Preliminary Testing of a .NET Based Educational Heat Transfer Simulator

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Introduction

This paper reports preliminary results of using a .NET based educational heat transfer simulation to improve learning for two adjacent undergraduate chemical engineering heat transfer classes. This simulation was developed to help improve students understanding of one-dimensional conductive heat transfer concepts by allowing them to engage in interactive exploration. Two different approaches were compared in this work. In the first semester we encouraged individual simulation exploration by asking our students to complete a homework assignment consisting of prediction-type conceptual questions using the simulation (see Appendix A). During the second semester the simulation was incorporated into an in-class active learning activity where students were grouped into 3 person teams and asked to answer those same questions. After they answered each question they were asked to check their conceptual understanding by using the simulation. Pre- and post-survey instruments were used to gauge student understanding of these concepts before and after the simulation exercise to determine the effectiveness of these two approaches.

Interactive computer simulations are widely available for inclusion in today's curriculums and can be found in many textbooks which regularly include DVDs or URLs

to websites containing simulations. They can provide a correct visual mental model of scientific concepts which can advance discussions and analysis in the classroom. However, although the goal of simulations is to provide a correct model and perhaps to eliminate existing student misperceptions, some investigators have observed the creation of new misperceptions through the use of simulations [Prince, 2006]. Others have noted that that the quality of student learning facilitated by simulations also depends on the specific learning environment as a whole [Davies, 2002].

Studies have found that simulations that incorporate interactivity, animation and context can promote learning, but that the student's ability and interest in using the simulation depends greatly on the design [Adams et. al., 2007]. Some of their findings are as follows: The best start-up settings were found to include the least amount of animation and complexity possible. Real world connections are important. Color is an important visual queue. Objects should be represented consistently from simulation to simulation. Layout tips, such as limiting the number of tools/controls and arranging them in small groups, limiting text and don't use abbreviations are suggested. Also, the play area should be distinct from the control panel. Text is a distraction in the play area. Students notice large bright tabs. Students like to use play/pause buttons for no reason if they have been shown to them. Verbose help can be a deterrent to exploration.

Student users have little difficulty immediately interacting with new simulations when the tools used are consistent with interfaces that the students have learned previously. Since a majority of students use Windows computers and Microsoft software we decided to use the .NET development environment in order to develop a simulation with a consistent look and with typical Microsoft interfaces. The results of the two

different approaches to exploration with the developed simulator were measured by surveys to determine the students' understanding of various conduction heat transfer concepts that were explored using the simulation.

Problem Description

The objective of this simulator was to address heat conduction. The simulator was created to represent a one-dimensional conduction heat transfer problem with Dirichlet boundary conditions. A user is allowed to change the properties of the materials using the control panel to the right side of the application (see Figure 1). The initial temperature of the semi-infinite block and the thickness of the semi-infinite plate can be specified as well as the boundary temperatures. Sliders are also provided on each side of the semi-infinite plate to allow students to change the boundary temperatures while the simulation is in progress. Two different heat transfer profiles (the temperature profile and heat flux profile) are generated using the two independent grid settings.

One of the major advantages of using Microsoft Visual Studio 2005 (VS2005) as a development platform is that ANSI C++ can exist in the same program as the C++/CLI .NET code [Microsoft, 2006]. This allows us to develop one consistent program that can handle both the technical computing requirements to solve the equations and create the visually pleasing .NET interface for the Windows operating system. The standard VS2005 toolbox also makes it easy to incorporate windows common controls like sliders which students intuitively understand how to operate. A VS2005 setup project was also created to install the application on the department's laboratory computers so that the necessary version of .NET is also installed if required.
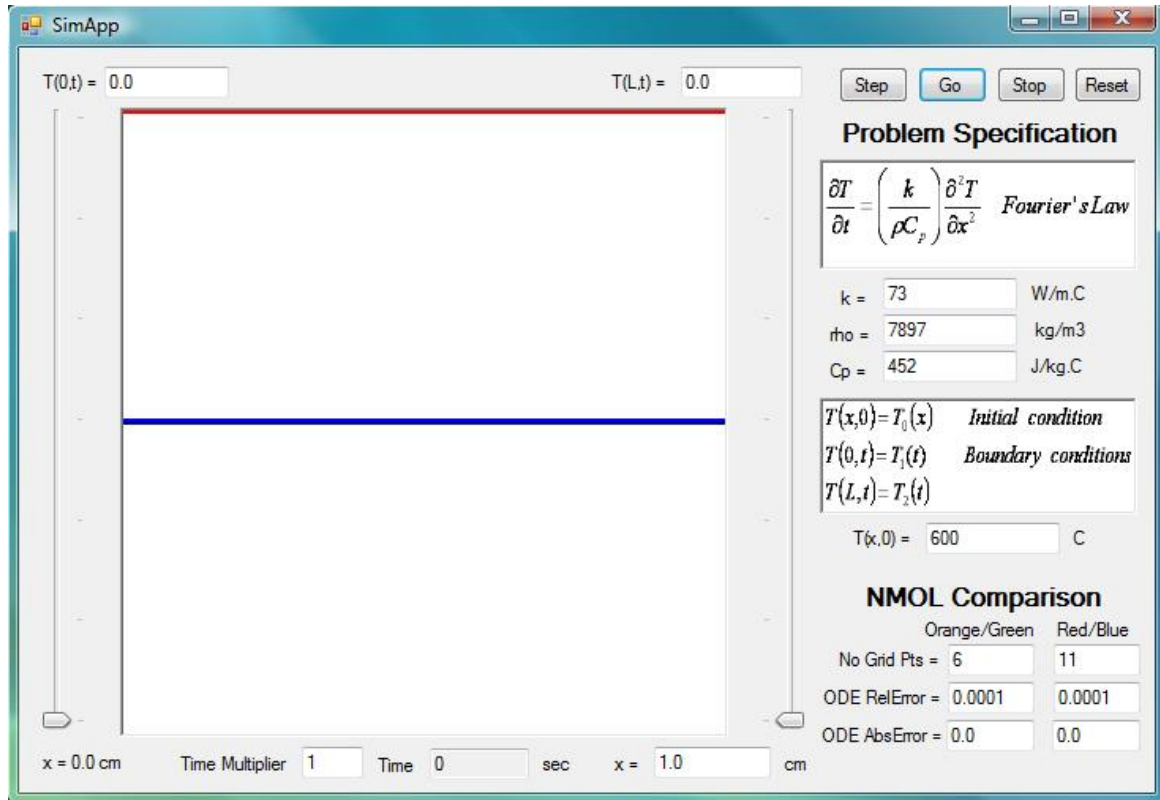
Figure 1. The .NET heat transfer simulation interface.

The transient one-dimensional heat transfer conduction problem is described by

Fourier's second law for heat conduction in Cartesian coordinates as

$$\frac{\partial T}{\partial t} = \left(\frac{k}{\rho C_p} \right) \frac{\partial^2 T}{\partial x^2}$$

(1)

in terms of the temperature T and its spatial position x and time t. The group $(k/\rho C_p)$

represents the solid's thermal diffusivity in consistent units. One initial condition is

required to prescribe the initial temperature distribution as a function of x at $t=0$ (typically

a constant)

$$T(x,0) = T_0(x) \tag{2}$$

and two boundary conditions are required and in this case we chose Dirichlet boundary

conditions specifying the dependent variable T at $x=0$ and $x=L$.

$$
\begin{aligned}
T(0,t) &= T_1(t) \\
T(L,t) &= T_2(t)
\end{aligned}
\tag{3}
$$

The solution was coded in ANSI C++ using the method of lines [Schiesser, 1991].

The method of lines replaces the partial derivatives with respect to x in Equation 1 with

finite difference approximations, but the time is still treated as a continuous variable.

This leads to a system of ordinary differential equations (ODE) because we now have

only one independent variable t and they can be solved by a standard ODE solver such as

RKF45 [Forsythe, 1977].

The program was also designed to demonstrate the effect of grid size on a

numerical heat transfer solution. Therefore, the graphical user interface calculates and

displays two different solutions with different numbers of grid points simultaneously.

Figure 2 is a screen shot of the program after the "Step" button has been pressed once.

The transient temperature and flux profiles for 6 and 11 grid points at 0.2 seconds are

plotted in the display window. The red line is the temperature profile for the 11 grid

point solution and the orange line is the temperature profile for the 6 grid point solution.

The blue and green lines are the respective flux profiles.
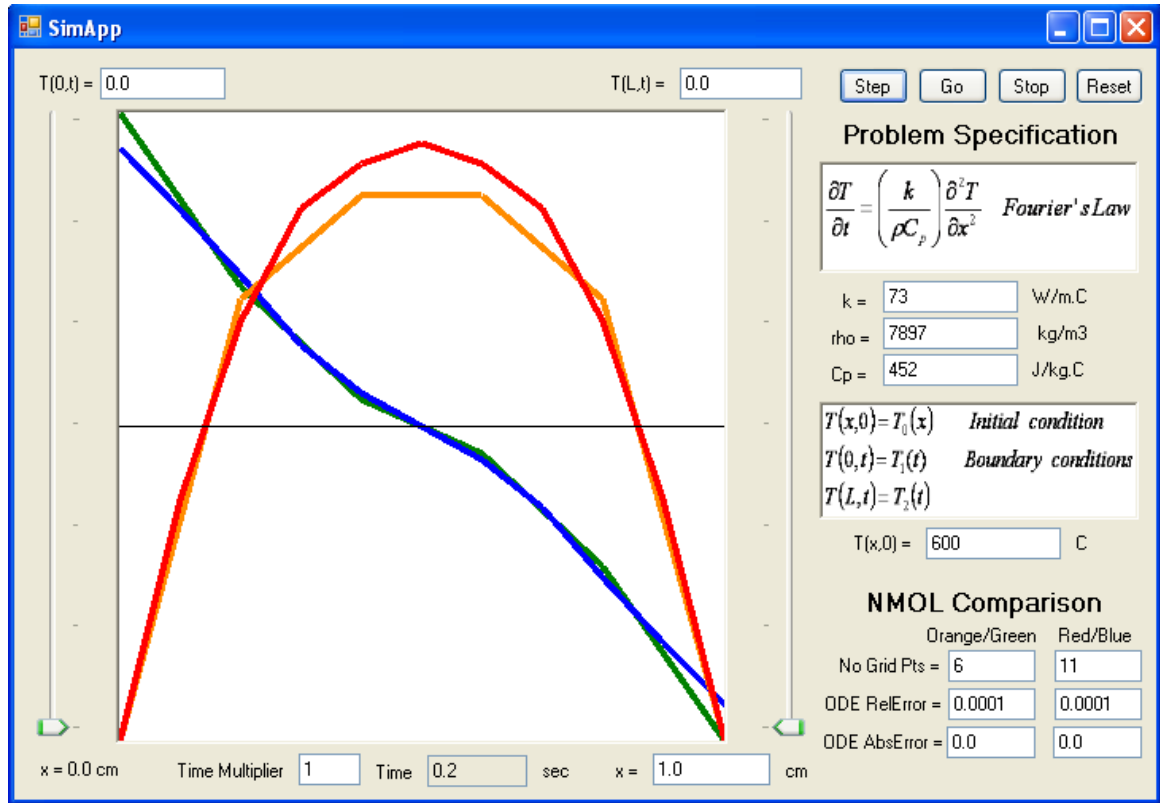
Figure 2. The .NET heat transfer simulation after pressing "Step" once.

Because this is a typical windows application, many copies can be executed simultaneously on the same machine. This allows a student to start another instance of the application, make modifications to the parameter settings and then compare the results side by side. For example, one of the exercise is to change the thickness x from 1.0 cm to 10.0 cm and then run the simulation until the computed profile matches that shown in Figure 2. To accomplish this task the student is instructed to leave the first instance of this application on his or her screen, invoke a second instance of the application, change the thickness to 10.0 cm and then run the simulation until the graphical display matches that of the first instance.

First Implementation

Seventeen students were enrolled in the Spring 2008 semester heat transfer class. For this class we encouraged individual simulation exploration guided by a prediction-type homework assignment. Students were given an overview of the simulation program during class and then provided with the homework assignments to be completed individually using the simulator (see Appendix A). Although only seven students actually returned the assignment, most indicated they had exercised the simulation. Students were given pre- and post- concept inventory surveys (Appendix B) to measure the effectiveness of the simulation as a pedagogical tool. The post-survey was provided to the students several days after the assignments. Seventeen (17) out of a total of 19 students completed and returned the surveys.

Second Implementation

In the Summer II session 2008 heat transfer class we incorporated an active learning session using the simulation. The twelve students taking this class were grouped into 3 person teams and asked to predict the answers to questions in the assignment. All groups learned and practiced how to use the simulator in class. Students were picked randomly to answer the questions in the assignment. After each group made their prediction they used the simulation to generate the answer and then discussed the results. Again, students were given pre- and post- concept inventory surveys. The post-survey was provided to the students several days following the in-class exercise and 10 of the 12 students completed and returned the post-survey.

Results and Discussion

Survey questions 1-5 are mathematical conceptual questions; questions 6-10 are visual conceptual questions; and questions 11-15 are affective questions. The answers to the mathematical conceptual questions can be deduced directly from the heat transfer formula. Where as the answers to the visual conceptual questions require knowledge of the visual shape of the temperature solution to the transient one-dimensional heat transfer problem and represent a correct mental model of the phenomena. Questions 11-15, the affective questions, were only included in the post-survey. The survey results from the Spring 2008 and Summer 2008 classes are listed in Table 1.

Table 1. Survey results before and after the simulation activity.

Question	Spring 2008			Summer 2008		
	Pre-Survey	Post-Survey	Change (%)	Pre-Survey	Post-Survey	Change (%)
Mathematical Conceptual Questions (maximun possible score = 5.0)						
1	4.8	4.8	0.0	4.6	4.3	-6.5
2	3.1	4.0	30.7	2.9	3.3	13.8
3	3.5	3.9	11.8	2.8	3.7	32.1
4	2.4	2.5	2.5	3.0	2.8	-6.7
5	2.4	2.3	-2.6	2.3	2.2	-4.3
Average	3.2	3.5	8.5	3.1	3.3	5.7
Visual Conceptual Questions (maximun possible score = 1.0)						
6	0.5	0.8	74.5	0.4	0.3	-25.0
7	0.7	0.7	0.0	0.3	0.6	100.0
8	0.5	0.4	-34.0	0.5	0.8	60.0
9	0.4	0.2	-41.5	0.3	0.4	33.3
10	0.6	0.6	0.0	0.5	0.9	80.0
Average	0.5	0.5	-0.2	0.4	0.6	49.7
Affective Questions (maximun possible score = 5.0)						
11		4.6			4.2	
12		3.8			4.2	
13		4.0			3.9	
14		3.7			3.8	
15		3.6			4.3	
Average		4.0			4.1	

From the responses of the affective questions 11-15, the students in both classes are in favor of using the simulator (average scores ≥ 4.0). It is strongly agreed that the simulator is easy to use (question 11). From question 12, it is clear that the students feel that active learning sessions help them understand heat transfer better than individual exploration. The students liked to see the usage of simulation in other classes (question 13). The active learning makes students feel more comfortable to predict the effect of their actions on the simulation (question 14) and helps students discover how heat transfer works (question 15).

Considering the responses to the mathematic conceptual questions 1-5, the Spring class using individual exploration performed equal or better in each question than the Summer class using an active learning exercise. The Spring class also improved slightly more for those questions as shown by the change between pre- and post- surveys. Given that only eight students actually returned the homework assignment we don't feel that we can state that individual exploration was more effective at improving our student's performance on answering mathematical conceptual questions than active learning. However, it is clear that the active learning activity employed for the Summer class did not improve our student's ability to answer the mathematical conceptual questions correctly.

Considering the responses of questions 6-10, the Summer class using active learning had a higher average score in the post-survey than the Spring class even though their pre-survey scores were lower. In addition, their score improved in four out of the five questions between the pre- and post- surveys while students using the individual exploration method averaged the same for the pre- and post-survey questions 6-10 with

some scores higher and others lower. This indicates that although individual exploration with a simulation may correct some misperceptions other misperceptions may actually be created during that process. We feel that using an active learning exercise in conjunction with a simulation can help students understand visual conceptual problems better with less potential for creating new misperceptions.

Conclusions

A .NET based educational heat transfer simulator was developed and used to help students understand one dimensional conduction heat transfer concepts. The simulator was used both as an individual exploration tool and as part of an active learning exercise to explore these heat transfer concepts. The heat transfer simulator when coupled with an active learning approach was effective in helped students correct existing misperceptions without creating new misperceptions. Although the simulation provides students with a cursory visual mental model of the one-dimensional heat transfer phenomenon, it did not help (at least not much) students understand the theory or mathematics used in heat transfer calculation. However, this cursory understanding could serve as a basis for developing a deeper understanding of the more complex mathematical concepts.

Acknowledgements

References

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Appendix A

Heat Transfer Interactive Computer Simulation Assignment

Name: _____

ID#: _____

Date: _____

SimApp simulates the internal temperature of a semi-infinite plate with a thickness L. The plate's initial temperature is specified as T_0 at time = 0 and at time > 0 its surface temperatures T_1 and T_2 are specified on its left (x=0) and right (x=L) boundaries. The exercise that follows involves using the SimApp program to investigate how this system responds to various changes.

1. Start SimApp by using the Start-All Programs-SimApp menu command.
2. Left-click the "Step" button and identify the four lines in the graph area. The orange line is the semi-infinite plate temperature calculated using 6 grid points while the red line is the plate temperature calculated using 11 grid points. The green and blue lines represent the respective temperature derivatives. What best describes the shape of the temperature curve?
3. Consider the equation listed below the problem specification.
4. Observe the time (0.2 seconds). Then, start another copy of the program and increase the plate size from 1.0 cm to 10.0 cm thick. Left-click the "Go" button and when the shape matches the original program click the "Stop" button. How much time elapses before the second temperature profile looks the same as in step 2?
5. Start another copy of the program and decrease the thermal conductivity k value from 73 W/m.C to 7.3 W/m.C. Now how much time must elapse before the temperature profile looks like the result of step 2?
6. Start another copy of the program and increase the heat capacity Cp to 4520 J/kg.C. Again, how much time must elapse for the temperature to match the profiles above?
7. Explain the results of steps 4 through 6 in terms of Fourier's Law displayed below the problem specification.
8. Run the original program for about 15 seconds to reach steady-state and then left-click the "Stop" button. The temperature is constant (0 C) throughout the plate and the temperature derivative is zero.
9. Change the left surface temperature to 600 C while leaving the right surface temperature at 0 C and run the program for another 15 seconds to again reach steady-state. What is the shape of the final temperature curve? What is the shape of the final temperature derivative?
10. The magnitude of the temperature derivative is proportional to the amount of heat that is being transferred. Reset the program that the plate size has been increased to 10 cm. Step the solution and note where the largest derivatives occur. Left-click the start button. Do the temperature derivatives (heat flux) increase or decrease as the simulation proceeds?

11. Start another copy of the program and change the number of grid points from 6 and 11 to 11 and 21. Is the difference between the 11 and 21 grid solutions larger or smaller than the difference between the 6 and 11 grid solutions?
12. Start another copy of the program and change the number of grid points from 6 and 11 to 21 and 41. What the difference between the 21 and 41 grid solutions. Which solution is closer to the true answer?
13. Experiment and determine the different ways the program can be made to fail. Create a step-by-step procedure to re-create each method that causes the program to fail.

Appendix B

Survey
for
Improving Heat Transfer Learning by Interactive Computer Simulation

Name: _____
ID#: _____
Date: _____

Consider a semi infinite plate with a thickness L has a uniform initial temperature T_0. The temperatures on both surfaces are suddenly changed to T_1 and T_2 on its left (x=0) and right (x=L) surfaces. How will the temperature inside the plate change?

1. When the surface temperatures on both sides of the semi-infinite plate are decreased, the temperature in the center of the plate will also decrease (a) strongly agree, (b) agree, (c) not sure, (d) disagree, or (e) strongly disagree

2. The time it takes for the temperature in the center of the plate to reach its final steady-state value is proportional to the square of the plate thickness (a) strongly agree, (b) agree, (c) not sure, (d) disagree, or (e) strongly disagree

3. The heat flux remains constant during the unsteady-state period (a) strongly agree, (b) agree, (c) not sure, (d) disagree, or (e) strongly disagree

4. The time it takes for the temperature in the center of the plate to reach its final steady-state value is inversely proportional to the plate heat capacity decrease (a) strongly agree, (b) agree, (c) not sure, (d) disagree, or (e) strongly disagree

5. The time it takes for the temperature in the center of the plate to reach its final steady-state value is proportional to the initial temperature decrease (a) strongly agree, (b) agree, (c) not sure, (d) disagree, or (e) strongly disagree

6. What best describes the characteristic shape of the semi-infinite plate temperature during the unsteady-state period? (a) constant, (b) linear, (c) quadratic, (d) S-shaped

7. When the surface temperatures on both sides of the semi-infinite plate are decreased symmetrically what is the heat flux at the center of the bar? (a) negative, (b) zero, (c) positive

8. If the surface temperatures on both sides of the semi-infinite plate are different, then the steady-state temperature profile is best described as (a) linear, (b) parabolic, or (c) constant

9. If the surface temperatures on both sides of the semi-infinite plate are different, then the steady-state temperature derivative is best described as (a) linear, (b) parabolic, or (c) constant

10. The location of the maximum heat flux during the unsteady-state period is at (a) one or both ends, (b) the center of the plate, (c) somewhere between the center and the end of the plate

Mark your level of agreement with the following statements:

1. Using the simulation was easy. (a) strongly agree, (b) agree, (c) not sure, (d) disagree, (e) strongly disagree

2. The simulation helped me understand heat transfer. (a) strongly agree, (b) agree, (c) not sure, (d) disagree, (e) strongly disagree

3. I would like to see other subjects use simulations. (a) strongly agree, (b) agree, (c) not sure, (d) disagree, (e) strongly disagree

4. I could predict the effect of my actions on the simulation. (a) strongly agree, (b) agree, (c) not sure, (d) disagree, (e) strongly disagree

5. The simulation helped me discover how heat transfer works in practice. (a) strongly agree, (b) agree, (c) not sure, (d) disagree, (e) strongly disagree

Note: This survey will NOT be counted towards your grade.