ANALYZING THERMAL PERFORMANCE OF BUILDING ENVELOPE COMPONENTS USING 2-D HEAT TRANSFER TOOL WITH DETAILED RADIATION MODELING

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ABSTRACT

THERM is a freely available, user-friendly two-dimensional heat transfer model for analyzing the impacts of thermal bridges in building components such as windows and doors. This paper begins by describing THERM as a tool for analyzing individual building components as well as envelope assemblies. The significance of THERM's detailed radiation heat transfer model, which incorporates a view factor based radiation heat transfer algorithm, is then presented in detail. Radiation heat transfer plays a significant role in projecting building components (i.e., Greenhouse windows, skylights, etc.), and projecting wall sections. The difference between results using a traditional black body assumption and the detailed radiation model can be as high as 30%.
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INTRODUCTION

THERM's (Finlayson et al., 2000) two-dimensional conduction heat transfer analysis is based on the finite element method, which can model complicated geometries of building products. The program's graphic user interface allows one to draw cross sections of products or components to be analyzed. It incorporates basic CAD capabilities, so that building component cross sections can be easily created from a dimensioned drawing. The program also has the capability of importing CAD drawings through a DXF file format, and can also read the bitmap (.bmp) file format as an underlay (i.e., trace-over). THERM uses a radiation view factor algorithm, VIEWER, which is a derivative of the public domain computer program FACET (Shapiro, 1983). This feature enhances the program's accuracy by modeling element to element radiation heat transfer directly. This is particularly significant for products with self-viewing surfaces at temperatures that are different than the temperature of the surrounding air. Radiation heat transfer constitutes more than a half of the total surface heat transfer coefficient for surfaces that are subject to natural convection. Significant variations in radiation heat transfer can therefore significantly affect the overall rates of surface heat transfer and correspondingly the overall U-factor of a building envelope component.

Typical examples of products that incorporate self-viewing surfaces are projecting fenestration products (e.g., green house windows, skylights, curtain wall systems, etc.) In addition to products themselves, integrated assemblies (i.e., window-wall interface) create locally significant areas that are self-viewing (see Figure 2). Currently, windows are being accounted for in building simulation models (*DOE 2.1E, 1994, EnergyPlus, 2000*) as "nodes". Each node has associated Area, U-factor, SHGC, and VT. There is no consideration about how windows affect neighboring wall assemblies and vice versa. Two-dimensional (2-D) heat transfer effects at the window-wall interface are currently ignored in building simulation models.

While the window products are tested in a laboratory with fixed environmental conditions, and installed in an insulating homogenous wall, their actual U value may differ in the actual environment (i.e. when they are assembled with other building components). Previous studies have shown that THERM can accurately predict thermal performance of building components (Griffith et al., 1998, Arasteh et al., 1998 and Huizenga et al., 1999). This paper demonstrates the capability of THERM as an analysis tool for the more accurate prediction of thermal performance of building components, as installed in real buildings.

METHODOLOGY

In this paper, building components have been analyzed starting from a simple window assembly as tested in laboratory to a real situation in which a window is located in the wall of a room. The analysis has further been extended to include THERM's detailed radiation view-factor algorithms. Fig 1 shows the typical cross section of a window sill. The example window, used in this analysis is an Aluminum clad, wood casement window. The glazing system consists of nominal 25.4mm thick insulating glass unit (IGU) with a nominal 15.7mm air space and 0.04 emissivity low-e coating on surface number 3 (surfaces are numbered from the outside in). Thermo physical properties of materials used are given in Table 1.

For rating and product comparison purposes in the US, the National Fenestration Rating Council (NFRC) specifies that this window be modeled with THERM as if it were installed in the well insulated surround panel of a hot box, located in a controlled laboratory environment (*NFRC 1997).* In the software model, this configuration is modeled as an adiabatic boundary condition at the bottom of the frame (see Figure 1). In addition, computer modeling of 2-D heat transfer is done only on the frame profile and an adjacent short portion of the glazing system, called the edge-of-glass. This is done to simplify the analysis of the whole window, because for the rest of the glazing system, the heat transfer is considered to be 1-D. This center-of-glass region is easily modeled as a set of nodes, corresponding to glazing layers and surfaces. The total product's overall U-factor is calculated as an area weighted average of frame, edge-of-glass and center-of-glass sections.

In reality the window is assembled in a wall, which has non-homogenous elements and/or thermal bridges. The typical wall cross section and interface with the window is shown in Figure 2. In addition to thermal bridging effects, which are reflected in increased conduction heat transfer rates, the extended sill, jamb, and head surfaces affect radiation heat transfer. To properly account for these effects, the 2-D conduction and radiation heat transfer model in THERM is used on complete window cross sections (Arasteh et al., 1998).

This analysis has been further extended for more realistic conditions by placing this window in the wall of a 4.6m x 4.6m x 2.4m room. The room consists of two internal walls and two external walls, with two different configurations, one with the window in the other external wall, and the other without. The floor plan and elevation of the room are given in Fig. 3. The wall is assumed to be typical North American framed wall construction, with 2x6 studs, and plates, insulation in-between, wood siding on outdoor side and gypsum wall on indoor.

RESULTS AND DISCUSSIONS

The NFRC also specifies standard environmental conditions for the purposes of rating fenestration products (*NFRC 1997).* Since test conditions are mimicked in a simulation program, correlations are used to model wind speed on the cold side of the hot box and natural convection on the warm side. Standard conditions in United States are: the outdoor and indoor temperatures are assumed at -17.8^{o}C and 21.1^{o}C respectively, while the wind speed on the cold side is approximately 6.7 m/s. The corresponding cold side surface heat transfer coefficient is 29.03 W/m^{2}K, while the warm side coefficient depends on the product tested and laboratory hot box setup, but it is typically around 7.6 W/m^{2}K. Fig. 4 shows the isotherms and U values calculated using this set of conditions and the NFRC simulation procedure (*NFRC 1997).*

When this same cross section is simulated as a part of a window-wall assembly (see Figures. 4 and 5), the U-factor of the frame increases from 2.68 W/m^{2}K for the "rating" configuration to 3.94 W/m^{2}K for the actual window-wall configuration. For the whole window the U-factor increases from 2.04 W/m^{2}K to 2.28 W/m^{2}K. This shows that the performance of a window can drastically change in the actual environment. This increase can be attributed to two different effects; one is the thermal bridging introduced by the presence of wood plates at the window-wall interface, and the other is increased exposed area on the outdoor (cold) side of a window. This discrepancy is not necessarily bad, because we use rated performance parameters to compare products. However, if we routinely use these rating numbers to simulate building energy performance, (which we currently do), then there is a problem which needs to be addressed.

On the other hand, the introduction of more accurate radiation modeling will further affect calculated U-factors. The radiation module in THERM is used to examine the effect of surfaces at different temperatures radiating to one another (*ISO 15099,* Arasteh et al*, 1998).* Two different cases were analyzed, (1) a window-wall interface, without any effects of surrounding walls, and (2) a window-wall assembly as a part of a room.

For the model of the window-wall interface, the surrounding enclosure was considered to be a black body at the room temperature, while the window and wall surfaces were assigned surface emissivities (0.9 for all surfaces except glass which is 0.84). The program calculates view factors and surface temperatures. Because of the dependence of radiation to the fourth power of temperature, the model is highly non-linear, and occasionally requires a relaxation parameter to be introduced in order to achieve convergence. From Table 2, one can observe that the overall U-factor has significantly dropped for the model with the use of a detailed radiation enclosure. This is the result of reduced radiation exchange between self-viewing surfaces.

For the model of a wall-window assembly as a part of a room, a smaller cross sections was modeled, while the reminder of the room was modeled through the use of a radiation enclosure. This was done because of prohibitively excessive mesh size that would result if conduction and radiation were modeled for the entire room. Because we were looking at the performance of a fenestration system-wall assembly in a room enclosure, the window-wall assembly was cut at the point where 2-D heat transfer effects were not dominant any longer. In this case, the glazing was extended 4 in., while the wall was extended 6 in. below wood studs. From Figure 6, it is clear that the isotherms are parallel toward the end, indicating that heat transfer is essentially 1-D. A further extension of the model would not improve the accuracy any more. The wall and other window surfaces were represented by their emissivity and estimated temperature (see Figure 7). The temperature was estimated from the 1-D models, and that represents good assumption in this model.

Each of the building components in the room could be modeled in the same way, and its corrected temperature used in refining estimated radiation temperature, which in turn would produce refined temperature fields and U-factors for a Window-wall assembly. This process could be repeated until satisfactory convergence is obtained. In this work, the very first iteration produced insignificant changes, so further iteration were not done.

The model of the room with a window is given in Figs. 7 and 8. The temperature of the ceiling and floor were estimated. . In Fig. 7, top and bottom sides represent the ceiling (T=21.1C) and floor (T=17.8C) respectively. The temperature for the wall at which window is situated has been calculated by THERM and another wall has been considered internal and assumed at 20^{o}C. Similarly for the case in Fig 8, top and right walls were considered internal walls (T=20C) and left and bottom sides are assumed as external walls for which the temperatures have been calculated by THERM. Calculations for the case in Fig 8 have also been performed by introducing the second window at the wall at the left side. The results for all these cases have been summarized in Table 2.

It is interesting to observe that the U-factor of a sill cross-section and of the whole window has significantly increased for the case where the window is installed in a real wall. Introduction of a radiation model and addition of the realistic radiation boundaries in a room has the effect of decreasing the overall heat transfer, but the total U-factor is still significantly higher than for the basic “rating” case. For this higher performance window, the overall discrepancy was on the order of 5% (For the individual frame U-factors this difference is as high as 30%). For lower performing windows, and less insulating wall structures, this difference is expected to go over 10%. It should be noted that additional heat flow that occurs in a wall section due to a presence of window-wall interface had not been counted. It is expected that this effect will further increase U-factors and therefore increase the discrepancy between laboratory determined and real world U-factors.

CASE SUDY: SIMULATION OF A SKYLIGHT

Although skylights are sometimes installed at a tilt, and it is possible to model tilted products in THERM, for NFRC certified simulations, skylights are modeled in the vertical direction in order to match the conditions under which they were tested. In THERM, skylights are modeled as full-height products with a radiation enclosure surrounding the interior of the product in order to take full advantage of the modeling capabilities of the radiation enclosure feature. Fig. 9 shows a typical sill section of the skylight.

The skylight is also simulated using the detailed radiation model, under the standard NFRC rating conditions. For this product, the roof-skylight interface was not analyzed, but it is believed that the general trends, observed for the “flat” window would apply, although somewhat magnified because of the projecting nature of the product itself.

The results from the THERM and WINDOW (LBL 1994) simulations were combined into the overall U-factor of the skylight. Fig. 10 shows isotherms and U-factors of a skylight using the radiation model. The overall U factor for the skylight is 3.18 without using the radiation model while it is 2.99 with the radiation model. The radiation model has reduced the overall U-factor by about 7%.

CONCLUSIONS

The importance of accurate radiation modeling when analyzing heat transfer in building assemblies has been demonstrated. The effects of radiation heat transfer in fenestration systems where there is significant self viewing between projecting surfaces (e.g., between frame and glazing) can be significant and, depending on particular geometry and materials used, can greatly affect both local and overall heat transfer results. The difference between results using a traditional black body assumption and the detailed radiation model varies between a couple of percent up to 25%. The use of this 2-D detailed radiation model in THERM has contributed to increased accuracy when such products are simulated and rated in North America. The results obtained from the THERM and WINDOW programs can be used in building simulation models such as DOE2 for detailed and accurate energy analysis.

Future work should provide guidance how such tools can effectively be used as a part of advanced building energy simulation models. Due to the rapid development of computers, it is possible that in the near future, it will be possible to use 2-D, or even a 3-D heat transfer analysis as a standard module of building energy simulation tools.

Also, further research into the real world effects of various window-wall interfaces can yield correlations or correction factors for use with performance parameters determined by rating procedures. Such factors would improve software's ability to determine the absolute (as well as relative) energy impacts of fenestration products.

The NFRC rating system in the United States has made effective use of 2D heat transfer software to develop a cost-effective rating system. This system's effectiveness is in part due to the fact that since it is simulation based, it is easily integrated into the product design process. This has led to an increase in the awareness of energy efficiency by manufacturers and an improvement in the energy efficiency of products manufactured. Similar software could also be used to rate and evaluate wall systems and other building components where better accounting for the impacts of thermal bridges is needed.

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Table 1: Thermo physical Properties of the material used in the analysis

Material	k (W/mK)	κ
Aluminum	160.0	0.2
Polyurethane	0.03	0.9
Polyisobutylene	0.24	0.9
Silica Gel	0.03	0.9
Silicone	0.36	0.9
Wood (Pine)	0.14	0.9
Steel-ANSI 1040	48.0	0.2
Gypsum	0.016	0.9
Insulation	0.043	0.9

Table 2: Summary of results

	Overall heat transfer coefficient (U-factor) (W/m²K)			
	Cross section		Whole window	
	With detailed radiation	Without detailed radiation	With detailed radiation	Without detailed radiation
Isolated window (hot box installation)	2.46	2.68	1.98	2.04
Window/wall interface	3.56	3.94	2.19	2.28
Window/room interface (vertical)	3.40	-	2.14	-
Window/room interface (horizontal)	3.30	-	2.12	-
Window/room interface and window at another wall also	3.26	-	2.11	-

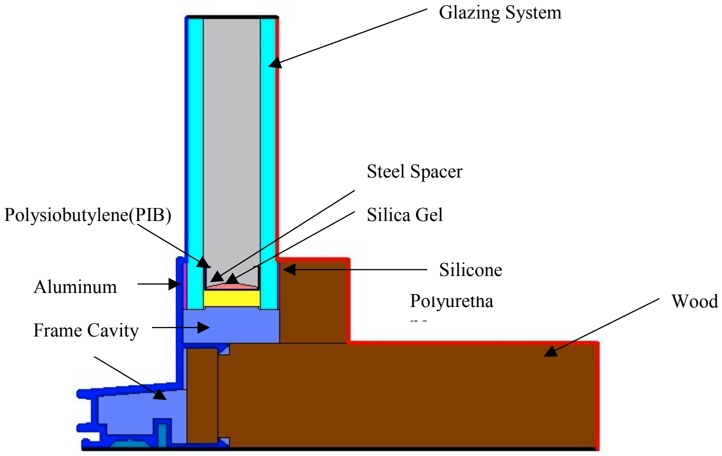

Figure 1. Cross Section of a Window Sill as Installed in Hot Box

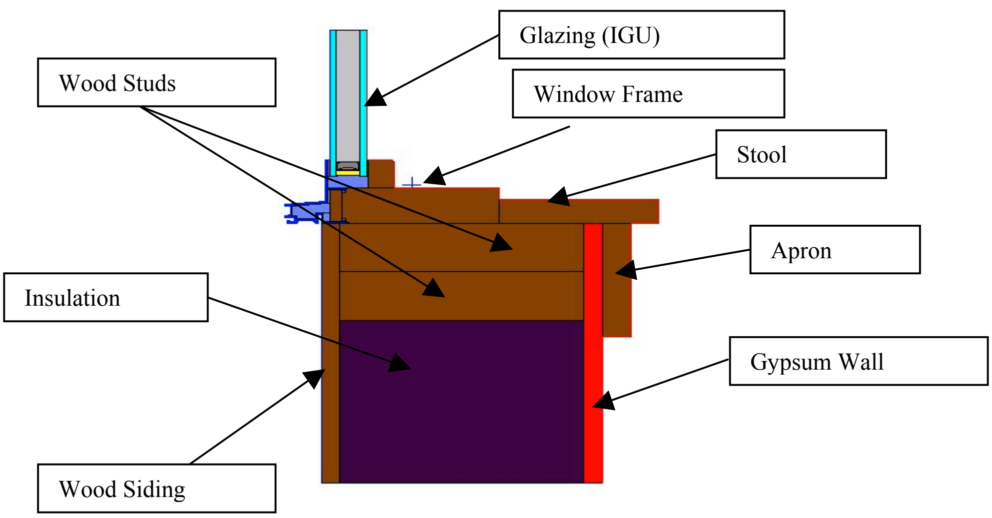

Figure 2. Window in a Typical North American Frame Type Wall

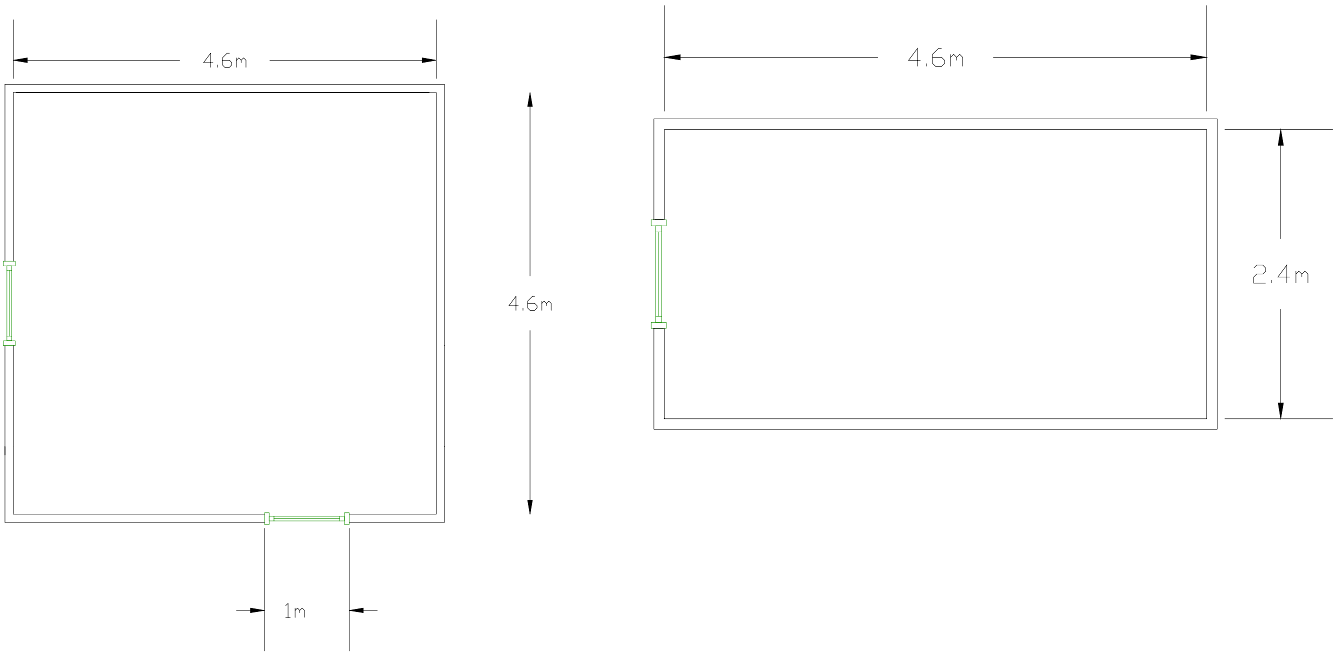

Figure 3. Window Location in a Room

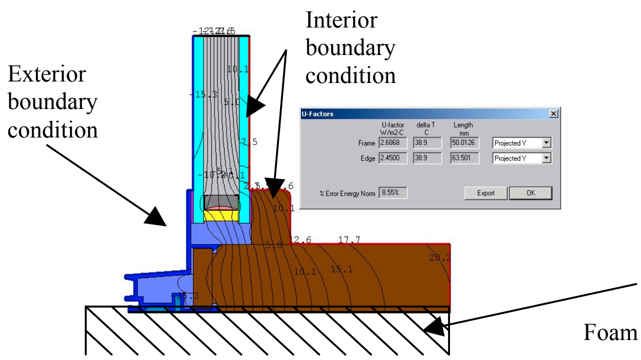

Figure 4. Isotherms and U-factors For The Sill Cross Section

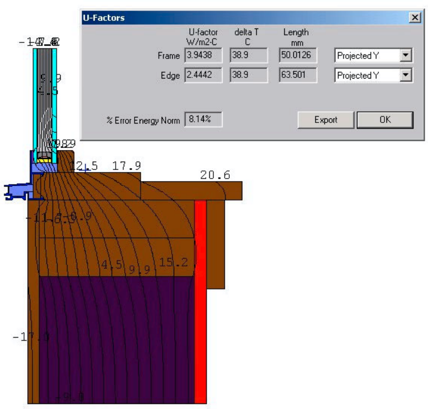

Figure 5. Isotherms and U-Factors for Window Incorporated into Wall Assembly

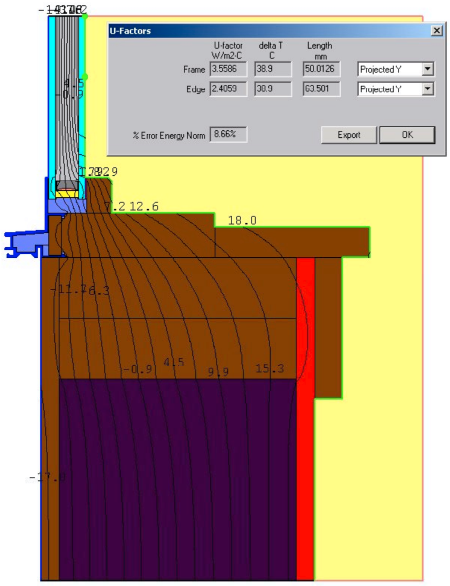

Fig 6: Isotherms and U-factors for Window in a Wall Assembly with Radiation Modeling

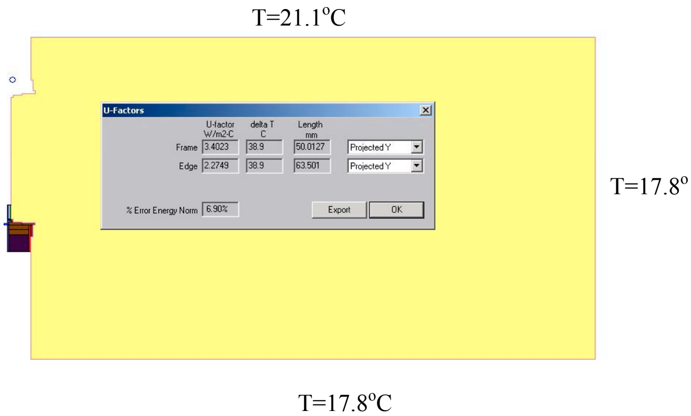

Fig. 7: Simulation Model for Window in a Vertical Position.

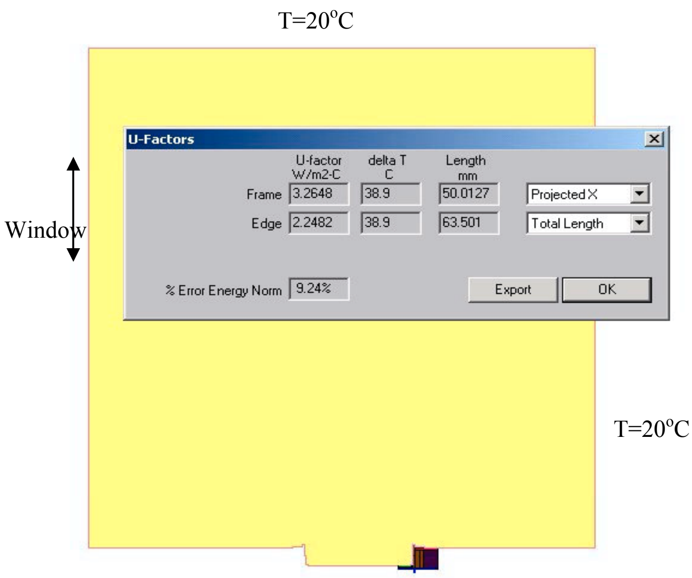

Fig 8: Simulation Model for Window in a Horizontal Position

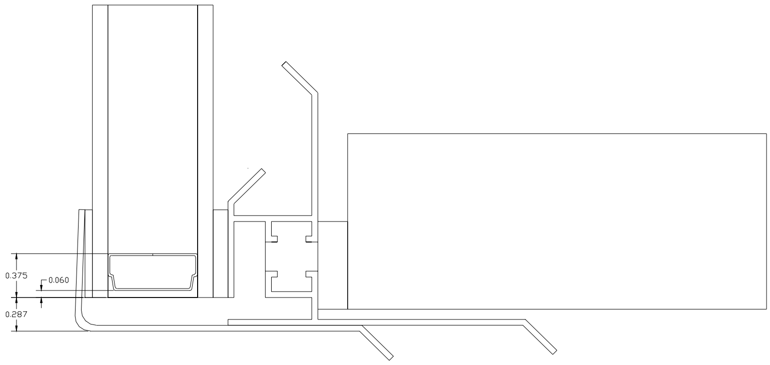

Fig 9 : Typical Cross Section of Skylight

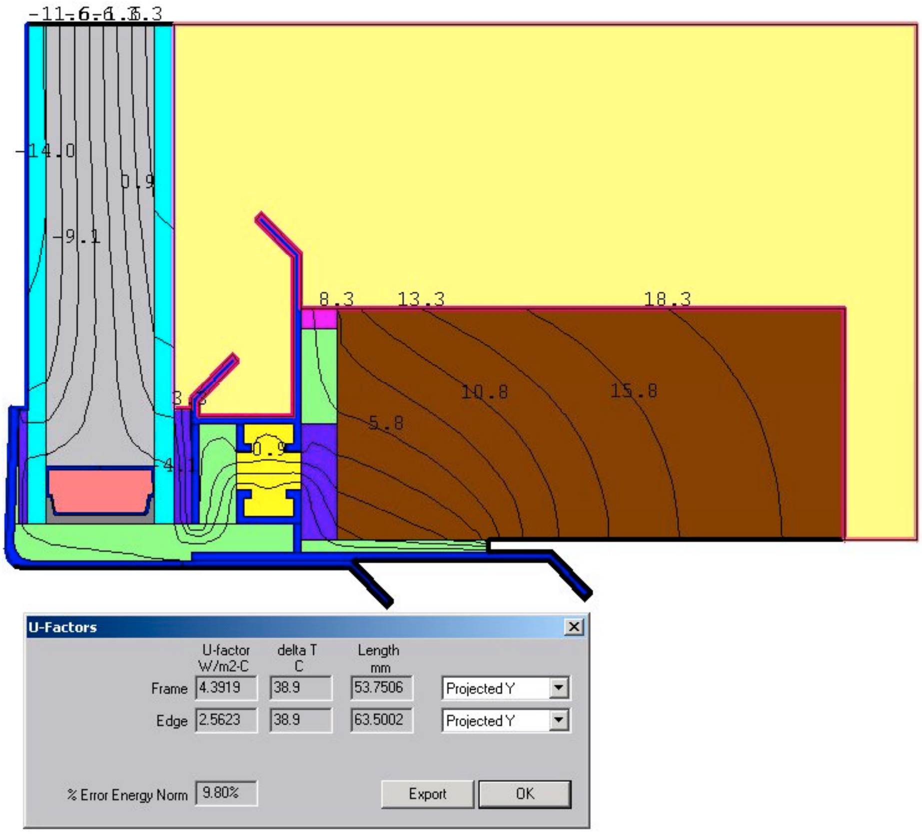

Fig 10 : : Isotherms and U-factors for Sill Cross Section in THERM with Radiation Model