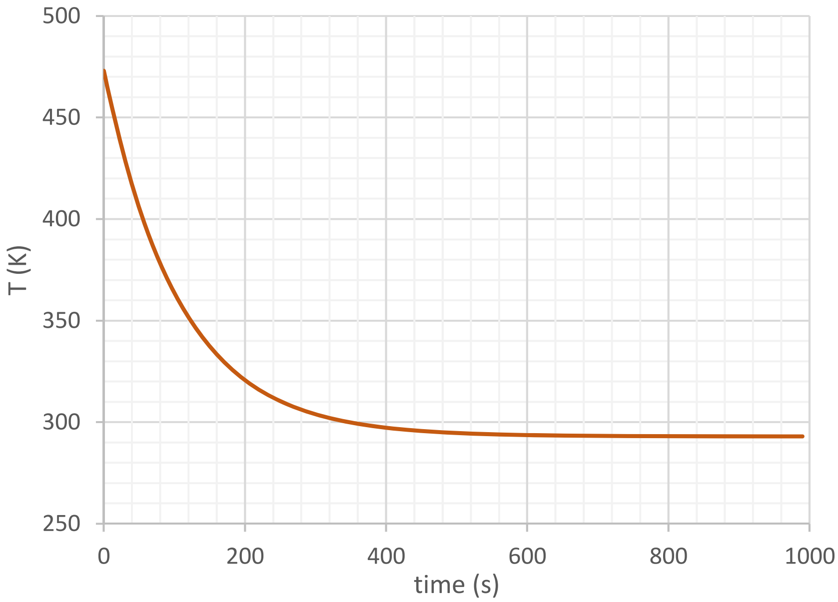

Fig. 2, Temperature versus Time Chart

The heat transfer equation in case Bi < 1 is given as follows [11]:

$$\boldsymbol{m\,c\,\frac{dT(t)}{dt} + \ h\ A_s\,(T(t) - \ T_\infty) = \ 0}$$

The first term of this equation is time dependent. In this first term, m is the mass of the sphere, c is the specific heat of the sphere, T(t) is the time dependent temperature of the sphere, and t is the time.

The second term represents the convection heat loss at the outer surface of the sphere. In the second term, h is the convection coefficient, A_s is the surface area of the sphere, and T_∞ is the temperature of the cooling fluid medium.

The analytical solution of this equation is as follows, where T and Ti are the transient temperature and the initial temperature of the sphere, respectively [12]:

$$\boldsymbol{\frac{T(t) - \ T_\infty}{T_i - T_\infty} = exp\left[-\frac{h\ \ A_s}{\rho\ \ V\ \ c}\ \ t\right]}$$

A 100-minute lab follows where students self-enroll to work in teams. Each team of two students is given a computer with the required software and a learning management system (Blackboard eLearning) where the lecture slides and tutorials are loaded. Each 24 students (12 teams) are supported by a teaching assistant during the lab. The work described below is completed by the students during the lab session.

In this lab, the students are asked to generate a plot of temperature versus time in MATLAB using the analytical equation. A lecture on this software is offered earlier in the course and some support in creating a script to set the equation and plot the temperature is offered to the first-year students during the lab.

A tutorial is given to help students draw a sphere with the given diameter in SolidWorks and define its physical properties. The thermal simulation application of SolidWorks is used to set the initial condition, a convection boundary condition, an ambient temperature, and run a transient heat transfer simulation. The students plot instantaneous contour plots of the temperature in the sphere to observe a hot center of the sphere and a cooler surface temperature (Fig. 3). However, since $Bi < 1$ the conduction heat transfer in the sphere makes the difference between the highest and coolest temperature very small.

The students are also asked to add a transient sensor in the simulation and plot the average temperature of the sphere versus time. Here, they realize the value of integration (numerical integration included in SolidWorks) to evaluate the average temperature of the sphere.

Comparing the temperature versus time curve obtained by SolidWorks to that obtained using the analytical equation can show quite a difference when there is an error in the calculations. However, when the calculations are correct, the curves are found to have excellent agreement.

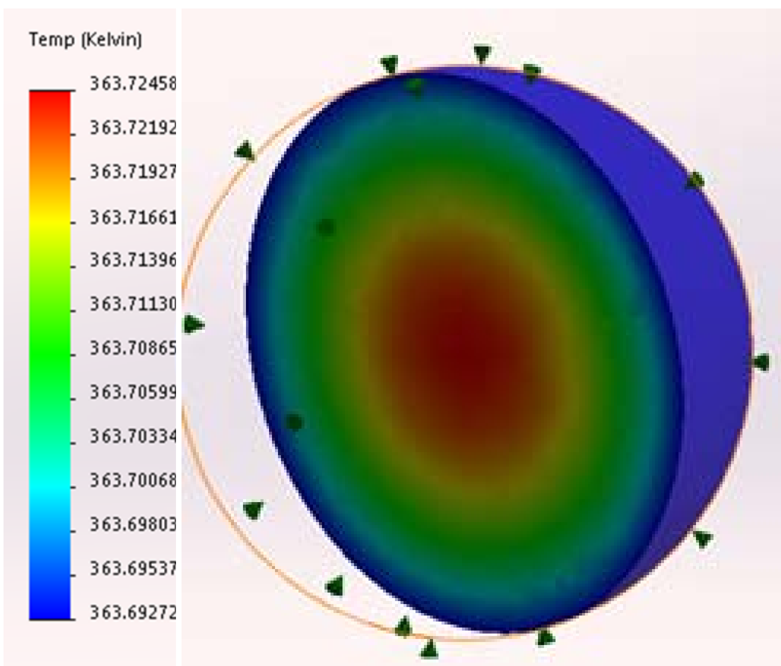

Fig. 3, Temperature Contours in the Sphere

4. Goal Attainment

Exam questions revealed that the first-year students were able to remember the terms of the heat transfer equation shown in Section 3, above. Questions were also included in the exam regarding the equations and assumptions, including the significance of the Biot number, and the cooling phenomenon. Most students were able to answer the questions correctly.

Engineering reports, provided by the students, indicate an ability to plot the temperature of the sphere using the analytical solution and the numerical simulation. The students were able to compare the temperature versus time plot obtained using the analytical solution to that obtained by the numerical simulations. Most students demonstrated that they comprehend how physical properties and numerical solutions can affect the solutions of the heat transfer equation. Some teams were careful to use correct physical properties. They selected a fine mesh and a time step that resulted in curves revealing an agreeable comparison, these students provided meaningful statements confirming that the comparison met their expectations. Others did not get an agreeable comparison quantitatively. They attributed discrepancies to the numerical mesh or the numerical time step. In many cases, they corrected the physical variables or improved the mesh or time step to achieve agreeable comparisons.

One student commented on the lumped parameter assumption used in developing the analytical solution. The student wrote in the report, “Copper is very conductive so the [temperature] variation throughout the sphere is minimal which was expected knowing the properties of Copper. It’s very low Biot Number makes it a good conductor it cools evenly throughout the solid.”

Another related the speed of heat transfer to the temperature difference between the sphere and the cooling air. The student wrote in the report, “From the initial temperature, the copper sphere cools at a rapid rate until reaching ~320K. After, it takes significantly longer to cool down.”

5. Student Perception

A simple survey was used to capture the student’s perception of the activity. Results of the survey indicate the activity was well enjoyed, appreciated, and valued by the first-year students.

The survey was administered in the spring semesters of 2017 and 2016 where five sections of the course were offered. It was also administered in the fall semester of 2016 where only one section of the course was offered. The number of students involved in the surveys are shown in Table 1.

Table 1, Number of Students Involved in the Surveys

Semester	Students	Surveys Completed
S’17	221	153
S’16	237	151
F’16	48	22

The following statement is included in the survey: “I understand how a solid body can cool down due to convection.” The answers were requested on a 5-point Likert scale according to Robbins and Heiberger [13]. Students responded as shown in Fig. 4 during the three semesters when the survey was given. Even though the work was in simulation form and not physical, the students were able to observe the cooling process and generate temperature versus time plots. At the end of this activity, the first-year students felt they understood the cooling phenomenon.

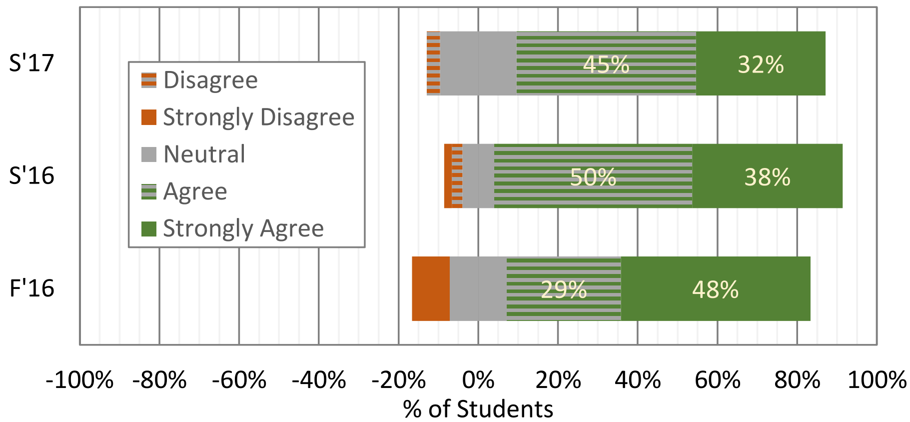

Fig. 4, Student’s Response to
Understanding How a Solid Body Can Cool Down

The students enjoyed the activity. They responded as shown in Fig. 5 (plotted according to [13]) to the following statement: “I enjoyed working on this activity.”

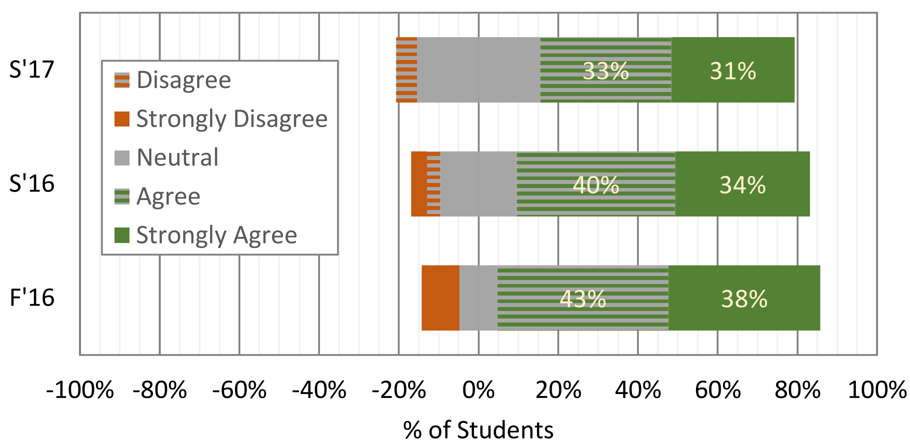

Fig. 5, Student’s Response to Enjoying the Activity

The students also considered the activity of value to them. They responded as shown in Fig. 6 (plotted according to [13]) to the following statement: “The concepts I learned while working on this activity will be of value to me.”

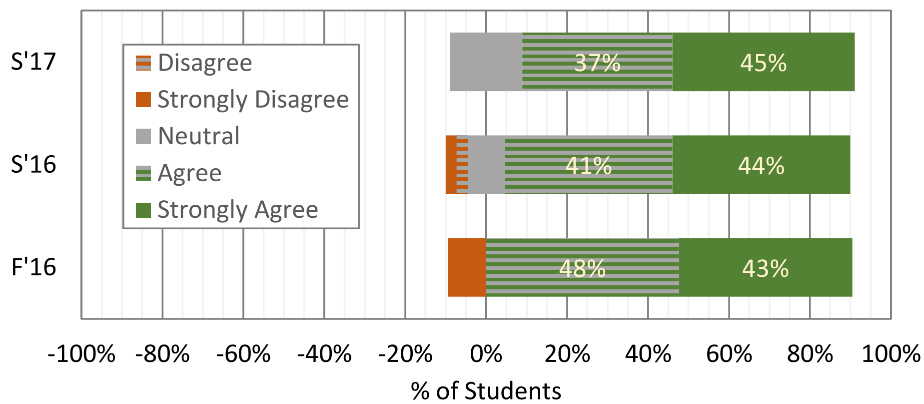

Fig. 6, Student's Response to the Value of the Activity

6. Summary

An activity is presented for first year mechanical engineering students. The goal of the activity is to introduce first-year students to equations that govern physical behavior, in this case, cooling heat transfer. The students are expected to remember the equation terms and comprehend how physical properties and numerical solution variables affect the solutions of the heat transfer equation.

Following this activity, the students learn new skills. They learn how to use Biot number to justify implementing the lumped parameter solution. They learn how to use engineering software to run a numerical simulation. They appreciate the value of using the correct physical properties in the analytical solution and the numerical simulation. They also learn the value of meshing and time step to get valuable results from numerical simulations.

The activity is considered effective in meeting its goals. At the conclusion of this activity, exams revealed that the students were able to remember the heat transfer governing equation terms. Students were also able to draw meaningful conclusions in their reports demonstrating their comprehension of physical properties and variables that affect the numerical simulation.

Finally, a survey revealed that the students enjoyed the activity and considered it valuable.

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