AC 2011-682: BALANCING THEORY, SIMULATION AND PHYSICAL EXPERIMENTS IN

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Balancing Theory, Simulation and Physical Experiments in
Heat Transfer Education

Abstract: Some big problems for students studying heat transfer are (1) difficulty in visualizing both basic and complex theoretical concepts, (2) unsure how to design changes effect heat flow or temperature distributions, (3) unclear how to apply theoretical concepts in the development of components / systems and (4) confusion with how to extend single point experiments to generic applications. It is impossible for students to solve complex heat transfer problems through theoretical hand calculations or execute real experiments when the boundary conditions are complicated because of time and laboratory equipment cost constraints. During the laboratory experience, students are guided in the use of SolidWorks/Simulation for conducting virtual experiments and comparing them to theoretical concepts presented in lecture along with simple physical measurements in the laboratory.   Thru the use of virtual experiments in the SolidWorks environment, students have full control of the experiment by having the ability to change virtual boundary conditions and running the virtual experiments as many times as needed until they understand the concepts. The applications of virtual experiments which include geometric sensitivity studies help students to visualize the application of concepts in simulated design applications. From our direct observations in several classes, students gain a better understanding of both the theoretical concepts and application to design refinement by creating virtual components in addition to gaining hands-on experience directly applicable to industrial applications. With the introduction of true 3D CAD and associated simulation software such as SolidWorks/SolidWorks Simulation, the concept of balancing virtual simulations for comparison to theory and physical experiments are presented in this paper for effectively teaching heat transfer in a mechanical curriculum.

Introduction:

Developing student understanding, visualization and theoretical concept application to design are key components to successful education of future engineers. Application to design is not satisfied simply by conducting physical experiments without imparting a deeper understanding of the underlying phenomenon relative to design decisions. Developing experiments that address design change sensitivity on system performance can be both exceedingly costly and time consuming. Experiments alone can actually be detrimental if the students are not able to visualize the broader impact of complex boundary conditions encountered in real life on design decisions. A potential solution to impart better understanding is to combine concept validation type physical experiments with virtual experiments that extend the basic phenomenon covered in lectures using available analysis software packages in wide spread industrial use such as SolidWorks [1].

The concept of developing virtual parts, assemblies and the analysis of virtual parts using SolidWorks and Simulation [1, 2, 3 and 4] can be extended to enhancing student theoretical visualization and laboratory experiences. This paper presents two examples of a balanced approach for using virtual experiments with physical experimentation in teaching basic concepts of heat transfer; one dimensional conduction and conduction in extended surfaces. The internal temperature distributions in these two examples are compared to theory and available laboratory hardware.

One Dimensional Heat Transfer:

References [5 and 6] provide a traditional development of the general heat conduction equation in both rectangular and cylindrical coordinate systems based on sound thermodynamic principles. The concept of thermal conductivity as a material property is presented along with illustrations of the experimental set up used to quantify the value for various substances. The simplified Fourier equation for conduction expressed in both differential and algebraic forms in rectangular and cylindrical coordinates is provided below as equations 1 thru 5 with the associated temperature distributions as equations 6 and 7.

$$\dot{Q} = -kA\frac{dT}{dx} \quad (1)$$

$$\dot{Q} = -kA\frac{T_2-T_1}{L} \quad (2)$$

$$\dot{Q} = kA\frac{T_1-T_2}{L} \quad (3)$$

$$\dot{Q} = -kA\frac{dT}{dr} \quad (4)$$

$$\dot{Q} = 2\pi kL\frac{T_1-T_2}{\ln(r_2/r_1)} \quad (5)$$

$$T(x) = \frac{T_2-T_1}{L}x + T_1 \quad (6)$$

$$T(r) = \frac{\ln(r/r_1)}{\ln(r_2/r_1)}(T_2 - T_1) + T_1 \quad (7)$$

Hampden Engineering Corporation provides typical heat transfer training systems for both academia and industry. Model H-6862A "Thermal Conduction Trainer" shown in figure 1 is utilized in the laboratory portion of the course. The purpose is to demonstrate the different temperature distributions associated with both coordinate systems, various materials and to duplicate the measurement of thermal conductivity as described in the literature.

The radial portion utilizes an 11" diameter 1/8" copper plate with a 100 Watt cartridge heater positioned at the center. The linear portion of the set up utilizes a 1" diameter brass bar with a 100Watt cartridge heater and a swappable section which can be used to insert insulated bars made of various materials. Both setups are instrumented with thermocouples at 1" intervals to allow the students to plot the temperature data as a function of distance from the heat source. A water cooling loop on the opposite boundary from the heater is utilized to achieve thermal equilibrium.

H-6862A
Thermal Conduction
Demonstrator
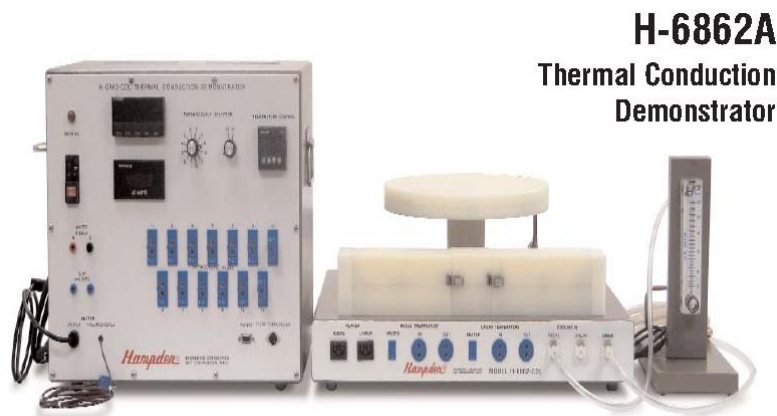
MODEL H-6862A-CDL Thermal Conduction Demonstrator with CDL Option

Figure 1: Thermal Conduction Test Equipment

While this is a quality piece of equipment and satisfies the basic demonstrations, it is limited in the number of cross sectional shapes, sizes, material types and temperature data points. The other fundamental drawback of any thermal equilibrium experiment is time to stabilization seems to lose student interest as indicated on course evaluations. Simple Finite Element Analysis (FEA) virtual experiments were subsequently conducted in parallel to physical experiments which allow the students more flexibility in performing "what if" sensitivity comparisons and extending beyond the capability of the experimental setup. Based on class surveys and student course evaluations subsequent to the implementation of virtual experiments, it seems that the digital age students would rather have the quicker feedback in the tactile / visual world of FEA and are extremely comfortable without physical contact with experimental hardware other than physical observation of the mechanisms.

Conduction Virtual Experiment:
The experimental write up requires students to compare theoretical calculations to data obtained during the lab with FEA results. The students are then required to extend the analysis for multiple materials and cross-sectional shapes, areas and lengths with a constant heat rate applied to a particular boundary. The baseline lab calculations and finite element analysis are typically carried out in the lab by the time the physical hardware reaches thermal equilibrium for the first configuration.

The basic boundary conditions include specifying a heat rate and initial temperature of 100 watts and 298K respectively. Figures 2 and 3 are sample results obtained from SolidWorks Simulation for a rectangular cross section. The results clearly show the linearity of the temperature distribution in both color and graphical plots.
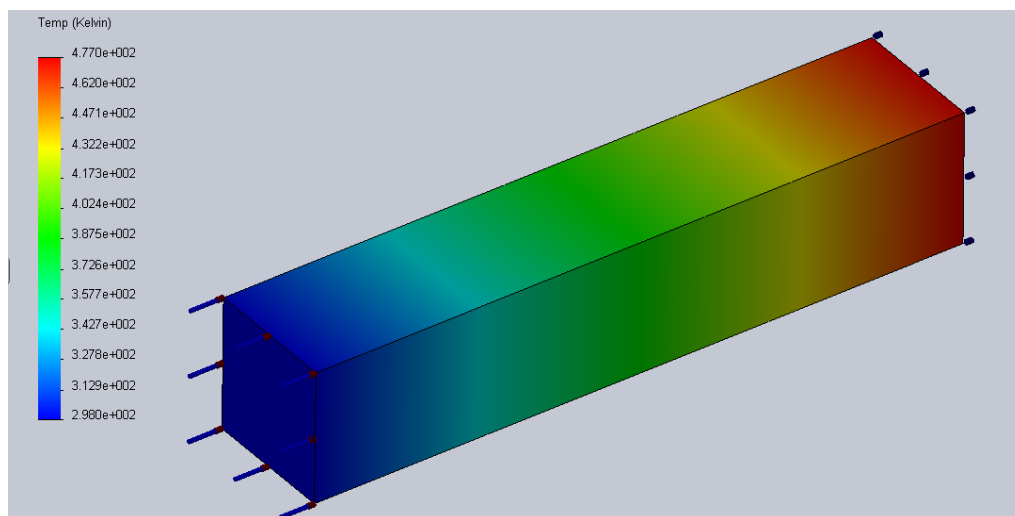

Figure 2: FEA Temperature Distribution For Basic Linear Conduction Virtual Experiment
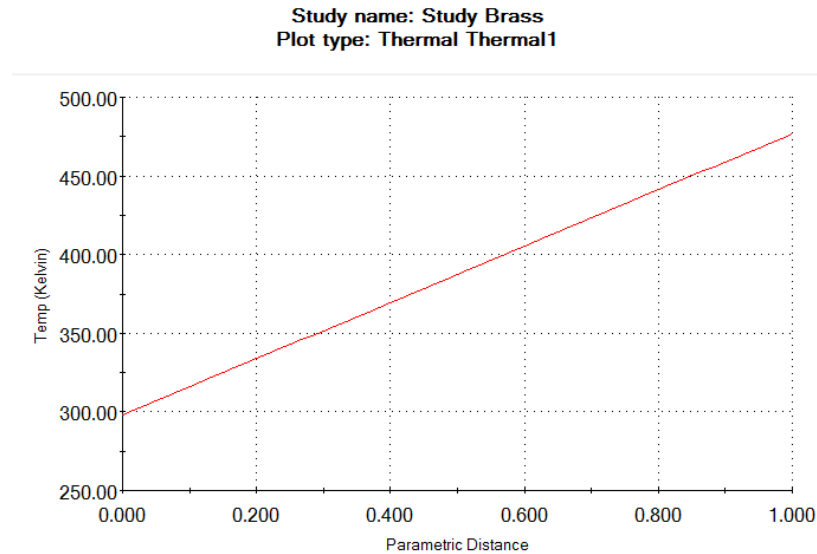
Figure 3: FEA Generated Plot of Body Temperature vs. Parametric Distance (Linear Results)

A sample of the FEA results for the cylindrical portion of the experiment are provided as figures 4 and 5. The results clearly show the parabolic nature of the temperature distribution in both color and graphical plots. The color graphics of the FEA along with the parametric distance plotting features allows students to quickly see the differences in temperature distribution for rectangular vs. cylindrical coordinates.
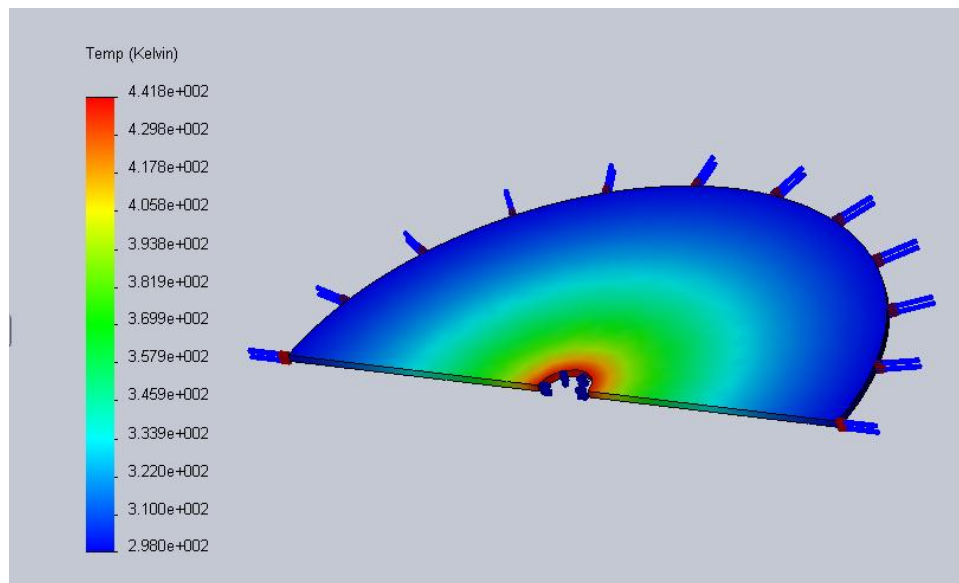

Figure 4: FEA Temperature Distribution For Basic Radial Conduction Virtual Experiment
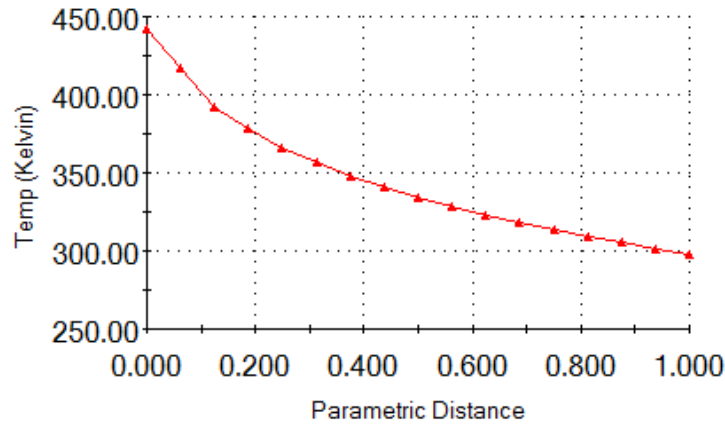
Figure 5: FEA Generated Plot of Body Temperature vs. Parametric Distance (Radial Results)

The virtual experiment is extended to evaluate various materials to give the students a glimpse of how material choices effect the temperature distribution with a given set of boundary conditions.

Conduction in Extended Surfaces:
References [5 and 6] again provide a traditional development of the fin equation based on thermodynamic principles. The temperature distribution is then derived along with the heat rate equations for various boundary conditions. The application of fins in a design is often confusing to students in determining the proper length and number of fins to utilize. Rather than use guess and try methods combined with FEA, students are encouraged to create high level simulations to determine a near ideal solution with only the need for simple refinement after conjugate heat transfer analysis if required. Equations 8 thru 12 are the basic governing equations for heat rate and temperature distribution in a fin with convection at the tip.

$$\frac{\theta}{\theta_b} = \frac{\cosh m(L-x) + (h/mk) * \sinh m(L-x)}{\cosh(mL) + (h/mk) * \sinh(mL)} \quad (8)$$
$$\theta_b = (T_b - T_\infty) \quad (9)$$
$$\theta = (T(x) - T_\infty) \quad (10)$$

$$q = M \frac{\sinh(mL) + (h/mk) * \cosh(mL)}{\cosh(mL) + (h/mk) * \sinh(mL)} \quad (11)$$
$$M = \sqrt{hPkA_c} * (T_b - T_\infty) \quad (12)$$

One of the difficulties in understanding the theoretical aspects of heat transfer governing equations from extended surfaces are the effects of fin dimensions, material thermal conductivity and convection parameters have on the heat transfer rate from the base surface. Low cost experimental setups that can vary the fundamental parameters in a controlled manner are virtually non-existent. With the addition of a series of virtual experiments, the students are able to compare the sensitivity of heat transfer while quickly varying governing parameters.

Extended Surface Virtual Experiment:
The extended surface experiment is conducted entirely in the virtual world due to lack of low cost readily available experiments that easily hold steady convection coefficients. Students are required to evaluate the performance of a plate, plate with a single fin and plate with an array of

fins with a prescribed base temperature or 395.15 K and opposite side convection coefficient of 100 W/m^2-K. They must compare the 3 configurations relative to total heat rate and temperature distribution from the back of the plate to the tip of the fins with varying materials and geometric constraints. Figures 6 thru 8 are sample results from the FEA students develop as part of the virtual experiment.

The students are also required to compare the effects of fin length to that of a 99%, 98% and 90% of infinite length fin configuration. Thru comparison of hand calculation methods using thermal circuit analysis techniques to desired base temperatures and heat rates, students gain insight into the general design decision making process prior to detail modeling. The analysis can be conducted from two perspectives, evaluating the heat rate with a prescribed base temperature and convection conditions and determining the physical configuration needed to achieve a prescribed heat rate. Various tools can be utilized to conduct the trade studies including Microsoft Excel, Engineering Equation Solver or Math CAD software.
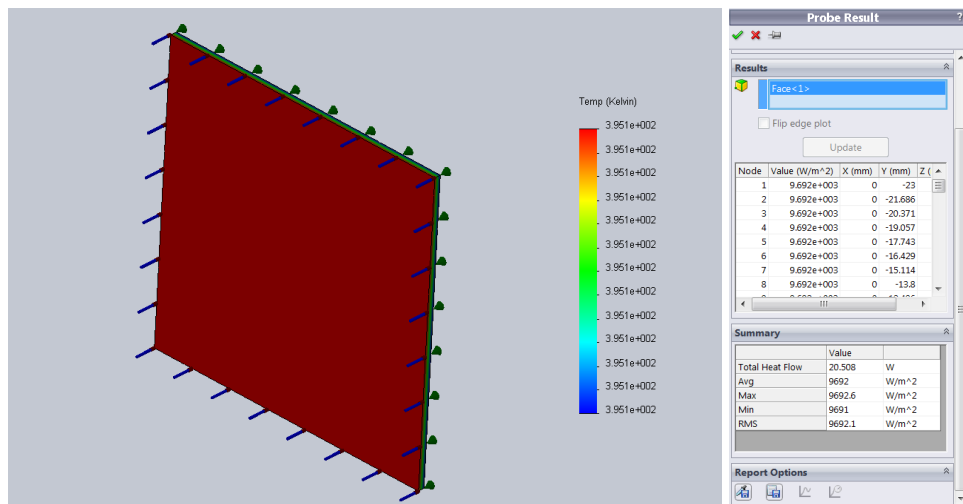

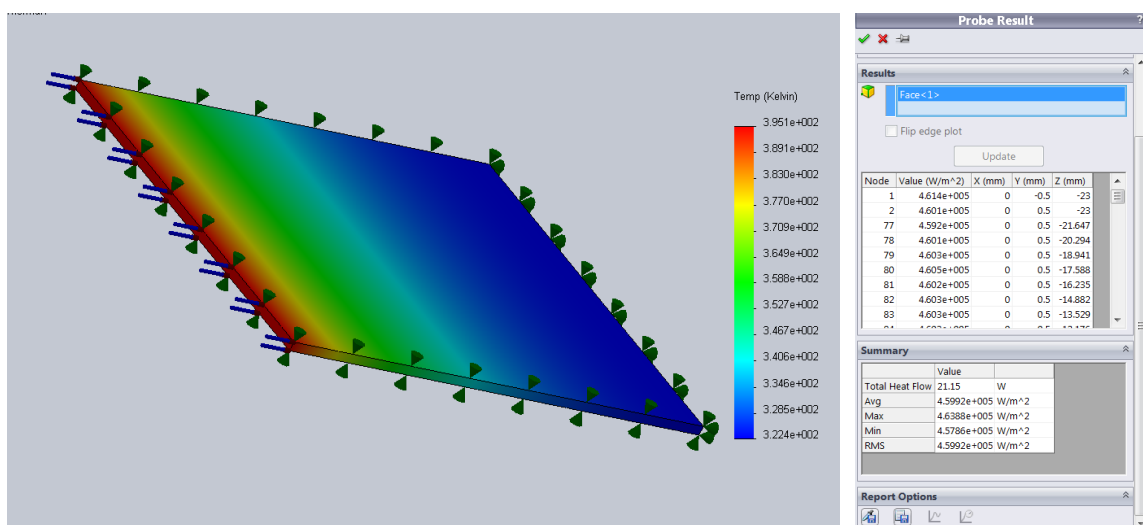Figure 6: Base Plate without Fins and Resultant Heat Rate Probe Results

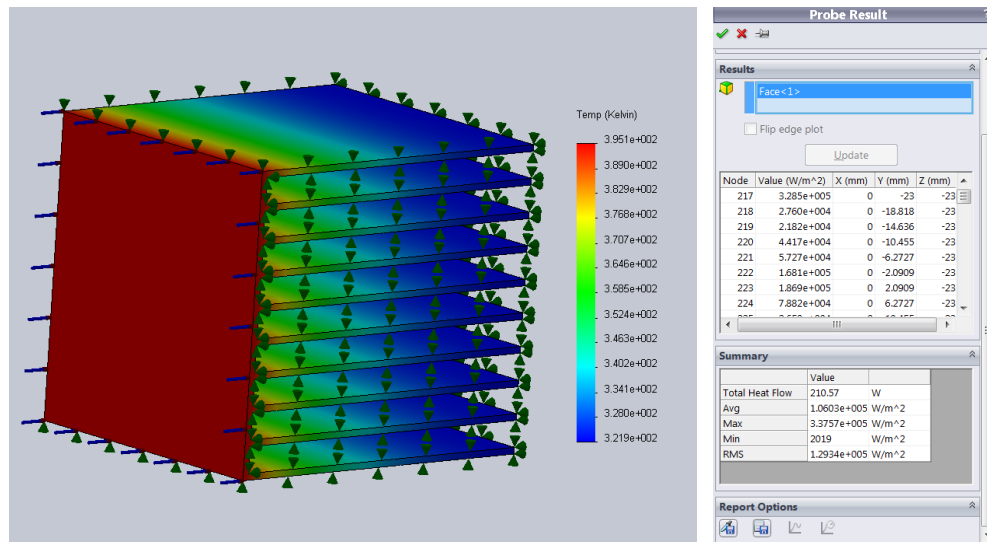Figure 7: Single Fin and Resultant Heat Rate Probe Results

Figure 8: Array of Fins and Resultant Heat Rate Probe Results

Discussion and Conclusions:

Anecdotally, it seems the digital age students seem more comfortable than previous generations in a virtual lab setting. This observation is based on limited student feedback during the semester and thru course evaluations. The students seem more creative in developing software based simulation tools for themselves when multiple configurations are required. This is supported by observing the students use of mathematical derivations of phenomenon in equation driven geometric constraint simulations prior to them creating virtual prototype models for FEA analysis.

It is the belief of the authors that the digital age students require a pedagogical shift in how courses are delivered to accommodate their growing comfort with simulation based design, virtual hardware and virtual experimentation. Further by embracing this shift, educators are able to provide more open ended scenario's for students to exercise their individual creativity while using industry relevant tools in developing solutions to problems both technical and potential social impact.

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