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Teaching Students About Two-Dimensional Heat Transfer Effects in Buildings, Building Components, Equipment, and Appliances Using THERM 2.0

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ABSTRACT

THERM 2.0 is a software program, available for free, that uses the finite-element method to model steady-state, two-dimensional heat-transfer effects. It is being used internationally in graduate and undergraduate laboratories and classes as an interactive educational tool to help students gain a better understanding of heat transfer. THERM offers students a powerful simulation engine combined with a simple, interactive interface and graphic results. Although it was developed to model thermal properties of building components such as windows, walls, doors, roofs, and foundations, it can be used to model thermal bridges in many other contexts, such as the design of equipment. These capabilities make it a useful teaching tool in classes on heating, ventilation, and air conditioning (HVAC); energy conservation; building design; and other subjects where heat-transfer theory and applications are important. The program's interface and graphic presentation allow students to see heat-transfer paths and to learn how changes in materials affect heat transfer. It is an excellent tool for helping students understand the practical application of heat-transfer theory.

INTRODUCTION

Two-dimensional heat-transfer problems are important in buildings because thermal bridges in walls, windows, and other components can have significant effects on energy performance and occupant comfort. Knowing the insulating value of a material is not sufficient to determine the energy performance of a wall or other component in which the material is used because the entire area of the wall is not completely filled with the insulating material. Parallel path heat flow assumptions often produce misleading energy performance data because small conductive elements that penetrate the insulation or go around it create thermal bridges, "short circuits" through which heat can travel. Thermal bridges significantly lower effective insulation values and create unanticipated temperature gradients that can lead to thermal stress, condensation, and other effects. For example, the thermal bridging effects of a narrow (13 mm) but highly conductive aluminum spacer between the glazing layers in a high-performance window system can increase total heat transfer by 50%.

Despite their importance, thermal bridging issues are often not studied extensively in architectural and engineering classes. When these issues are addressed in less technical classes, handbook correlations are typically presented; these correlations do not help students gain insight into heat transfer processes that would help them in a different situation. In more technical engineering classes, students are typically presented with the theory of two-dimensional heat transfer and given textbook problems to solve by writing simple computer codes or by deriving solutions using finite-difference techniques. Although solving these problems from first principles is a valuable exercise for students learning basic theory, the large amounts of time required to generate the solutions often means that students will acquire only a general sense of heat-transfer theory with little or no experience of how it is applied.

In most real-world building applications, a two-dimensional analysis can be successfully used to obtain representative results or it can be combined with handbook methods to obtain acceptably accurate three-dimensional results. Fully three-dimensional heat transfer simulations require complex methods for describing the model geometry. This added complexity is usually not justified by the modest increase in

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accuracy for most applied problems in buildings, nor do these models provide students with much additional understanding of heat transfer.

THERM 2.0 (Finlayson et al. 1995, 1998), a software tool available for free, uses the finite-element method to model steady-state two-dimensional heat-transfer effects and allows students to model the thermal properties of building components such as windows, walls, doors, roofs, and foundations, as well as products such as appliances.

Although there are other programs that can solve two-dimensional heat-transfer problems, they are typically more difficult and complex to use than THERM. They often address structural issues as well, and their heat-transfer solutions may be more simplified. Learning to use these programs requires substantial investments of time, whereas THERM can be learned in a day and thus used easily in the context of a semester-long course. Although it was developed originally for use with WINDOW (Arasteh et al. 1994; Finlayson et al. 1993), a program that models heat transfer in fenestration, THERM is applicable to other building components and products in which heat transfer is important.

OVERVIEW

THERM has three basic components:

- A graphic interface that allows the user to draw a cross section of the product or component for which thermal calculations are to be performed.
- A heat-transfer analysis process that includes an automatic mesh generator to create the elements for the finite-element analysis, a finite-element solver, an error estimator, and a view-factor radiation model.
- A graphic results display.

THERM is capable of explicitly modeling conductive and radiant heat transfer. It models natural convection within cavities using correlation, and it models convection boundary conditions using standard or custom heat transfer coefficients. It is also capable of modeling absorbed solar radiation or other heat flux sources.

Drawing and Graphic Capabilities

THERM has powerful drawing capabilities aimed at minimizing the effort required to define the geometry, materials, and boundary conditions for a given problem. A cross section can be drawn based on an imported computer-aided drawing (using a DXF file) or a dimensioned drawing. The user can assign material, cavity, and boundary condition properties from customizable libraries.

The program has standard graphic capabilities, including mouse and cursor operations; editing features such as *Cut*, *Copy*, and *Paste*; a toolbar to access frequently used commands; and windows so that multiple projects can be open concurrently. These features allow the user to define a cross section as a collection of polygons. The program has many features that help create the cross section with no gaps or overlapping elements (this is critical to the solution method). Figures 1 and 2 are examples of some of the key drawing features.

Calculation Routines

THERM is a two-dimensional, finite-element heat-transfer analysis tool. Many excellent reference books describe the finite element method in detail (Zienkiewicz and Taylor 1989; Pepper and Heinrich 1992). The model's steady-state conduction algorithm, CONRAD (Curcija et al. 1995), is a derivative

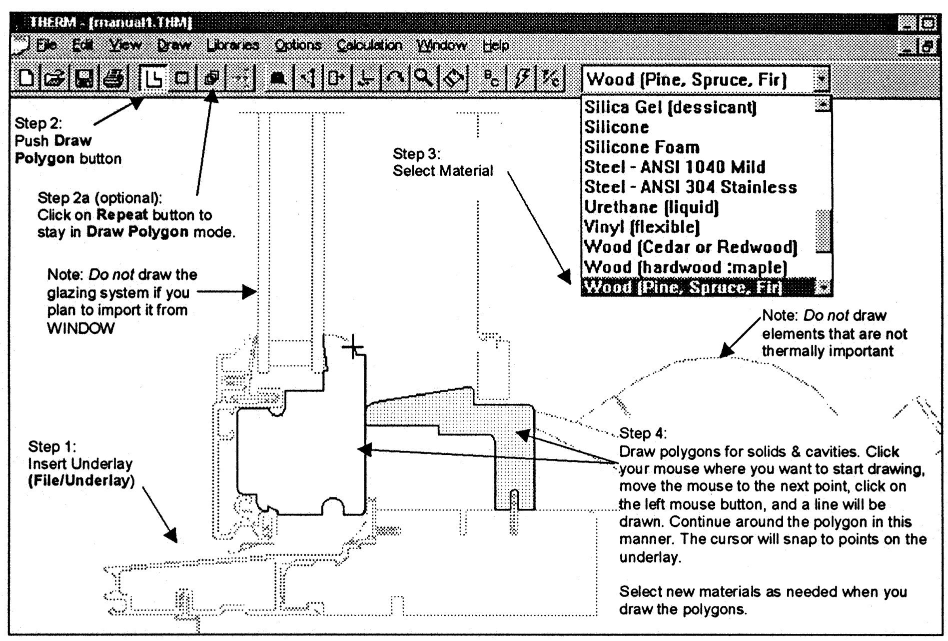

Figure 1 *Drawing polygons and assigning materials.*

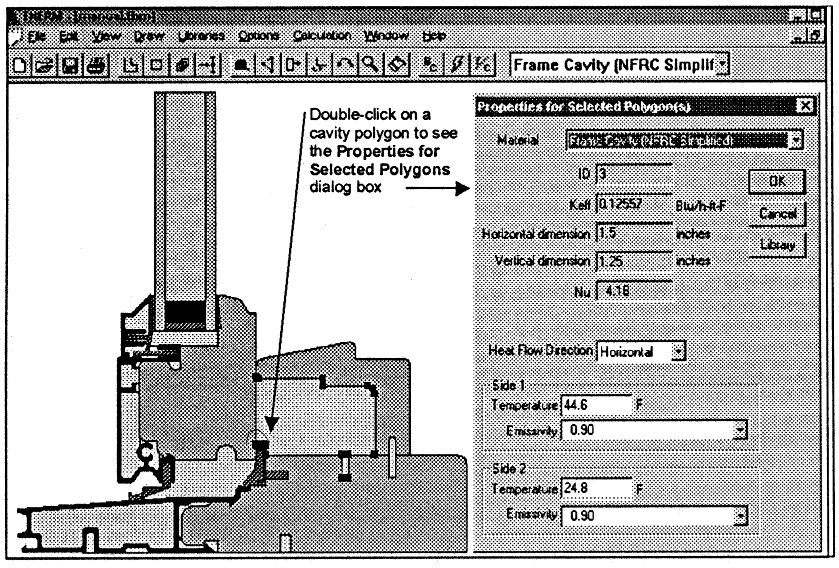

Figure 2 *Assigning materials to polygons.*

of the public-domain computer program TOPAZ2D (Shapiro 1986, 1990). Its radiation view-factor algorithm, VIEWER, is a derivative of the public-domain computer program FACET (Shapiro 1983). THERM contains an automatic mesh generator that uses the finite quadtree (Baehmannet et al. 1987) algorithm. The program checks solutions for convergence and automatically adapts the mesh as required using an error-estimation algorithm based on the work of Zienkiewicz and Zhu (1992a, 1992b).

THERM's calculation routines evaluate conduction and radiation from first principles. The radiation view-factor feature enhances the program's accuracy when it analyzes nonplanar surfaces that exchange energy through radiant heat transfer. This heat-transfer mechanism is important in components such as greenhouse windows, which have surfaces that "see" other surfaces that are at temperatures significantly different from the ambient temperature. Convective heat transfer is approximated through the use of film coefficients obtained through detailed experiments or highly sophisticated computer simulations (ASHRAE 1997; Rosenhow et al. 1985; Zhao et al. 1996).

Model Output

When THERM has finished a heat-transfer calculation for a cross section, students can view total product U-factors as well as graphic results in the form of

- isotherms,
- color-flooded isotherms,
- heat-flux vector plots,
- color-flooded lines of constant flux,
- temperatures (local and average, maximum and minimum).

Of particular interest are isotherm plots, flux vectors, and calculated U-factors. Isotherms are useful for seeing where there are extreme temperature gradients (isotherms very close together) that may lead to thermal stress or structural problems. Isotherms are also useful for identifying hot or cold areas in the cross section in order to predict thermal degradation or condensation. Flux vectors indicate the amount and direction of heat flow through the cross section. U-factors are important for showing the overall heat transfer rate and thus quantifying the total degradation resulting from a two-dimensional heat-transfer effect. The program generates a text report that contains a summary of the U-factor results as well as a description of the elements in the cross section.

USING THERM IN THE CLASSROOM

The authors have found that THERM serves as an excellent teaching supplement to show students how the design of a building component or product affects its energy performance. For less technical classes, it gives students the opportunity to gain an understanding of the significance of heat transfer issues. For more technical classes, it can be used to give students the opportunity to analyze detailed heat transfer problems quickly, supplementing heat transfer theory. This section presents three examples of building-related products suitable for use in classroom exercises.

The use of good insulating materials in the walls of residential buildings does not guarantee good energy performance; the studs used in these walls create thermal bridges that compromise the insulation's performance. In the past, studs have typically been wood, which does not create severe thermal short circuits. However, as wood is becoming scarce, some builders have begun using steel studs, which create much more severe thermal bridges and greatly reduce the effectiveness of the wall's insulating material. One negative result is moisture buildup on cold spots of the building's interior walls. THERM allows students to model changes in materials so they can see, graphically, the results of using steel in place of wood studs.

As an example, THERM was used to model a "thermal worst case" wall section with the following specifications: a layer of 13 mm plywood; 41 mm × 92 mm × 1.1 mm steel C-section wall studs (spaced 610 mm on center); 13 mm gypsum board; wall and stud cavities completely filled with 1.94 $m^2 \cdot °C/W$ fiberglass batt insulation. Figure 3 shows THERM's results as isotherms. The overall R-value was calculated at 1.57 $m^2 \cdot °C/W$. THERM also shows that the surface temperature of the wall next to a stud was 10.6°C compared to 18.9°C next to a cavity. These results show that the overall thermal performance of the wall is degraded by approximately 33% from the level it would have if there were no stud. Using a wood stud in this example would reduce the overall performance by 9% (not shown). More importantly, the lowered interior surface temperatures (10.6°C as opposed to 18.9°C) along the stud indicates that it is likely that the wall will experience problems with moisture condensation and ghost marks (higher rate of dust and dirt deposits). Students could use THERM with an example like this to develop thermal breaks for use with such steel studs, which will minimize this thermal bridging problem.

Figure 4 shows a greenhouse or garden window modeled under typical ASHRAE winter design conditions (–17.8°C outside with a 6.7 m/s wind; 21.1°C inside, nighttime). As shown in the figure, the coldest spots on the window are around the spacer (thermal bridge). These are the areas most likely to develop condensation or frost on them. The student

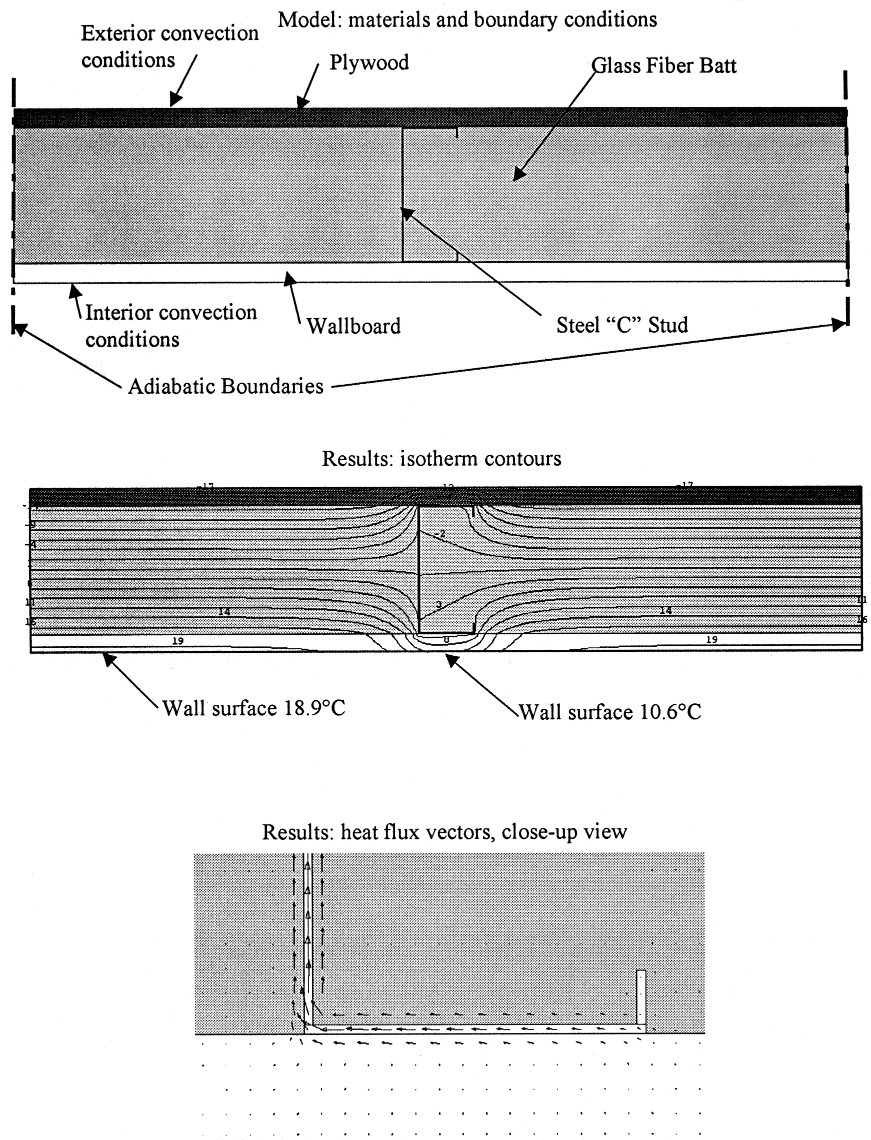

Figure 3 *THERM model of an "insulated" steel stud wall: cross section (top), results—isotherms (middle), and results—heat flux vectors (bottom).*

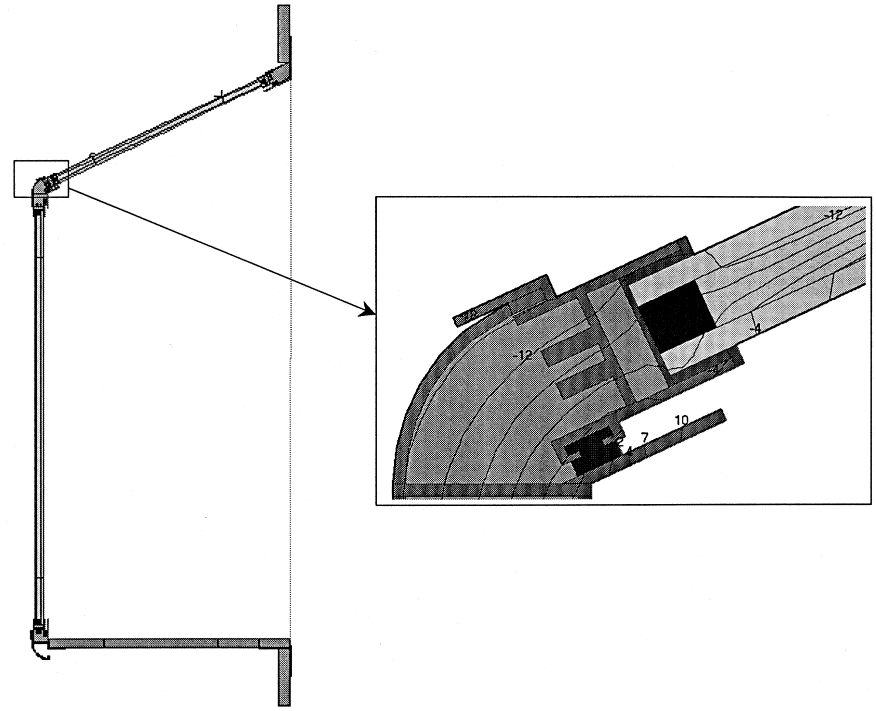

Figure 4 *Greenhouse window; detail shows isotherms indicating the cold spot near the spacer.*

can examine under what environmental conditions (humidity, temperature) condensation or frost will develop. In this example, the radiation module was used to model radiant heat transfer between the surfaces of the greenhouse windows that "see themselves." The students can see that ignoring this effect would lead to artificially high predictions of heat transfer rates.

THERM can also be used in the design of mechanical components. Consider the situation where an instrument, such as a control box, needs to be mounted on a long exhaust duct. Students can be asked how hot the control box will get if the exhaust gases in the duct reach 600°C (see Figure 5). The duct wall is modeled as painted, 0.83 mm sheet metal with 25 mm of glass fiber insulation. The polymer control box is about 5 mm thick, mounted to the duct with steel fasteners and a standoff. (Note that because the duct is long and wide compared to the control box, we assume that a two-dimensional model is appropriate.) Students can be asked to determine whether a person could safely touch the top of the box, which is exposed to substantial thermal radiation from the warm wall of the duct. Because the self-viewing surfaces in this model exchange thermal radiation, the problem was solved both with and without THERM's radiation modeling to demonstrate the effect of the radiation view-factor algorithm on the results. Figure 5 shows the results of both calculations. When we account for thermal radiation, the top part of the control box nearest the duct is much hotter (63°C, nearly hot enough to burn a person) than was predicted by THERM's pure conduction model (23°C, not hot enough to burn someone).

CONCLUSIONS

THERM has numerous advantages as a tool for teaching students about two-dimensional heat-transfer problems. It is easy to learn and enables students to solve complex heat-transfer problems more accurately than is possible using hand calculations and predetermined handbook values. The model's graphic capabilities allow students to quickly define and analyze real-world heat-transfer problems, comparing the impacts of different choices of materials on a product's thermal performance. The radiation module allows students to examine the effects of surfaces at different temperatures radiating to one another, and it can directly model the effects of heat sources as well as temperature-difference-induced heat transfer. Using THERM as a teaching aid in engineering, architecture, and other classes offers students an effective means to understand how the theory of heat transfer they are learning applies to real-world problems. Future improvements will include a transient model and the ability to model internal sources of heat generation.

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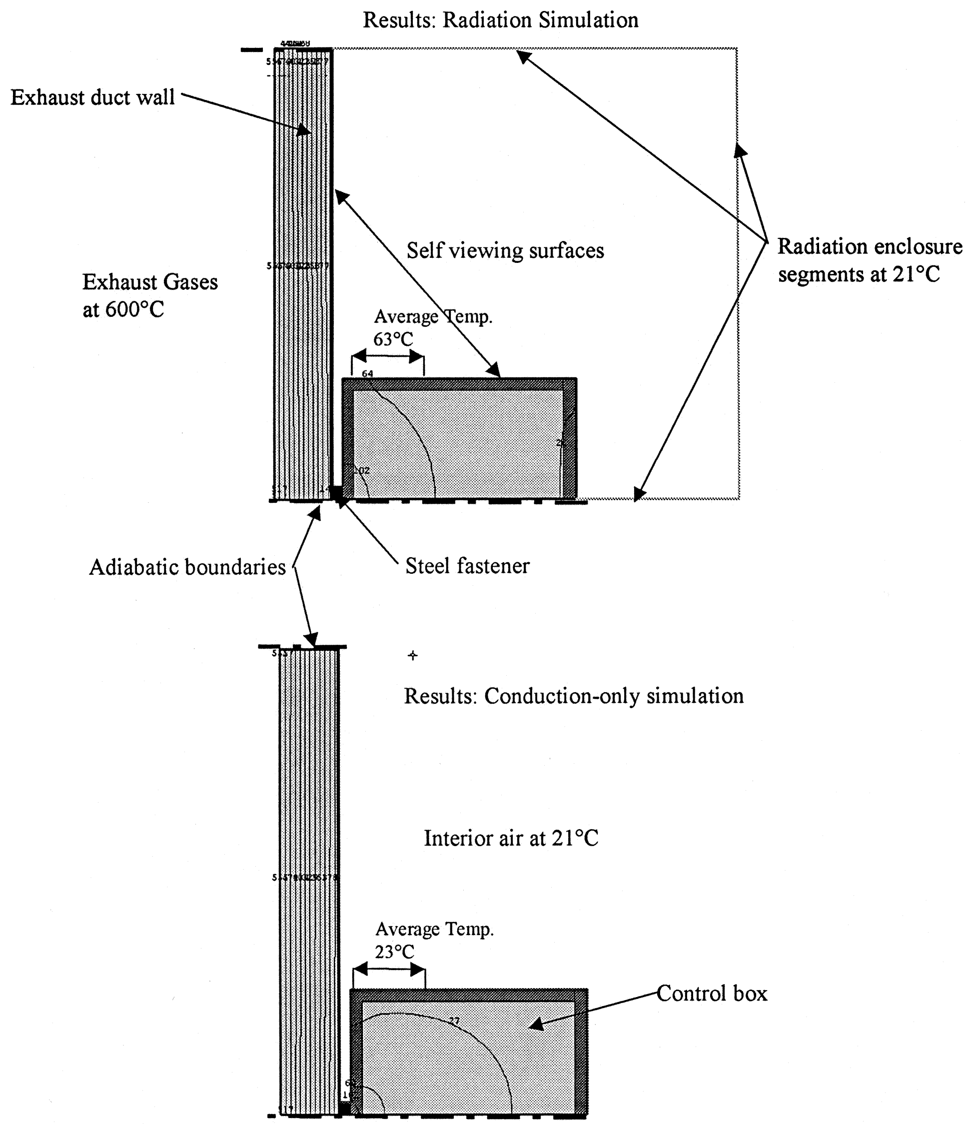

Figure 5 *THERM model of a control box on a hot exhaust duct with radiation self-viewing effects modeled (top) and with self-viewing effects ignored (bottom).*

More information on THERM and how to obtain a copy can be found at the following web site: http://windows.lbl.gov/software/software.html.

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