Examining Three-Dimensional Heat Transfer Effects in Fenestration Products: A Comprehensive Review

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Abstract:- This review paper explains that fenestration products like windows, doors, glazed walls, and so on account for close to 40% of all energy used in buildings in India are the largest components of buildings' energy loss. It is essential to accurately evaluate the thermal performances of fenestration systems in order to improve product performance and predict the overall energy consumption of a building. Because 3-D analysis is a highly complex process that requires significantly more time, effort, and cost than 2-D analysis, it is typically used to evaluate their thermal performance. For each product, a different method of evaluation, such as a physical test in a hotbox, is not feasible due to their high cost. Fenestration products' effects on overall heat transfer must be investigated because heat transfer is a three-dimensional process. In contrast to the results obtained in two dimensions, this thesis examined 3-D heat transfer effects in fenestration systems. No huge work has been done already as far as three dimensional displaying of windows, which incorporated every one of the three types of intensity move for example conduction, convection and radiation.

For current framing and glazing systems, this review study demonstrated that the overall 3-D heat transfer effects are relatively small (less than 3%). 3-D effects were quite significant (10%) at the individual component level (such as sill, head, and Jamb), but when the overall fenestration system effect is calculated, they are cancelled by their opposite sign of variation. These three-dimensional heat transfer effects are more pronounced in products of smaller sizes and for glazing and framing systems that are less convective or use less energy. The spacer frameworks didn't muchly affect the three dimensional impacts on heat move. 3-D effects on heat transfer, which may necessitate the development of specialized 3-D fenestration heat transfer computer programs or the application of correlations to 2-D models, should be taken into account as the market shifts toward products with greater insulation and performance.

Keywords*: 3-D heat transfer, fenestration products, thermal performances, glazing systems.*

1. Introduction

Products for fenestration must meet a variety of performance requirements, and Energy is one of them. When designing or selecting these products, designers of fenestration systems must also incorporate structural, acoustical, and durability performance requirements.

The following three heat transfer mechanisms operate through a window: -

- Radiation from the indoor and outdoor surfaces to their respective environments and radiation between the glazing cavity surfaces Heat gain from solar radiation and heat loss or gains from air infiltration are also factors in the performance of the fenestration system.

- Conduction through the solid components of the window.
- Natural convection on the indoor surface, forced convection on the outdoor surface, and laminar or turbulent convection (depending on the condition) in the glazing cavity (or cavities).

A fenestration system's energy performance indices are as follows: Solar Heat Gain Coefficient (SHGC), also known as the fraction of incident solar radiation admitted through a window that is both directly transmitted and absorbed before subsequently being released inward, visible transmittance (VT), and Air Leakage Rating are also known as the U-factor. The U-factor, which is the total heat transfer (excluding solar transmission) for a particular set of environmental conditions (boundary condition), is what defines the thermal performance of the fenestration system. Thermal transmittance or U-value are two other names for the U-factor. It is a common method for determining the insulating value of non-homogenous building envelope components or fenestration products. The actual multi-dimensional heat transfer that takes place through the fenestration system is represented by this value as a one-dimensional ideal. The lower the U-factor, the less heat is lost (or gained) through the window. The primary factor that determines a product's thermal rating is its U-factor. As a result, in order to produce high-performance products, manufacturers strive to reduce the U-factor to increase their product's rating.

In this research paper section one contains the introduction, section two contains the literature review details, section III contains the details about the current performance evaluation, combined heat and power, section IV contains the result details, and section V describe the conclusion of this research paper.

2. Literature Review

In these studies, the main approximation was to replace the air or other gases in the IGU with a solid material whose conductivity is the same as what happens when convective and radiative heat transfer are combined with the value of a still gas's conductivity. The effective thermal conductivity is the term for this. The set of boundary conditions is also simplified, with constant surface heat transfer coefficients on the fenestration boundaries, which were derived from 1-D heat transfer correlations for flat surfaces, serving as an approximation. The primary benefit of this approach is its effortlessness, since it supplanted a confounded convective, radiative, and conductive intensity move issue (with four synchronous nonlinear halfway differential conditions to tackle) with a conduction just intensity move issue (with a solitary direct fractional differential condition to settle). The method's inability to anticipate localized effects is its main drawback. For instance, it failed to anticipate the situation in which the IGU's convective heat transfer results in asymmetric velocity and temperature fields, which in fact result in local variations in heat flux rates and temperatures. Because the effective thermal conductivity method creates a temperature field that is artificially symmetric in the edge-of-glass region, the results are only useful for predicting overall U-factors, which may not fully account for localized effects.

2.1 Radiation heat transfer

In a fenestration product, radiation heat transfer is an important component of the overall heat transfer. Radiation heat transfer occurs at the exterior surfaces, where natural convection occurs, in the glazing cavities, and in the frame cavities of fenestration products. The most recent version of THERM5.2 includes detailed radiation modelling, which accurately models heat transfer in two dimensions of radiation using view factor rather than the conventional black body assumption. The detailed radiation model and results based on a conventional black body assumption can differ by as much as 30%. According to Shapiro (1983), THERM makes use of the radiation-view-factor algorithm VIEWER, which is a fork of the free software program FACET. By directly modelling element-to-element radiation heat transfer, this feature improves the accuracy of the program. This is especially important when products have self-viewing surfaces at temperatures different from the ambient air temperature. For surfaces that are subject to natural convection, radiation heat transfer accounts for more than half of the total surface heat transfer coefficient. As a result, a building envelope component's overall U-factor and rates of surface heat transfer can be significantly impacted by significant variations in radiation heat transfer. The correlations are used in WINDOW5 calculations to figure out the heat transfer for the glazing cavities. For simplicity's sake, frame cavities are modelled as a solid component, and their effective conductivity is used for modelling.

2.2 3-D heat transfer modelling of window

3-D heat transfer effects may not be negligible for fenestration products, according to some previous studies (Curcija and Goss 1995, Svendsen 2000), but there was no focused effort to determine the degree of effect for various types of windows. Using computer models, Curcija and Goss (1995) examined the 3-D heat transfer of a wood picture window with a double-glazed Insulated Glazing Unit (IG). According to their findings, the window's total U-factor varied by approximately 3% due to 3-D heat transfer effects. Because only one kind of window and one size of window were examined, no effort was made to develop a universal correction that would take into account effects in three dimensions. This difference may be greater for projecting products and higher conducting frames.

The convection and radiation heat transfer in glazing cavities and other cavities of fenestration systems has been the subject of research since the 1990s, but most of it has been limited to 2-D modelling. Laminar heat transfer and radiation in a fenestration system and laminar convection in a vertical, rectangular slot were the subjects of two-dimensional numerical calculations by Wright (1990). In order to replicate the experimental apparatus setup, the combined convective and radiative heat transfer in an IGU cavity and the conductive heat transfer in the glazing covered with neoprene pads were modelled for a variety of Raleigh numbers (Ra). The temperature difference and the cavity's size determine the definition of Ra, which can be found in Equation (2.1). Ra is primarily responsible for determining the heat flow rate for a particular window with a fixed aspect ratio. The fluid flow within the cavity will typically behave like a laminar flow when Ra is lower, but when Ra is higher, it is more likely to generate turbulence with a higher heat transfer rate.

Smith and others 1993) modelled the convective and radiative heat transfer in an IGU cavity as well as the conductive heat transfer between glass panes using the finite-difference method. Real frame sections were replaced with rectangular blocks on the top and bottom, where the conductive and convective heat transfers were modelled. Three fenestration systems were subjected to a variety of numerical calculations by Power (1998): PFM01, PFM02, and the IEA (Global Energy Organization) coating unit. Idealized one-dimensional conduction by WINDOW 4.1 LBL (1994), 2-D conduction by THERM LBL (1996), and 2-D conduction, laminar flow, and turbulent flow by utilizing FDI (1996) were among these. He used a transient solution, incorporated gray body radiation between the cavity walls, and carried out the laminar and turbulent flow calculations. A segregated solution method was used in the numerical method for all fenestration system calculations. There were some differences in the edge of the glass regions, but overall, the numerical calculations of heat transfer through two fenestration products and the measured data were well-matched.

Because of an enormous PC framework prerequisites and expanded computational intricacy, three dimensional models of intensity move in windows were restrictively costly to run before. Rather than requiring a 3-D analysis, it may be less expensive to test the building component in some instances. In any case, some 3-D effects may be minor enough to be ignored, saving money and time. Some researchers have been studying 3-D window and component modelling since the 1990s.

The first researcher to take into account 3-D heat transfer throughout the entire fenestration system was Curcija (1992). The local heat flux distribution was derived from his numerical calculations of the laminar natural convection heat transfer on the indoor fenestration surface. The convective boundary conditions for the indoor surface of a prototype window were based on these findings; laminar constrained convection heat move on the outside fenestration framework surface; and making use of the findings regarding local heat flux as convective boundary conditions for the prototype window; numerical calculations for laminar heat transfer and radiation in a fenestration system in three dimensions as well as in two dimensions for both constant and changing boundary conditions. The 3-D numerical modelling produced a slightly higher edge of glass region U-factor (Ueg) as a result of the end effects of the 3-D glazing cavity, which is one of the important results. His research recommends modifying 2-D results. Despite the fact that it was unable to adequately describe the window at the time, it does offer a useful guide for subsequent work.

Carpenter and others 1998) used a three-dimensional finite difference program to investigate three complete wall systems (HEAT3, Blomberg, 1995). In this study, only conduction heat transfer was taken into account. The 2-D program would be able to model 3-D effects if it used one of three different methods—parallel path, effective conductivity, or area of influence. In order to determine which method is the most accurate, the outcomes of these three approaches were contrasted with those of the 3-D model. This study's "effective conductivity method" is comparable to the area-weighted method. It is simple to use and provides a conservative performance estimate. When the material layers have a low thermal conductivity, this method fails to accurately predict 3-D effects. However, the absolute 3-D effects are minimal.

Gustavsen and others 2001) simulated the internal window frame cavities using 3-D conjugate CFD (Computational Fluid Dynamics). To determine the limitations of treating complete (four-sided) window frames with internal cavities as if they were made up of simple jamb sections, they analyzed the differences between single vertical and horizontal frame sections and four-sided frame sections. The CFD simulations also appear to indicate that the average of the horizontal and vertical profile U-factors can be used to determine the U-factor of a complete window frame. Two correlations in THERM are ASHRAE U-factors and CEN U-factors. ASHRAE U-factors compare well to the results of the 3-D horizontal sections simulated with the CFD program, while CEN U-factors compare well to the results of the vertical 3-D profiles.

2.3 Natural convection in glazing cavities

The problem of heat transfer occurred within any cavity in the windows is a classical topic, which usually is addressed as the natural convection in rectangular enclosures. A successful solution to a 3-D cavity flow is the key element in solving the heat transfer problem for windows, thus a brief review for the study on 3-D cavity flow is also made for the matter of complete3-D analysis in the future.

Convective heat transfer in insulated glazing unit (IGU) cavities is a major component of the overall heat transfer in fenestration systems. Accurately quantifying the heat-transfer coefficient within the cavity is of great significance in calculating the center-of-glass U factor, the edge-of-glass U-factor, and therefore the overall U factor.

There are three dimensionless parameters that affect the cavity flow regimes. Theses are aspect ratio (A), Ra and Prandtl number (Pr). The aspect ratio is the ratio of the cavity height (H) to its width (W) along the direction with the largest temperature gradient. The Rayleigh number is a function of the fluid properties of the cavity as well as the cavity width and cavity temperature difference (see equation (4)), and the Pris a function of the fluid properties of the cavity.

According to previous study on natural convection in 3-D cavities, when the flowbecomes3-D, an additional variable is introduced: the span wise aspect ratio H/S (where is the cavity length in the third dimension), such a system is more complex than its 2-D simplification, but has received less attention. For air fillings, there are a few published works on3-D natural convection with in cavities. For 3-D natural convection in a box, by the investigation of Fusegi (1991), a few people (Aziz and Hellums(1967), Chorin(1968), Willams(1969), and Mallinson (1973) and deVahl Davies (1976) have presented finite difference method for the calculation of internal flows driven by buoyancy forces. Morrison and Tran (1978) describe experiments on a slender (H/W=5) vertical cavity, detailing the effects of sidewall conduction on the flow pattern. Symonsand Peck (1984) studied flow and heat transfer with H/W = 7.5 and H/W = 45. Wintersand Brown have undertaken a numerical study of a short cavity (H/ S/ H /W 2).Several studies (Eckert and Carlson 1960; MacGregor and Emery 1969; Yin et al. 1976;Raithby et al. 1977; ElSherbiny et al. 1982; de Vahl Davis 1983; Wright 1990; Curcija (1992) were carried out for cavities with higher aspect ratios ,typical of fenestrations systems. The results are usually reported in the form of an integrated (averaged) Nusselt number or average heat transfer coefficient for the cavity.

Mallinson &Vahl Davis (1973) studied a 3-D window cavity. The window cavity exhibits symmetry about the vertical middle plane. Therefore, solutions were obtained over only one half of the cavity. The average Nusselt number is, in every case (different Ra number), lower than predicted by the 2-D model and within 2.5% of the 2-D estimate. It is concluded that the end effect has a decreasing influence on average Nusselt number (Nu) as Ra increases, this can be attributed to the reduction in the thickness of the end-wall boundary layer with increasing Ra. In all cases, the 2-D estimate of the Nu is a better estimate of the vertical average at the centre of a 3-D cavity than it is of the overall average.

Reddy (1982) is the first one to consider the solution of the window cavity problem in three dimensions by the finite element method. The natural convection in a cubical box subjected to differential heating was studied. It was concluded that the fixed wall in the 3-D cavity has the effect of reducing the strength of the flow field. Also, the average Nu along the vertical wall of the 3-D model is lower than that obtained from 2-Dmodel.

Peutrec and co. (1990) also discussed discrepancies in Nu at the isothermal walls can be used as an indication of the strength of the side-walls. He found "In the vertical middle plane (y=0.5), the flow is almost the one obtained with 2-D simulations. Some changes are seen in the regions adjacent to the isothermal walls, especially for the velocity plots presented for y=0.011". However, it should be noted that the development of 3-D flows produced only by no-slip boundary conditions at the sidewall appears to be weak, in particular at high Ra numbers. As discussed by Le Peutrec and Lauriat (1987), such weak 3-D effects have little influence on the heat transfer provided that the longitudinal aspect ratio Ay is greater than one and Ra< 106.

Fusegi (1992) studied 3-D natural convection in a cubical enclosure with walls of finite conductance. The main emphasis of this study is placed on scrutinizing changes in the local physical properties of flow and temperature fields due to conducting walls. 3-D variation of heat flow inside the cavity is illustrated by altering the thermal conductance of the horizontal walls and that of the end-walls. He investigated the distribution of the local Nu at the isothermal vertical walls. As the thermal boundary layer near the heated wall develops from the bottom plate toward the ceiling, the Nu varies significantly in the vertical direction. However, Nu is rather uniform in the z-direction, except for regions close to the end-walls located at z=0 and z=1.

Experimentally, the challenges in realizing boundary conditions even for a simple geometry such as a square enclosure provide scope for further research. The literature survey on this class of problem is fairly exhaustive. From an overall view of what has been accomplished experimentally, some noticeable end effects were mentioned; for example, N. Ramesh and S.P. Venkateshan reported an experimental study of laminar natural convection heat transfer in a square enclosure using air as the medium and having differentially heated isothermal vertical walls and adiabatic horizontal walls. Mac Gregorand Emery conducted experiments on rectangular enclosures of various aspect ratios (10,20, 40).

Curcija (1992) also performed 3-D simulation of natural convection and radiation in glazing cavity. He obtained very similar results to Mallinson and Vahl Davis(1973). As for the window cavity, mainly the cavity within the glasses, which account for a large amount of heat transfer, usually has a very big aspect ratio in two directions. Secondly, the boundary condition of window cavities is undefined, which is subjected to the change of the boundary condition of the entire window, thus creating larger uncertainty in the study.

2.4 Conduction heat transfer

Conduction heat transfer in governed by the modified energy equation where the velocity components are set equal to zero, and therefore the energy reduces to:

With the following assumptions for the problem being considered:

- Thesolidportionoffenestrationsystemaremadeofhomogeneousandisotropicmaterial,
- The material properties are constant (not temperature dependent),
- There are no internal heat sources in the fenestration system.

Conduction heat transfer in the solid portions of the fenestration system is solved simultaneously with the laminar natural convection in an IGU cavity. Boundary conditions for the conduction problem considered here consist of a prescribed combined convective and radiative heat flux on each of the boundary surfaces:

$$-k_s \frac{\partial T}{\partial x} n_j = q_c + q_r$$

where:

$$q_c = h_c(T - T_c)$$

$$q_r = \sigma\varepsilon(T^4 - T^4{}_r)$$

2.5 Radiation heat transfer

Radiation heat transfer is an important part of the overall heat transfer in a fenestration product. In fenestration products, radiation heat transfer takes place at the exterior surfaces (where natural convection takes place), in the glazing cavities and in frame cavities. The latest version on THERM5.2 has incorporated the detailed radiation modelling, which accurately models 2-D radiation heat transfer based on view factor instead of traditional black body assumption. The difference between results using at conventional black body assumption and the detailed radiation model can be as high as 30%.

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 programs accuracy by modelling element -to-element radiation heat transfer directly. This is particularly significant for products with self-viewing surfaces at temperatures that are different from 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.

For the glazing cavities, WINDOW5 calculations are based on the correlations for determining the heat transfer. In case of frame cavities, for simplicity, they are modelled as solid part and their effective conductivity is used for modelling purpose.

3. Conclusion

This review paper presents the first systematic investigation of 3-D corner heat transfer effects in fenestration systems. This study investigated and reported on four different glazing systems, which covered the entire range of current and future glazing designs, with the exception of single glazing. Three spacer types, which covered the entire range of current and future spacer materials and designs, were also taken into consideration. The study's first conclusion is that existing fenestration computer modeling tools can ignore 3-D corner conduction heat transfer effects for current frame, spacer, and glazing materials. Spacer conductivity has no significant impact on the degree to which 3-D and 2-D conduction heat transfer models differ from one another. Therefore, the extent of 3-D effects is determined by frame and IGU performances. The difference between 2-D and 3-D heat transfer effects becomes more pronounced and significant for frames and glazing with higher thermal resistance, and it exceeds 2% for smaller windows. Three-dimensional effects would need to be taken into consideration as the market shifts toward products for fenestration with higher performance. There were more 3-D effects in smaller windows with a higher frame to glass area ratio than in larger windows with a lower frame to glass area ratio. There were of greater magnitude, reaching 10%, at the individual component level. However, because the frame and edge of the glass sections typically have distinct signs in front of the differences, these distinctions would frequently cancel one another. The overall results do not reflect these significant differences. In order to accurately determine the temperature, condensation resistance, and heat flux in the area, accurate local information at the component level would be helpful. The local outcomes of the convection and conduction models were vastly distinct, despite the fact that their overall 3-D effects are comparable. For accurate temperature and heat transfer results, a convection model should be used for 2-D analysis.

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