

AC 2007-69: INTERACTIVE COMPUTER PROGRAM FOR TRANSIENT CONDUCTIVE HEAT TRANSFER CONCEPTS

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Interactive Computer Program for Transient Conductive Heat Transfer Concepts

Abstract

An interactive computer based learning tool for undergraduate students enrolled in Heat Transfer courses has been significantly expanded. A previous version of the program provided graphical depictions of two-dimensional steady state conduction solutions for cases where temperature boundary conditions were prescribed. The present research expands the features of the program to include prescribed heat flux boundary conditions as well as convective boundary conditions. Moreover, the expanded program also handles transient cases so that students can watch temperature changes in a material on a real-time basis. The addition of these boundary conditions also now allows one dimensional problems to be solved by specifying a zero heat flux condition on opposing sides of the body.

The solutions for the original version of the program were generated using a code developed for Sandia National Laboratory which was DOS based. The revised program has replaced this computational kernel with a numerical solution which is programmed as part of the native Visual Basic code. This feature allows the program to run more seamlessly, without the need for a black DOS window to appear on the screen.

The interface between the student and the kernel program allows visualization of the temperature field generated in the two-dimensional body. The program is used by students on an individual basis as a supplement to their usual textbook, homework and class involvement.

Input from the students is prompted via text boxes in a Windows based program. Coincident with the expanded features of the program is a need for considerably more input on the part of the students. The six input items required by the user in the previous program version have been expanded to 17, with a corresponding number of input boxes provided for that purpose. Additionally, there are two "calculate" buttons which start the program running, one for steady state problems and one for transient problems.

Students enrolled in the Heat Transfer courses at two separate institutions are given instruction sheets for operating the program, including prescribed temperature values for the boundaries. They are then asked to provide a written response to questions, requiring them to explain where the heat flux is the largest and the smallest in the body. An evaluation of the program by the students is included in the study as a means of determining the effectiveness of the program. Since the learning atmosphere in each of the two schools included in this study is very different, the reaction from the students at each of these schools is of special interest.

Introduction

A program was previously developed with the intent of giving students a physical feel for conductive heat transfer processes [1]. The program addressed prescribed temperature boundary conditions under steady state conditions in a two-dimensional rectangular object. The user

provided input related to the object dimensions, along with the prescribed temperature at each of the four boundaries. The temperature distribution was then displayed using color to depict temperatures on the computer screen. This program was originally based on a code developed through Sandia National Laboratory to find analytical solutions for steady state and transient heat conduction in solids [2]. The code developed for Sandia was intended for use in verification of numerical solutions and was DOS based.

The instructional program, which made use of the DOS code, was Microsoft Windows based and essentially served as an interface between the student user and the DOS program. The Windows based program was written in Visual Basic. An input file was required for the DOS program, which was somewhat cryptic. The Windows program provided a more intuitive data entry system and then generated the input file for the DOS program to simplify input for the student user. When the program was activated, a DOS window was automatically introduced onto the screen while the temperature calculations were underway. The exact solution generated by the DOS program was then written to an output file, which was read by the Windows program and displayed in color for the user. This program architecture was chosen because of the inherent speed and accuracy of the analytical solutions.

Ironically, a drawback of the DOS program turned out to be a relatively slow calculation rate. The analytical solutions are very fast when only one temperature is needed at one particular time in a transient conduction problem. This is because no previous time steps need to be calculated, as is required in a numerical scheme. Nor are any other temperature values at any other points in the body required to be calculated in order to compute the temperature at just one point. However, when a full temperature grid is required for the display of thermal gradients, the analytical solution offers no advantage over the numerical solution. Indeed, if the analytical solution is not designed for multiple calculations, and terms such as eigenvalues are unnecessarily recalculated for each point in the grid, the computation can become very inefficient.

Reference [3] describes a program which is very similar to the one presented in the current research. The added area of study in the present case is the inclusion of a structured set of homework questions given to the students to guide them into utilizing the program to its fullest extent. The questions are designed to make the students study and interpret the results so that they can extract the maximum amount of benefit from the features available in the program. Other initiatives aimed at teaching computational heat transfer are described in references [4] and [5]. The use of spreadsheets is a good teaching tool for getting the students involved in the calculation process. The present research, by contrast, endeavors to give students an intuitive physical feel for the heat transfer processes by looking at the results of calculations, rather than generating the calculations.

As part of the work for the program developed under the present research, a numerical solution within the native Visual Basic code was developed to replace the DOS based kernel in the previous version of the program. The numerical scheme was based on a finite difference solution with second order boundary conditions, using the Gauss-Seidel method to solve the equations. The program also now addresses not only steady-state, but transient heat conduction in a rectangular two-dimensional object. The grid contains 100 nodes, arranged 10 by 10, and

employs a fully implicit backward-difference method for transient cases. Additionally, the range of boundary conditions was expanded to include prescribed heat flux and convective cases. With the addition of prescribed heat flux boundary conditions, one-dimensional problems can also be dealt with by specifying a heat flux of zero on opposite sides of the object. The differential equation solved by the numerical scheme in the revised program is

$$\frac{1}{\alpha} \frac{\partial T}{\partial t} = \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \quad (1)$$

where temperature is T and the symbol α designates thermal diffusivity. This diffusivity is defined as $k / \rho c$, or thermal conductivity divided by volumetric heat capacity. The three types of boundary conditions are: constant temperature, designated by

$$T(0, y, t) = T_1 \quad T(L, y, t) = T_2 \quad T(x, 0, t) = T_3 \quad T(x, H, t) = T_4 \quad (2)$$

prescribed heat flux boundary conditions described by

$$-k \left. \frac{\partial T}{\partial x} \right|_{(0, y, t)} = q_1 \quad k \left. \frac{\partial T}{\partial x} \right|_{(L, y, t)} = q_2 \quad -k \left. \frac{\partial T}{\partial y} \right|_{(x, 0, t)} = q_3 \quad k \left. \frac{\partial T}{\partial y} \right|_{(x, H, t)} = q_4 \quad (3)$$

and convective boundary conditions designated by

$$\begin{aligned} k \left. \frac{\partial T}{\partial x} \right|_{(0, y, t)} &= h_1 [T(0, y, t) - T_{\infty 1}] & -k \left. \frac{\partial T}{\partial x} \right|_{(L, y, t)} &= h_2 [T(L, y, t) - T_{\infty 2}] \\ k \left. \frac{\partial T}{\partial y} \right|_{(x, 0, t)} &= h_3 [T(x, 0, t) - T_{\infty 3}] & -k \left. \frac{\partial T}{\partial y} \right|_{(x, H, t)} &= h_4 [T(x, H, t) - T_{\infty 4}] \end{aligned} \quad (4)$$

Note that each boundary can have its own convection coefficient and its own ambient temperature. The initial condition is described by

$$T(x, y, 0) = T_o \quad (5)$$

The initial condition for the object is allowed to be of uniform temperature only. In these equations, the width of the object in the x direction is considered to be L , and the height of the object in the y direction is considered to be H . As long as consistent units are used, the program will give correct results. For example, Table 1 below shows two possible systems of units that could be used.

| Unit of Measure | SI | U.S. |
|-----------------|---------------------|---|
| L | m | ft. |
| T | K | $^{\circ}\text{F}$ |
| k | W/m·K | Btu/hr·ft· $^{\circ}\text{F}$ |
| α | m ² /s | ft ² /hr |
| q | W/m ² | Btu/hr·ft ² |
| h | W/m ² ·K | Btu/hr·ft ² · $^{\circ}\text{F}$ |

Table 1: Two examples of consistent units that will yield accurate results. Other combinations of consistent units are equally acceptable. The units shown are the most commonly used.

Other possible unit systems which could be used include Dynes-cm-sec or Btu-in-sec. However, the unit systems in Table 1 are recommended, since they are the most commonly used.

Program Features

Coincident with the expanded number of features in the program is a need for considerably more input on the part of the students. The six input items required by the user in the previous version of the program have been expanded to 17, with a corresponding number of input boxes provided on the program screen for that purpose. Additionally, there are two “calculate” buttons to start the program instead of just one. The first “calculate” button is provided for steady state problems and the second one for transient problems. The input required is

- 1.) Rectangle height and width.
- 2.) Thermal conductivity.
- 3.) Volumetric heat capacity.
- 4.) Initial temperature for transient cases.
- 5.) Designation as to the type of boundary condition on each of the four sides:
 - a.) Prescribed Temperature.
 - b.) Prescribed Heat Flux.
 - c.) Convective Condition.
- 6.) Specification of the magnitude of the boundary condition.
 - a.) Prescribed temperature for prescribed temperature boundary condition.
 - b.) Prescribed heat flux for prescribed heat flux boundary condition.
 - c.) Ambient temperature for convective boundary condition.
- 7.) Convection coefficient must be specified if boundary condition is convective.

As with the previous edition of the program, the rectangular plot is scaled such that the longest of the two dimensions is 5000 pixels, and the other dimension is shortened proportionally. For example, if the user specifies a rectangle with a width of 4 and a height of 2, the program will scale the rectangle to have a width of 5000 pixels and a height of 2500 pixels. Also, 10 colors are used for depicting temperature, ranging from a bright yellow for the hottest temperature to a dark blue for the coldest. A legend is provided at the bottom of the window to show the user which temperatures correspond to which colors.

A sample of the program screen, depicting the results from a two dimensional steady state conduction case, is shown in Figure 1. This example involves one prescribed heat flux boundary condition at the top of the object, convective boundary conditions on both of the vertical sides and a prescribed temperature condition on the bottom surface. A legend is provided to convey the temperature values associated with each of the colors.

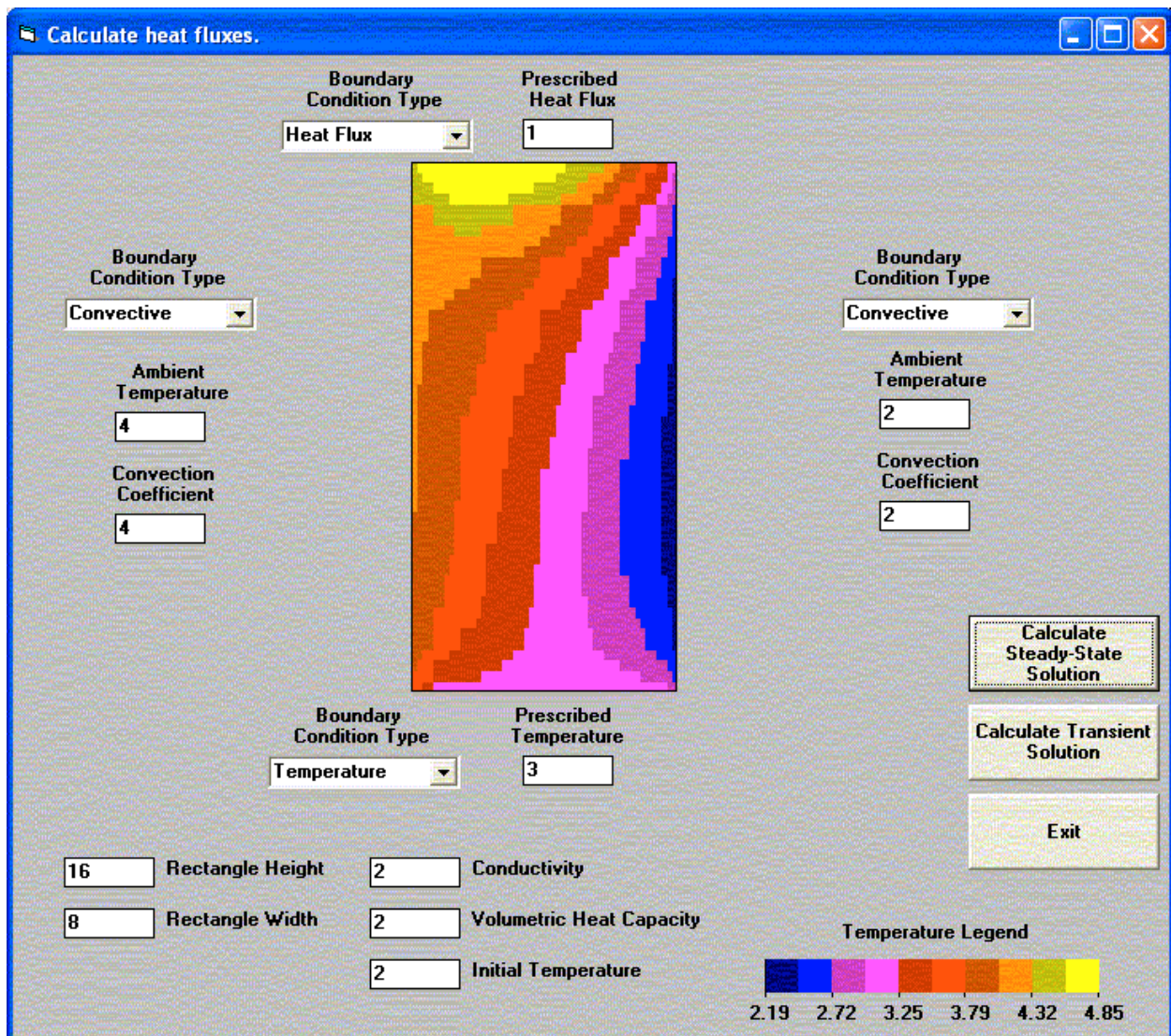


Figure 1: Sample screen from program.

Two Dimensional Heat Conduction Visualization Exercise

Problem 1

Consider a rectangular region over which heat conduction is occurring. The region has a length of 1 and a height of 0.5. The left boundary is at temperature of 100 and the right boundary is at a temperature of 200. The lower surface is adiabatic and the upper surface is in contact with a fluid at a temperature of 150 and a convective heat transfer coefficient of 2000.

- Provide a 2-D graph of the temperature distribution for a region thermal conductivity of 200.
- Provide a 2-D graph of the temperature distribution for a region thermal conductivity of 0.1.
- Comment on the differences between the two temperature distributions
- What happens to the temperature distribution as the convective heat transfer coefficient on the upper surface becomes very small?

Problem 2

Consider a rectangular region over which heat conduction is occurring. The region has a length of 1 and a height of 0.1. The left boundary is at temperature of 200 the remaining surfaces are in contact with a fluid at a temperature of 75 and a convective heat transfer coefficient of 5. We wish to explore the conditions under which this rectangle will behave as a fin. Graph the temperature versus vertical position at the horizontal halfway location for the following conditions.

- Varying region thermal conductivity
- Varying convective heat transfer coefficient
- Varying length

Using these graphs develop criteria for the condition under which we can use a fin model for this situation.

Problem 3

Consider a rectangular region 6cm wide and 4cm high which is maintained at 100°C on the top edge, is insulated on the right edge, has a heat flux of 100 W/m² on the bottom edge and a convection coefficient of 1000 W/m²K and an ambient temperature of 25°C on the left edge. This material has a thermal conductivity of 1 W/mK and a volumetric heat capacity of 10000 J/m³K and is initially at a temperature of 25°C. Using the transient analysis method,

- How long does the transient last (in seconds)?
- How does this change if k is changed to 2 W/mK? Is that what you expect?
- What is the final temperature range of the body?
- Now change the initial temperature to 98°C and comment on the differences you observe from the previous case. Explain why you believe these differences are exhibited.

Figure 2: Homework assignment given to students.

The program provides a notification window when calculations are in progress, but only appears for approximately 1 second on transient problems and does not even appear at all in steady state calculations. This seems to be fairly uniform between computers of various processor speeds. The program is available to the public for free upon request from the authors.

Results

The program was made available to heat transfer students at two independent State-supported institutions in two separate states. The first institution was very small with a total undergraduate enrollment of approximately 1,300 students, and a Mechanical Engineering department graduation rate of approximately 40 undergraduates per year. The second institution was very large with a total undergraduate enrollment of approximately 35,000 and a Mechanical Engineering department graduation rate of approximately 150 undergraduates per year. The assignment shown in Figure 2 was given to the students enrolled in the Heat and Mass Transfer courses in each of the two schools in conjunction with the use of the computer program developed as part of this research.

| Question | Strongly Disagree | Disagree | Neutral | Agree | Strongly Agree |
|--|-------------------|----------|---------|-------|----------------|
| 1. The problem enhanced my understanding of steady conduction heat transfer (heat flux) in a two-dimensional solid | 0 | 2 | 14 | 53 | 13 |
| 2. The problem enhanced my understanding of temperature distributions due to imposed boundary conditions. | 0 | 0 | 10 | 47 | 25 |
| 3. The problem enhanced my appreciation of the use of the computer in the solution of heat transfer problems | 0 | 5 | 8 | 41 | 28 |
| 4. I found the project enhanced my understanding of the course material | 0 | 3 | 28 | 47 | 8 |
| 5. The project was relevant to our study of conduction heat transfer | 0 | 0 | 3 | 54 | 25 |

Table 2: Survey results from students having used the program in conjunction with the homework assignment given above.

Following the completion of the assignment, students were surveyed to determine their reactions to the exercise utilizing the program. The survey questions and number of student replies are shown in Table 2. The reactions from the students were generally positive. This data is based on a 1-5 scale, 5 for strongly agree and 1 for strongly disagree. It is interesting to note that one class had a more positive reaction to the assignment than did the other class. This was also seen in the written comments from the students. Students in the first class seemed to have difficulty getting the program to run. They were disappointed in the resolution of the color graphics and a few were concerned with the accuracy of the software. The comments from the second class were all positive, noting that the software was “easy to use” and a “good program overall”. One of these students suggested that a Mac OS X version be created. Neither class was provided with a user’s guide or a tutorial session, which reinforces the ease of use of the software.

Figure 3 below provides a graphical representation of the student responses. As shown in the tables, the results were positive. One troubling observation is that the replies to question 4 resulted in the lowest rating from the students. Moreover, this question related directly to the students' understanding of the material. Figure 4 shows a graphical representation of the survey results from this question alone. As this figure shows, a clear majority of the students consider that the program was helpful in their understanding of the course material.

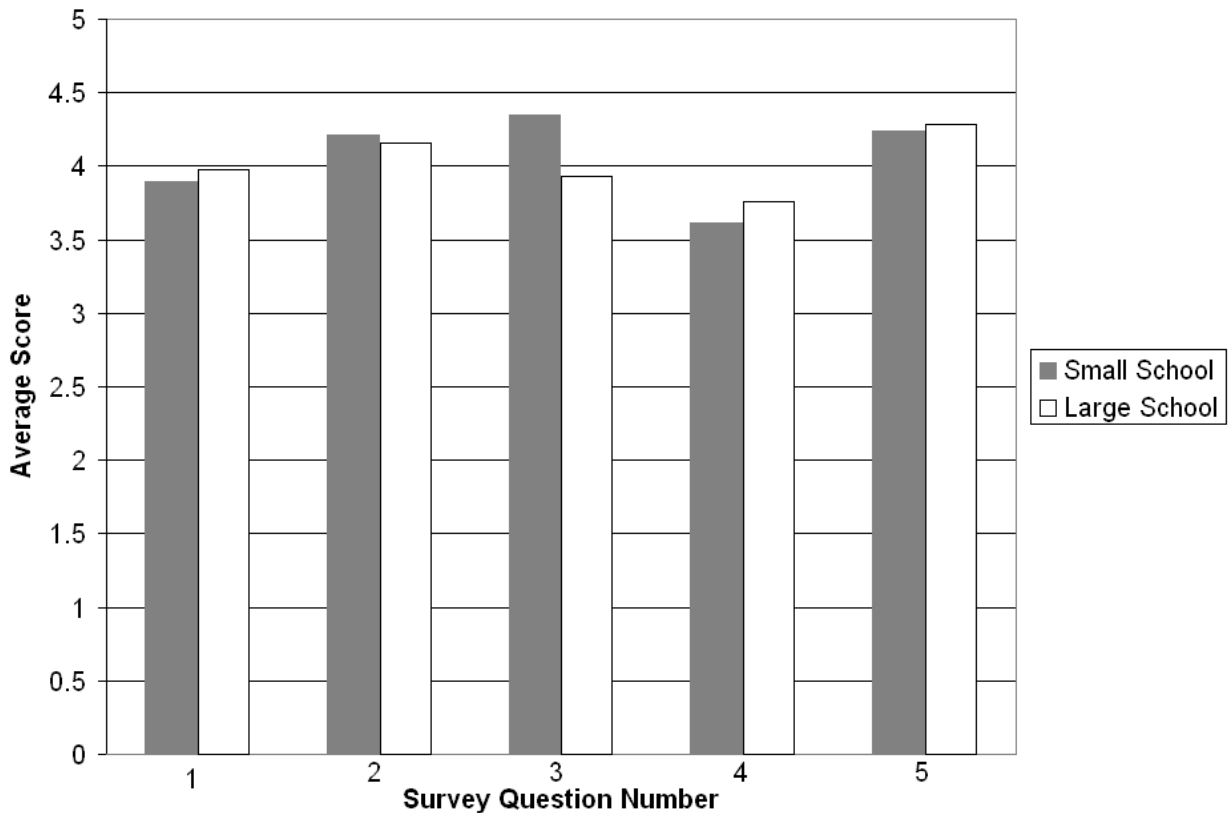


Figure 3: Survey results compiled showing the average ratings given by students on a 1-5 scale, 5 for strongly agree and 1 for strongly disagree.

Conclusions

The program was used in concert with the undergraduate Heat and Mass Transfer classes in the departments of Mechanical Engineering in two separate schools in separate states in the US. The heat transfer courses are required as part of the core curricula in each of the schools involved in this research. The results of the student survey show a favorable response from the students and the program has provided positive augmentation to the course and to the students' understanding of conductive heat transfer.

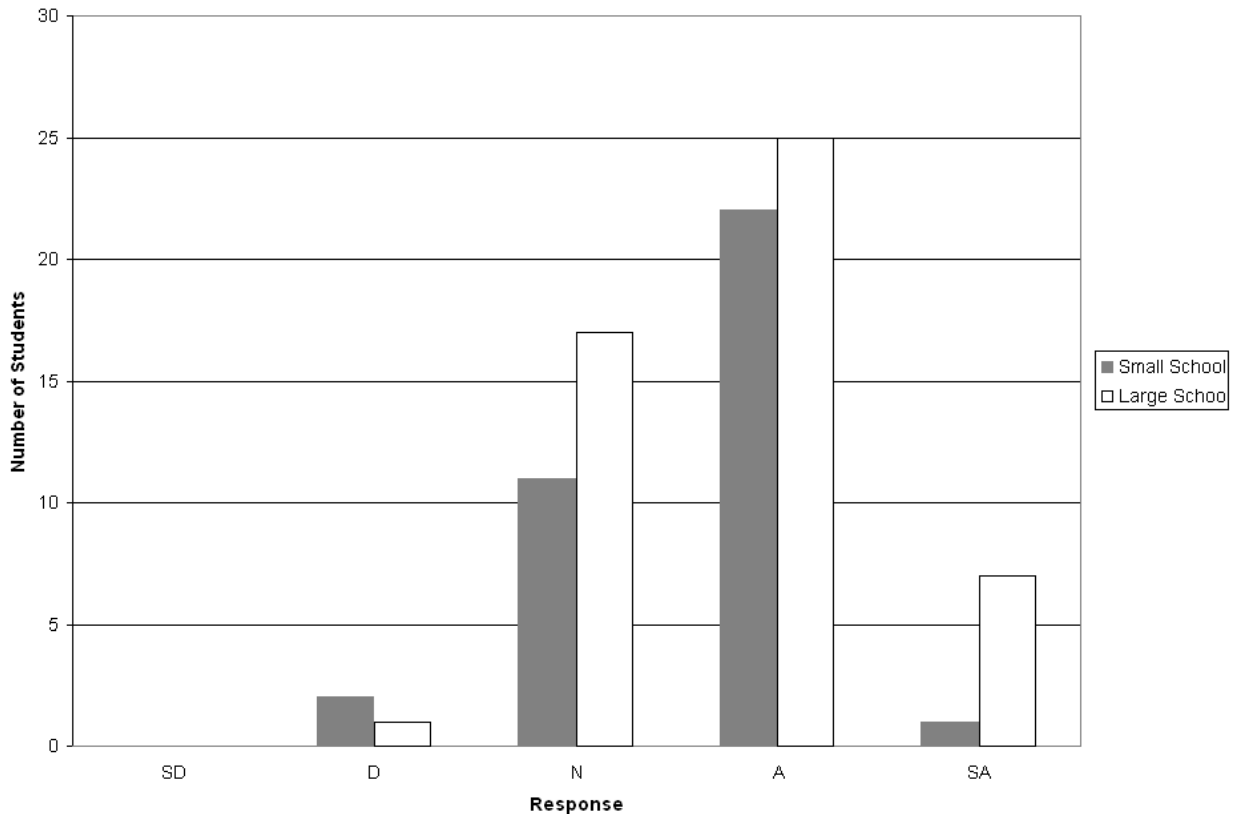


Figure 4: Survey results for question 4, regarding the enhancement the program offered in understanding the course material.

References

- [1] R. McMasters and M. Sexton, "Interactive Computer Program for Enhancing Conductive Heat Transfer Concepts", *Proceedings of the 2006 ASEE Conference*, Chicago, 2006.
- [2] R. McMasters, K. Dowding, J. Beck, and D. Yen, "Methodology to Generate Accurate Solutions for Verification in Transient Three-Dimensional Heat Conduction," *Journal of Numerical Heat Transfer, Part B*, Vol. 41, pp.521-541, 2002.
- [3] A. Ghajar, H. Al-Matar, and R. Delahoussaye, "Development and Implementation of Interactive/Visual Software for Steady State and Transient Heat Conduction Problems", *Proceedings of the 2006 ASEE Conference*, Chicago, 2006.
- [4] J. Baughn, "A Spreadsheet Approach to Teaching Numerical Methods for Steady and Unsteady Heat Transfer", *Proceedings of the 2006 ASEE Conference*, Portland, 2005.
- [5] M. Maixner, "Interactive Graphic Depiction of Working Fluid Thermal Properties Using Spreadsheets", *Proceedings of the 2006 ASEE Conference*, Chicago, 2006.