Finite Element Analysis Tutorials for an Undergraduate Heat Transfer Course

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Abstract

Commercial finite element packages are widely used in industry thereby making exposure to this analysis and optimization tool an important component of undergraduate engineering education. Finite element analysis (FEA) tutorials have been developed for various undergraduate engineering courses, including mechanics of materials, vibrations, heat transfer, fluid mechanics, and machine design and analysis; these tutorials serve as an effective teaching and learning resource that reinforces the fundamental concepts and applications of each course. This paper discusses the implementation, results, impact, and assessment of incorporating steady-state and transient heat conduction tutorials into an undergraduate heat transfer course using SolidWorks and COSMOSWorks commercial software. The primary goals of these tutorials are to provide the students with *(a)* a different insight into the heat transfer concepts that are covered in a traditional undergraduate course, *(b)* a basic knowledge of finite element theory, and *(c)* the ability to apply commercial finite element software to engineering problems involving thermal systems. Assessment has been done through the use of pre- and post-tutorial quizzes, student opinion surveys, and demographic surveys of student learning styles. Furthermore, the implementation of a design project that involves an application of the knowledge gained from the tutorials is also discussed.

Introduction

The finite element (FE) method is a widely used tool in industry for analyzing engineering problems. The most basic FE theory and applications are offered primarily as a graduate-level course, or in some cases, as an upper-level elective for undergraduate students. Therefore, the majority of engineering programs *do not require* coverage of FE theory and application as a component of their undergraduate curriculum. Industry is placing an increased emphasis on the ability to apply this powerful computational tool; so it follows that students earning an undergraduate degree in engineering should learn this skill in order to meet the demands of entry-level engineering job descriptions. The persistence of the deficiency of FE coverage in undergraduate engineering programs is due to various reasons, such as the recent focus on reducing credit-hours in engineering programs; the need to remove other material at the expense of adding this new material; and the fact that FE theory is very mathematics-intensive thereby making it more suitable for graduate students who have a more rigorous mathematical education. Nevertheless, there is clearly a need and curriculums should attempt to integrate this important component.

This paper discusses a mechanism for delivering FE instruction through the use of heat transfer tutorials that can be easily integrated into a *required* mechanical engineering course. The need for integrating FE theory and application across the engineering curriculum has been established and methods have been suggested by other authors[1-2]. **The primary focus of the current paper is to report the use of an instructional tool that would educate a broader spectrum of undergraduate engineering students with the basic knowledge of FE theory as applied to thermal analyses.** Furthermore, students using these tutorials will gain experience in applying commercial FE software to solve engineering problems. It should be emphasized that the focus of these tutorials is not to turn every engineering student into a FE expert.

More details of the NSF-funded CCLI project that this tutorial is a component of can be found elsewhere[3]; in short, instructional tutorials have been developed for several core engineering areas, including mechanics of materials, vibrations, heat transfer, fluid mechanics, and machine design and analysis. The current paper focuses in more detail on the heat transfer component of this project.

The educational goals of the heat transfer tutorials include the following:

1) to develop thermal FE tutorials that are easily accessible and require minimal instructor effort in order to integrate them into a required mechanical engineering undergraduate heat transfer course,

2) to provide undergraduate engineering students with a basic understanding of FE theory as applied to thermal analyses,

3) to provide undergraduate engineering students with an ability to apply commercial FE software in order to solve thermal engineering problems, and

4) to provide a different insight into the heat transfer concepts that are covered in a traditional undergraduate mechanical engineering heat transfer course.

Tutorial Summaries

A steady-state heat conduction problem and a transient heat conduction problem were chosen as the basis for the two heat transfer tutorials. Problems were chosen that could also be solved relatively easily by hand calculations using numerical methods in order to allow for a comparison between the FEA solution and the hand calculations. The steady-state and transient heat conduction problems are summarized in Figs. 1 and 2, respectively. The steady-state problem was adopted from Chapter 4 ("Two-Dimensional, Steady-State Conduction") of Incropera et al.'s textbook[4], while the transient problem was adopted from Chapter 5 ("Numerical Methods in Heat Conduction") of Çengel's textbook[5].

A long bar of rectangular cross-section (0.4 m × 0.6 m) with a thermal conductivity of k = 1.5 W/m · °C, is subjected to the following boundary conditions: two sides are maintained at 200°C, one side is insulated, and the remaining side is subjected to convection with the surrounding fluid at T_∞ = 30°C and h = 50 W/m^2 · °C. Using a grid spacing of 0.1 m, determine the temperature distribution in the bar and the heat transfer rate between the bar and the fluid per unit length of the bar.

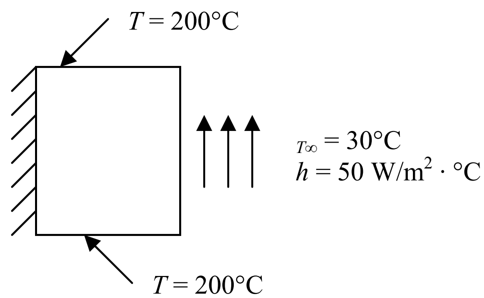

Figure 1: Steady-state heat conduction problem description (adopted from Incropera et al.[4]).

Consider two-dimensional transient heat transfer in an *L*-shaped solid body that is initially at a uniform temperature of 90°C and whose cross section is given in the figure below. The thermal conductivity and diffusivity of the body are k = 15 W/m · °C and α = 3.2 × 10^{-6} m^2/s, respectively, and heat is generated in the body at a rate of $\dot{e}$ = 2 × 10^6 W/m^3. The left surface of the body is insulated, and the bottom surface is maintained at a uniform temperature of 90°C at all times. At time t = 0, the entire top surface is subjected to convection to ambient air at T_∞ = 25°C with a convection coefficient of h = 80 W/m^2 · °C, and the right surface is subjected to heat flux at a uniform rate of $\dot{q}_R$ = 5000 W/m^2. The nodal network of the problem consists of 15 equally spaced nodes with Δx = Δy = 1.2 cm. Using the explicit method, determine the temperature at the top corner of the body after 1, 3, 5, 10, and 60 min.

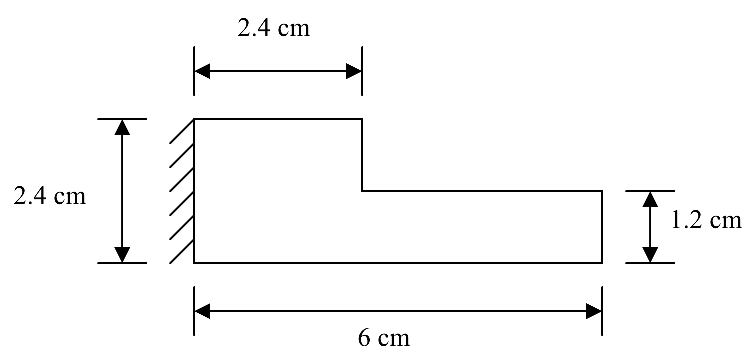

Figure 2: Transient heat conduction problem description (adopted from Çengel[5]).

After the introduction of the problem statement, each tutorial includes the following major steps:

1. *Using SolidWorks to create a 3-D model.*
   The steps required to draw the model in SolidWorks are summarized, including creating a two-dimensional sketch and extruding the sketch to make a 3-D object and dimensioning the 3-D object. These elements of the tutorial are presented such that a student with minimal background with SolidWorks will be able to model the problem.

2. *Submitting the model to COSMOSWorks.*
   The steps required to open the 3-D object in COSMOSWorks and create a thermal study are summarized.

3. *Defining material properties.*
   The steps required to assign the material properties which are necessary for a thermal analysis are summarized. Instructions for creating both custom-defined materials and common material types (aluminum, copper, etc.) are included.

4. *Defining the transient analysis time increments and the time of study (transient tutorial).*
   The steps required to define the transient conditions are summarized including the total time of study and the time increment.

5. *Defining the thermal boundary conditions, initial condition (transient tutorial), and heat generation (transient tutorial).*
   The steps required to define the thermal boundary conditions are summarized, including convection, specified temperature, heat flux, and adiabatic (zero heat flux) conditions. The transient tutorial includes steps for defining the initial condition and a uniform heat generation throughout the entire volume of the 3-D object.

6. *Meshing the model.*
   The steps required to create a three-dimensional mesh using second-order tetrahedral solid elements type are summarized.

7. *Running the FEA.*
   The steps required to run the finite element analysis are summarized.

8. *Analyzing the results.*
   Information on post-processing the FEA results is included, including using a temperature probe to determine temperature values at points of interest and creating 3-D color plots. For reference, the temperature plots that are the primary output from COSMOSWorks are included in Fig. 3 for the steady-state tutorial and in Fig. 4 for the transient tutorial

9. *Finite Element Analysis Theory.*
   As an appendix to the tutorials, background information on FEA theory is included; this material is aimed at students with minimal knowledge of FEA. Concepts such as element types and the effects of mesh size on the results are discussed, in addition to a list of references for more information on FEA theory.

Implementation

The steady-state and transient tutorials discussed above have been incorporated into an undergraduate heat transfer course at the University of the Pacific. The majority of students in this class have taken a course in SolidWorks, but this is not required since the tutorials are written such that no familiarity with SolidWorks is necessary. The topic of numerical methods in heat conduction is covered before the tutorials are used. Specifically, finite difference techniques for one- and two-dimensional steady-state and transient heat conduction are covered in class; Chapter 5 (“Numerical Methods in Heat Conduction”) of Çengel’s textbook[5] is used as a reference in covering this material. With this knowledge, students are able to solve the tutorial problems by hand and ultimately compare the FEA output with these hand calculations. To further demonstrate the principles learned by the tutorials, additional homework problems have been assigned, such as those included in Fig. 5 for steady-state heat conduction (Incropera et al.[4]) and in Fig. 6, which is directly related to the transient heat conduction tutorial problem described in Fig. 2.

Finally, a thermal design project has been implemented into the heat transfer course at the University of the Pacific where the students are required to apply the knowledge gained from the tutorials. In summary, the students are required to come up with a design that will meet the specified requirements by creating a 3-D computer model, submitting the model to COSMOSWorks, and analyzing the FEA output. These design projects are especially powerful in demonstrating the concept of optimization.

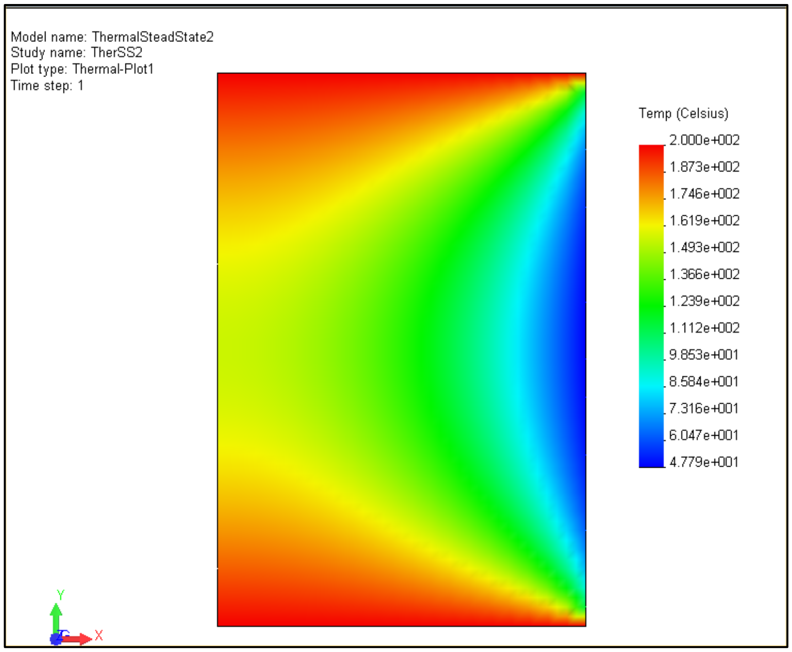

Figure 3: Temperature plot for the steady-state tutorial problem described in Fig. 1.

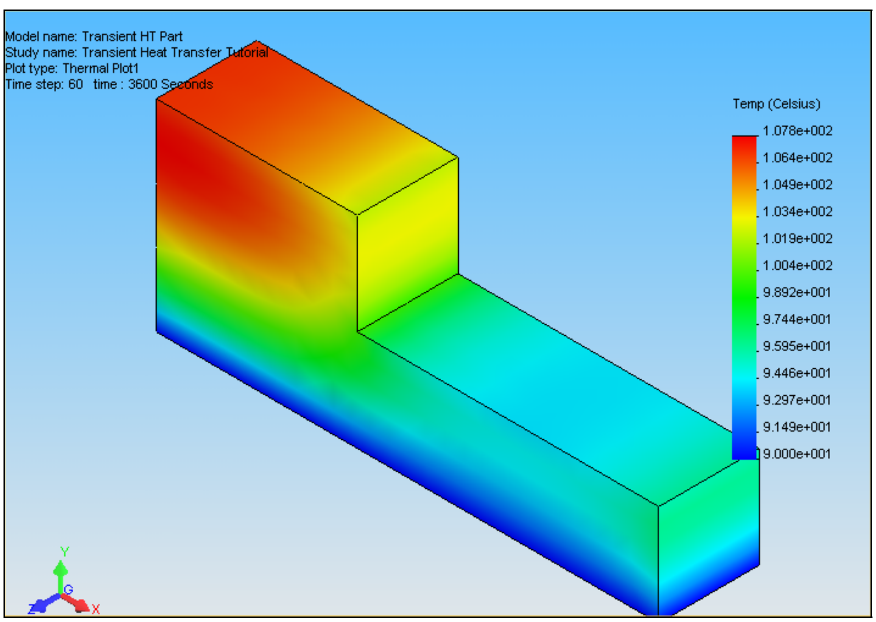

Figure 4: Temperature plot for the transient tutorial problem described in Fig. 2.

An aluminum plate (k = 190 W/m · °C) is in contact with a chip dissipating power. To cool the plate, water is passed through regularly-spaced rectangular channels within the plate. Power dissipation within the chip results in a uniform heat flux of $\dot{q}$ = 10^5 W/m^2 at the base of the plate, while the water flow provides a temperature of T_∞ = 15 °C and a heat transfer coefficient of h = 5000 W/m^2 · °C within the channels. Assuming the top surface of the plate is insulated, utilize symmetry and the nodal network below to solve for the steady-state temperature distribution within the plate by *(a)* hand calculations and *(b)* using COSMOSWorks computational finite element analysis. Compare the results at a few key points on the plate.

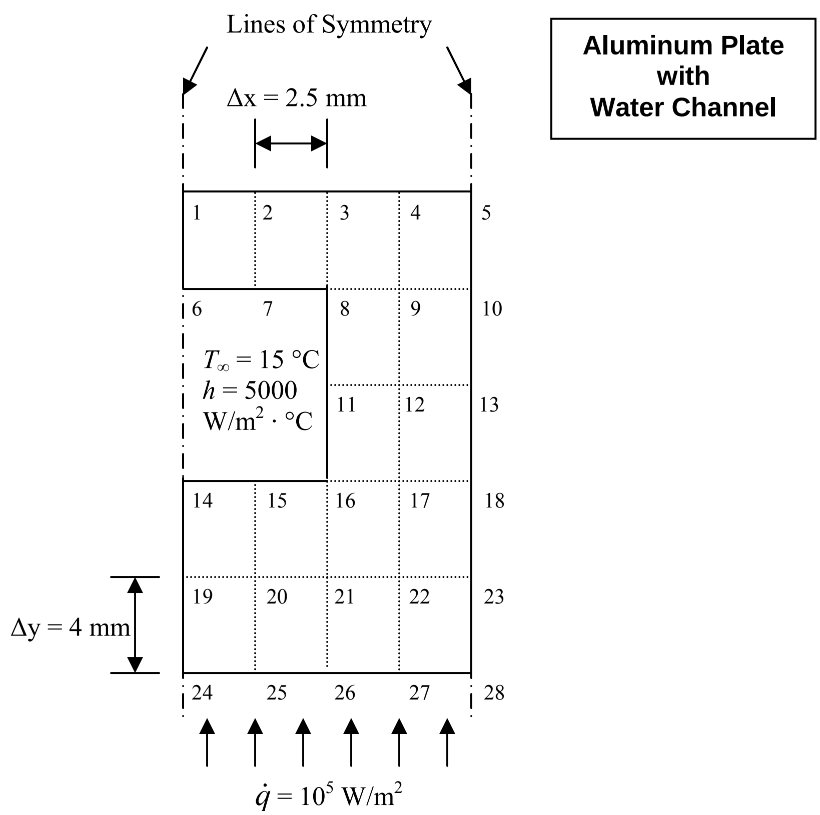

Figure 5: An additional steady-state heat conduction problem (adopted from Incropera et al.[4]).

Perform the "Transient Thermal Finite Element Analysis Tutorial" (see problem described in Fig. 2) for COSMOSWorks and complete the following:

a) Create plots of the temperature (in °C) versus time at the corner nodes shown below (Location #1 and Location #2).
b) Create temperature plots of the entire bar at 1 minute and 10 minutes.
c) Repeat part *b)* for $k = 1.5$ W/m·K and comment on the comparison between parts *b)* and *c)*.

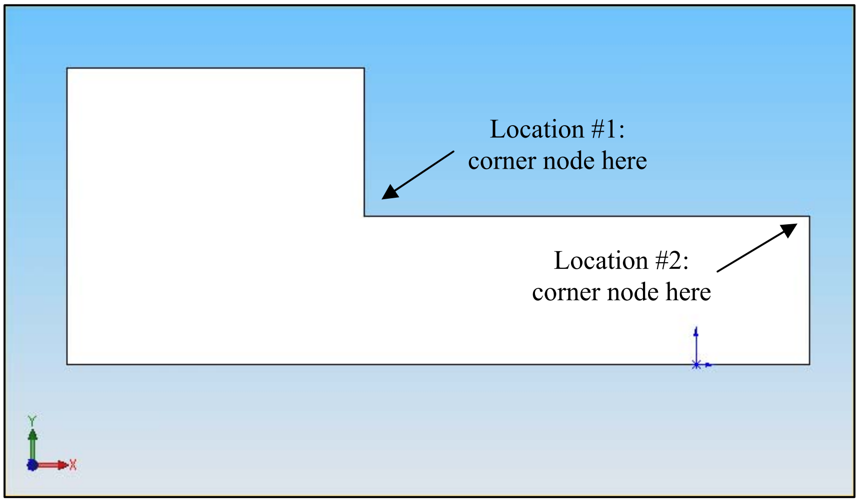

Figure 6: An additional transient heat conduction problem which is an extension of the problem described in Fig. 2 and used in the transient heat transfer tutorial.

Assessment

The primary method for assessing the success of the heat transfer tutorials is the use of pre- and post-tutorial quizzes. These quizzes were designed primarily to assess the success of the tutorials in meeting the goal of reinforcing the concepts that are covered in a traditional undergraduate mechanical engineering heat transfer course by providing a more visual and "hands-on" insight. The quiz consists of eight questions related primarily to the concept of heat conduction through a solid body and the application of Fourier's Law of heat conduction (see Appendix A). The same quiz is administered pre- and post-tutorial and the results are tracked for each individual student. During the spring 2008 semester, among 19 students the average quiz score improved from 63.2% pre-tutorial to 72.4% post-tutorial, showing a 14.6% improvement. Furthermore, of the 19 students, 12 showed improvement, 5 attained the same result, and 2 showed a decrease in quiz score. Information from demographic data sheets, Myers-Briggs personality profiles (http://www.humanmetrics.com/cgi-win/JTypes2.asp), and the Felder-Silverman Index of Learning Styles (http://www.engr.ncsu.edu/learningstyles/ilsweb.html) were also gathered for each student in an attempt to correlate the success of the tutorials for different learning styles. More information about these assessment tools and their use in this study can be found in Brown et al.[3].

Conclusions

This paper reports the use of heat transfer tutorials in a required mechanical engineering undergraduate heat transfer course. Increasing industry demand for graduates to have the ability to use and apply commercial FE packages has created a need for integrating FE instruction into the undergraduate engineering curriculum. These tutorials provide a tool for easily implementing the FE method and application into the curriculum in order to provide a basic understanding of FE theory as applied to thermal analyses. Additional tutorials have been developed for other core engineering areas making the use of these tutorials across the engineering curriculum an excellent means for providing substantial coverage of the FE method. Furthermore, results suggest that these tutorials aid in reinforcing the basic heat transfer concepts covered by traditional lecture material.

Acknowledgement

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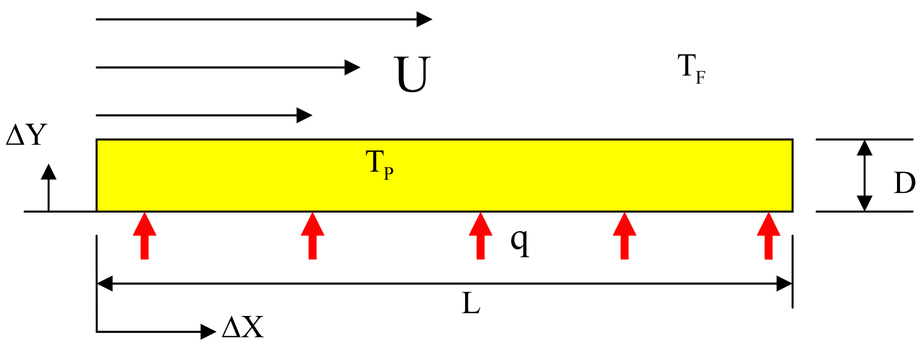
Appendix A (Pre- and Post-Tutorial Quiz)

Heat Transfer/Numerical Methods Basic Knowledge
(Pre/Post to completing the Two Heat Transfer Tutorials)

Your student ID is used only to match up your heat transfer basic knowledge prior to completing the finite element heat transfer tutorial and after completion of the tutorials. We will not correlate your knowledge or responses with your name or use in assessing your grade. Thank you in advance for your cooperation in our research efforts to improve learning under this NSF Grant. Prof. Ashland O. Brown

Pacific Identification Number: ____________________

We have a cross-section of a flat plate being heated from below with a constant flux q in an air stream with and average velocity U. We will assume the heat transfer is only one dimensional in the Y direction of this plate.



T_F - air stream fluid temperature
T_P - plate temperature
L - plate length
D - plate height
h - convection heat transfer coefficient
k - thermal conductivity of the plate
q - uniform heat flux
A - surface area of the plate into the paper

$Q_{conduction}$ - 1-D conduction in Y-dir
c_P - specific heat at constant pressure
α - thermal diffusivity
ρ -density

1. Define the rate of heat conduction in the Y direction for the plate between the two points 1 on the plate surface and 2 on underside of the plate. (circle the correct formulation)

$$Q_{Conduction} = k\,A(T_{P1} - T_{P2}) \qquad Q_{Conductin} = -kA\frac{(T_{P1} - T_{P2})}{D}$$

$$Q_{Conduction} = -k\frac{D(T_{P1} - T_{P2})}{A}$$

2. Thermal diffusivity α is used in a transient thermal analysis and represents how fast heat diffuses through a material and would have the following formulation: (circle the correct formulation)

$\alpha = \frac{Ak}{c_P}$ $\alpha = \frac{k}{\rho \cdot c_P}$ $\alpha = \frac{\mu \cdot k}{\rho}$ $\alpha = \frac{hA}{k}$

3. Define the rate of convection (Newton's Law of cooling) in the Y direction from the plate between a point in the air flow stream and a point 1 on the surface of the plate.

$Q_{Conv} = hD(T_F - T_{P1})$ $Q_{Conv} = \frac{h}{k}(T_F - T_{P1})$ $Q_{Conv} = hA(T_F - T_{P1})$

4. If there is a temperature gradient between the top and bottom of the plate, and we hold the heat flux constant but increase the air stream average flow velocity this plate temperature gradient would: (assume constant material and air properties)

Increase Decrease Remain the same

5. If there is a temperature gradient between the top and bottom of the plate, and we hold the air velocity fixed, but increase the heat flux rate to the bottom of the plate we would expect the plate surface temperature to: (assume constant material and air properties)

Increase Decrease Remain the same

6. If we performed a heat balance of the conduction through the plate and the convection from the plate's surface and used the thermal resistance concept our formulation for the steady rate of heat transfer through the plate would be:

$Q = \frac{\Delta T_{plate}}{hkA}$ $Q = \frac{\Delta T_{Plate} \cdot D}{kA}$ $Q = \frac{\Delta T_{Plate}}{\frac{1}{hA} + \frac{D}{kA}}$

7. The finite element method of modeling heat transfer in the plate approximates the differential equations with _____ _______ of equations.

a. finite differences b. nodal models c. linear arrays d. finite numbers

8. An object is undergoing transient heat conduction. If the thermal conductivity of the object is decreased by changing the material, the object will reach a steady-state temperature distribution:

a. faster b. slower c. in the same amount of time

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Biographical Information

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Kyle A. Watson is an assistant professor of mechanical engineering at the University of the Pacific. He has served in that position since 2003 and has taught undergraduate courses in thermodynamics, heat transfer, combustion, air-conditioning, dynamics, capstone design, and introduction to engineering. He received his B.S. in Mechanical Engineering from Villanova University and M.S. and Ph.D. in Mechanical Engineering from North Carolina State University. He has published numerous journal articles in the areas of experimental combustion science and engineering pedagogy.

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Ashland O. Brown is a professor of mechanical engineering at the University of the Pacific in Stockton, CA. He has held numerous administrative, management and research positions including Program Director, Engineering Directorate, National Science Foundation; Dean of Engineering at the University of the Pacific; Dean of Engineering Technology at South Carolina State University; Engineering Group Manager at General Motors Corporation; Principal Engineering Supervisor, Ford Motor Company; and Research Engineer, Eastman Kodak Company. He received his B.S. in Mechanical Engineering from Purdue University and M.S. and Ph.D. in Mechanical Engineering from the University of Connecticut. He has authored over 40 referred and propriety publications in automotive design, finite element modeling of automobile body structures, and photographic film emulsion coating instabilities. His most recent research includes development of innovative finite element tutorials for undergraduate engineering students and vibration analysis and measurement of human skeletal muscles under stress using laser holography.