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ABSTRACT

THERM 2.0 is a state-of-the-art software program, available without cost, that uses the finite-element method to model steady-state, two-dimensional heat-transfer problems. It includes a powerful simulation engine combined with a simple, interactive interface and graphic results. Although it was developed primarily to model thermal properties of windows, it is appropriate for other building components such as walls, doors, roofs, and foundations, and is useful for modeling thermal bridges in many other contexts, such as the design of equipment.

BACKGROUND

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%.

In most real-world building applications, two-dimensional analysis can be successfully used to obtain representative results or it can be combined with handbook methods to obtain acceptably accurate 3-D 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 accuracy for most applied problems in buildings.

THERM 2.0 (Finlayson 1998) is a state-of-the-art software tool, available without cost, that uses the finite-element method to model steady-state two-dimensional heat-transfer effects. Although it was developed originally for use with WINDOW (Arasteh 1994, Finlayson 1993), a program that models heat transfer in fenestration, THERM is applicable to many other building components and products.

THERM OVERVIEW

THERM is a fully integrated simulation environment that includes the following features:

- Graphic user interface: The user draws or imports a cross section of the product or component for which thermal calculations are to be performed.
- Heat-transfer analysis: This includes an automatic mesh generator to create the elements for the finite-element analysis, a radiation view-factor model, a finite-element solver, and an error estimator.
- Graphic results: Results can be visualized using isotherms, flux vectors, or color infra-red images.

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

USER INTERFACE

THERM has powerful drawing capabilities designed to minimize 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 drawing functions of THERM include some unique features that are important for the finite element simulation. If a drawing of a cross section contains a small gap between two elements, it may not effect how the image appears on the screen, yet it could have a large impact on the thermal properties of the object as simulated by the finite element model. Because of this, THERM includes several features to prevent to creation of small voids in the drawing. The most basic of these is a 'stickiness" function that forces a drawn point to stick to the closest point or line within a specified distance of the cursor on the screen. Using the screen distance rather than absolute distance allows the user to zoom in to work at greater detail. After the cross section is drawn, the program automatically checks to see if any voids were inadvertently created and identifies them graphically.

After the geometry is drawn, the program automatically locates all external boundary segments and the user can define the boundary conditions that apply to each segment. Boundary condition choices include convection (or linearized radiation), constant heat flux, constant temperature, or explicit radiation. The radiation boundary condition can be specified either by an external temperature, view factor and emissivity or a set of surfaces can be drawn (and assigned temperatures and emissivities) and the program will calculate the view factors automatically.

ANALYSIS

THERM uses two-dimensional (2-D) finite-element heat-transfer analysis as its solution method. Many excellent references describe the finite element method in detail (Zienkiewicz and Taylor 1989, Pepper and Heinrich 1992). THERM's steady-state conduction algorithm, CONRAD (Curcija 1995), is a derivative of the public-domain computer program TOPAZ2D (Shapiro 1986). THERM's radiation view-factor algorithm, VIEWER, is a derivative of the public-domain computer program FACET (Shapiro 1983). The automatic mesh generator uses a Finite Quadtree (Baehmann 1987) algorithm. THERM checks solutions for convergence and automatically adapts the mesh as required using an error-estimation algorithm based on the work of Zienkiewicz and Zhu (1992). An example of this mesh refinement is shown in Figure 2.

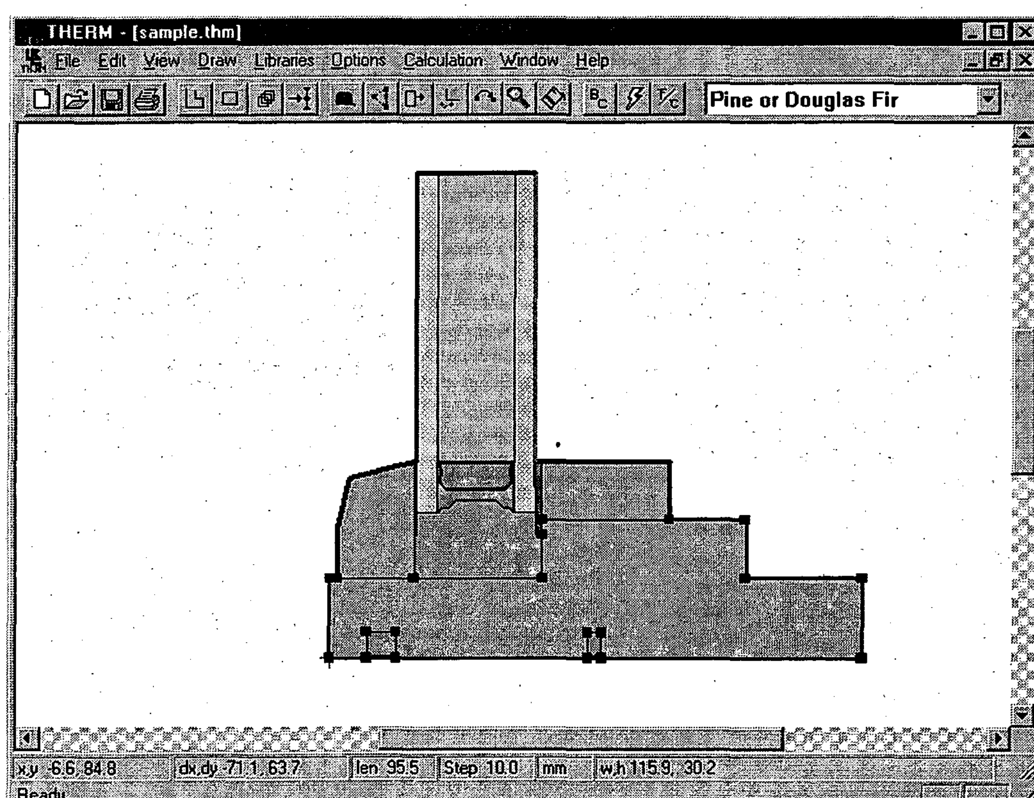

Figure 1. Example cross section of a wood window drawn in THERM.

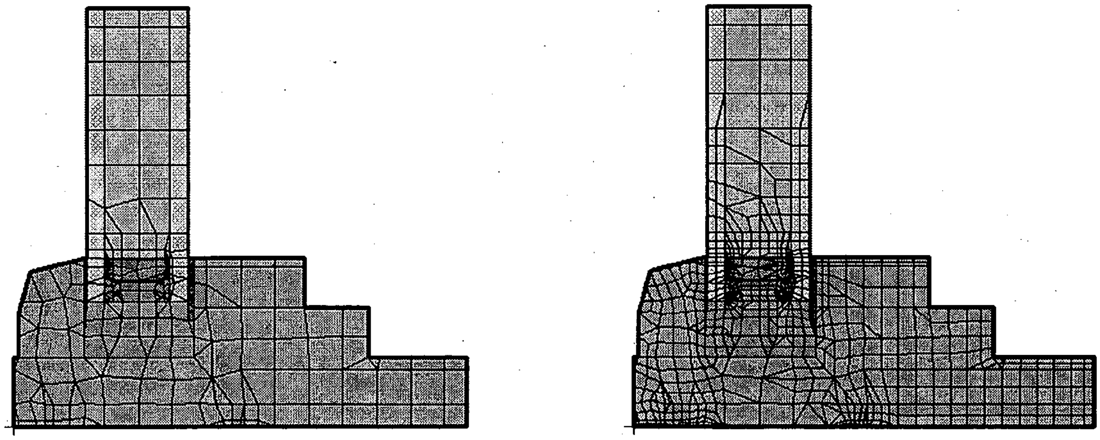

Figure 2. Example finite-element meshes generated by THERM. In the example on the right, automatic mesh refinement was enabled, causing the mesh to be refined where necessary to meet the estimated error criteria.

THERM's calculation routines evaluate conduction and radiation from first principles. The radiation view factor feature enhances the program's accuracy when it analyzes surfaces that exchange energy through radiation 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 surrounding air temperature. Convective heat transfer is approximated through the use of film coefficients obtained through detailed experiments and highly sophisticated computer simulations (ASHRAE 1997, Zhao et. al. 1996).

OUTPUT

When THERM has finished a heat-transfer calculation for a cross section, the program calculates 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)

The most commonly used of these are the isotherm plots, flux vector plots, and calculated U-values. Isotherms are useful for identifying large 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. THERM generates a report (rtf format) that contains a summary of the U-factor results as well as a description of the elements in the cross section.

EXAMPLE SIMULATIONS

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. Steel studs are of particular interest, since steel has such a high conductivity. To illustrate this effect, THERM was used to model a wall section with the following specifications: a layer of 13mm plywood; 41mm x 92mm x 1.1mm steel C-section wall studs (spaced 610mm on center); 13mm gypsum board; wall and stud cavities completely filled with 1.94 m2-C/W fiberglass batt insulation. The overall R-value calculated by THERM was 1.57 m2-C/W. Figure 3 shows the results as isotherms. 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

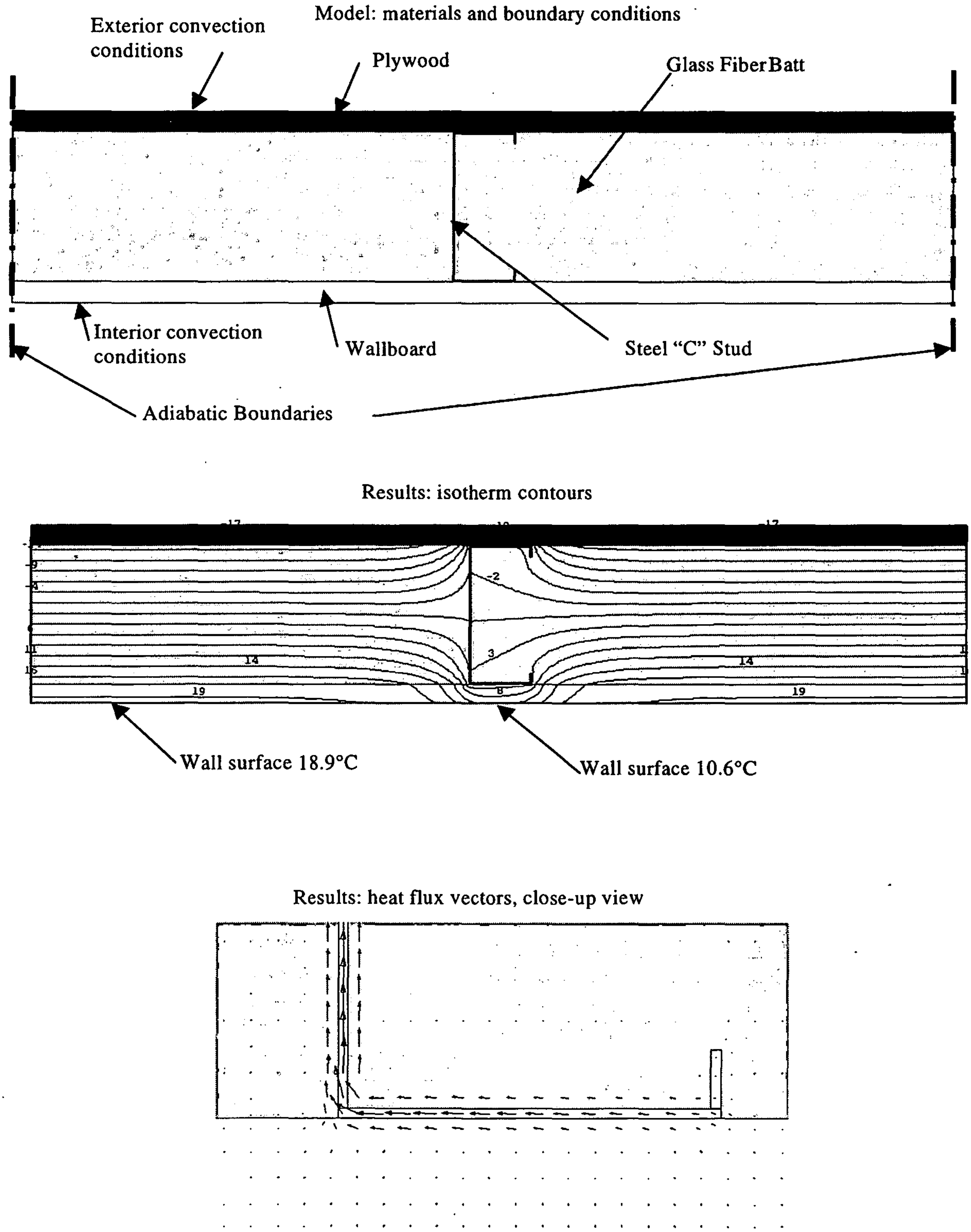

Figure 3. THERM model of an insulated wall with steel studs: cross-section (top), isotherms (middle), heat flux vectors (bottom).

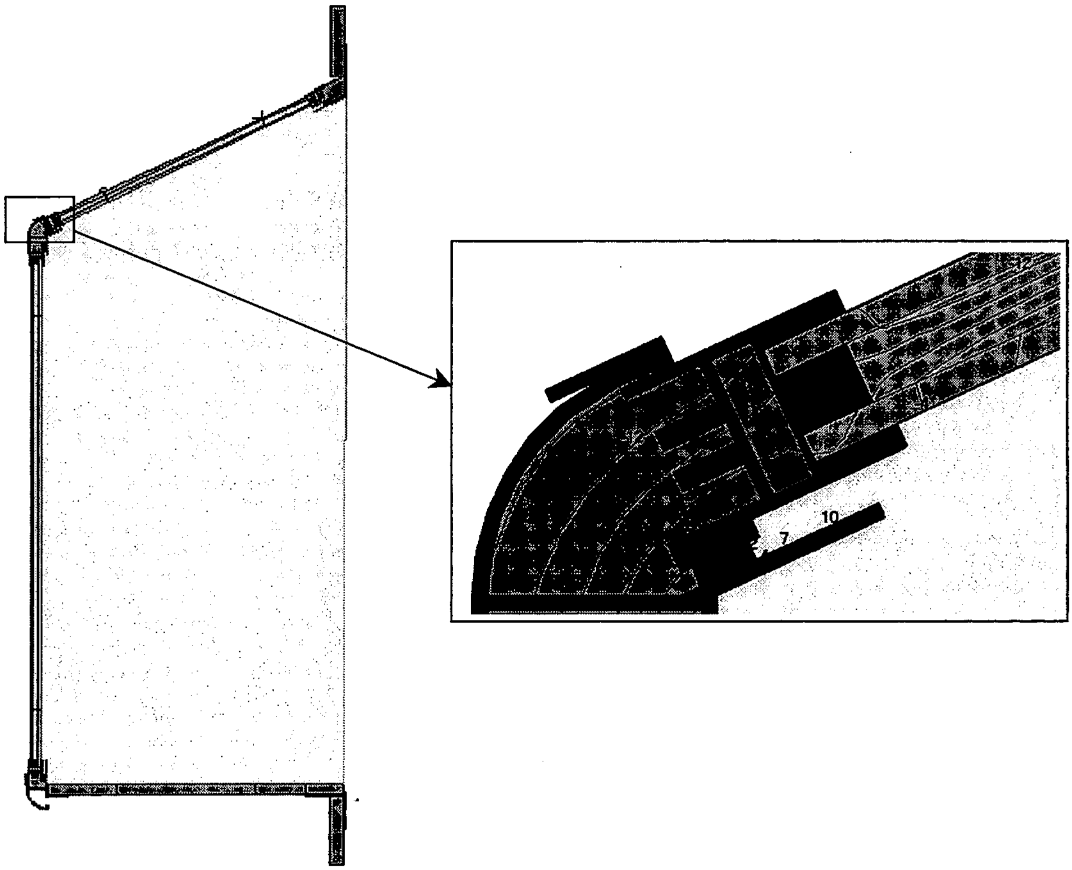

Figure 4. Greenhouse window. Detail shows isotherms indicating a cold spot near the spacer.

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, and 25% from the level with a wood stud. 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 wall will experience problems with moisture condensation and ghost marks (higher rate of dust and dirt deposits).

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. In this example, THERM's radiation module was used to model radiant heat transfer between surfaces of the greenhouse window.

CONCLUSIONS

THERM has numerous advantages as a tool for analyzing two-dimensional heat-transfer problems. It is easy to learn and can to solve complex heat-transfer problems more accurately than is possible using hand calculations and predetermined handbook values. THERM'S graphic capabilities allow the user to quickly define and analyze heat-transfer problems and compare the impacts of different choices of materials on a product's thermal performance. The radiation module allows can be used 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. Future improvements to THERM will include a transient model and the ability to model internal sources of heat generation.

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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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