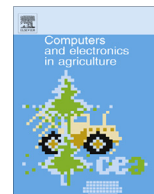




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A computational and experimental study of conjugate heat transfer through composite thermal envelopes in post-frame buildings

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ABSTRACT

The thermal performance of eight post-frame thermal envelopes was studied and optimized using a computational fluid dynamics model validated experimentally with a rotatable guarded hot box. In addition to providing thermal performance values for typical wall designs, this study proposed a new wall design that greatly increased thermal performance without sacrificing material efficiency. Study variables included structural geometry, level of insulation, and the presence and placement of radiant barriers. To reduce computational demand, modeling was primarily conducted using an area-weighted average of two-dimensional slices to represent three-dimensional assemblies. After modeling a portion of the assembly in three dimensions and comparing it with its two-dimensional counterpart, this simplification was found to result in less than a 6.7% error. Significant error (up to 57%); however, was determined to be integral to the simplifying assumptions commonly used by building designers, especially in envelopes common to the agricultural industry. This error was estimated to underpredict energy costs for a 2200 m² cold-storage warehouse in Wisconsin by approximately \$1700 a year.

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1. Introduction

1.1. United States energy consumption

According to the United States Energy Information Administration (U.S. EIA, 2016), 40% of domestic energy production is consumed by residential and commercial buildings. In 2014, this amounted to a total of 41 EJ, a near tripling of consumption since 1960. Of this total consumption, approximately 51% went to space heating and cooling in 2003 (the last year EIA published pertinent data).

When life cycle costs are calculated for a building, operation costs such as energy consumption often far outweigh initial capital expenditures. This means that relatively minor investments in the energy efficiency of a building can result in a significantly lower life cycle cost. Because major lifetime savings can be realized via minor changes in efficiency, developing accurate and accessible methods for determining—and comparing—the overall thermal efficiency of building envelopes would seem a practical way to slow the rise in domestic energy consumption.

1.2. Building envelope efficiency

Since its inception in the first half of the twentieth century, the post-frame structural system has gained a well-deserved reputation for structural efficiency, likely leading to its prevalence in the agricultural industry where economy is paramount. The same large bay spacing that leads to reduced material usage also reduces the number of thermal breaks present in a wall, thereby increasing the effectiveness of a building's thermal envelope, which controls the flow of heat between conditioned space and the surroundings. Despite the apparent benefits of the post-frame system with respect to temperature controlled warehouses and other structures that require a high level of energy efficiency, little public research has been conducted to date regarding the efficiency of post-frame thermal envelopes.

The consequent lack of data presents a problem when contractors attempt to promote post-frame buildings in markets currently dominated by other structural systems for which thermal performance data are readily available. Without accurate data, building component manufacturers may be forced to rely on design values calculated by over-simplifying complex heat transfer situations to create analogs that can be solved using basic resistance theory. Key among the simplifications is the assumption that neither natural convection nor radiation within a wall cavity has a significant effect on the thermal performance of the wall (Fig. 1). For certain

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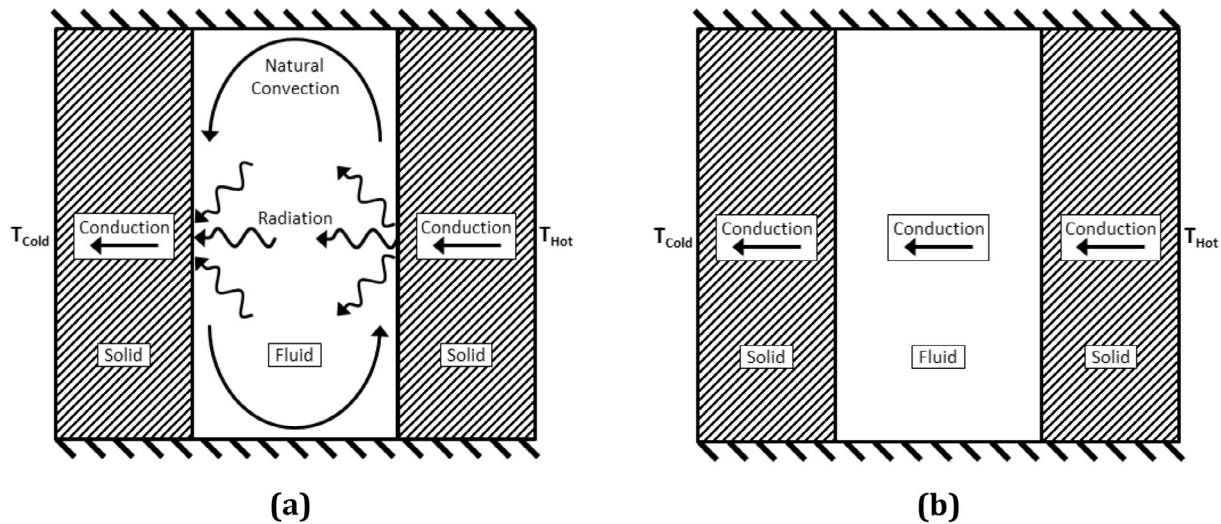


Fig. 1. (a) Model of internal fluid void with conjugate heat transfer and (b) simplified model assuming conduction only.

wall designs (e.g. residential stud-framed walls) this assumption is reasonable; however, research has shown that it may not always be true for wall designs that contain internal air voids (e.g. the post-frame walls prevalent in the agricultural industry).

1.3. The role of air in thermal envelope performance

Research at Oak Ridge National Laboratories (Christian et al., 1998) determined that relatively small air voids in a thermal envelope can still result in a significant loss of thermal performance. When testing a 51 cm (20 in.) straw-bale wall design in their Rotatable Guarded Hot Box, Christian et al. discovered that thin, discontinuous air gaps at the drywall/bale and stucco/bale interfaces resulted in a 50% reduction in thermal resistance compared to the estimated thermal performance of $RSI-5.6 \text{ m}^2 \text{ K W}^{-1}$ ($R-32 \text{ h ft}^2 \text{ }^\circ\text{F Btu}^{-1}$). After adjusting the construction method to eliminate these air gaps, the thermal resistance increased 62.5% to $RSI 4.6 \text{ m}^2 \text{ K W}^{-1}$ ($R-26 \text{ h ft}^2 \text{ }^\circ\text{F Btu}^{-1}$). It is important to note that even after improvements in the construction method, the thermal resistance of the wall remained significantly lower than had been predicted based on the thermal conductivity and airflow permeability of the anisotropic straw alone.

The observed loss in thermal performance ($\sim 19\%$) was supported by another research study (Bankvall, 1987) which determined that the influence of air movement on thermal performance is strongly tied to the thermal resistance of the envelope, with air movement having a much larger influence on assemblies with higher predicted thermal resistances. Powell et al. (1989) reviewed several other studies regarding the influence of air movement within wall cavities on overall thermal performance. They found that when the effects of air movement were considered, the thermal resistance of a wall was significantly less than the sum total of all the resistances of the individual layers.

Due to the considerable influence natural convection has on the overall thermal performance of a building envelope, many studies have examined a variety of methods for controlling air movement within thermal envelopes by altering the aspect ratio of enclosed air voids. Bejan (1980) determined that as a vertical cavity becomes shorter (i.e. as its aspect ratio decreases) and the Rayleigh number is held steady, the heat transfer rate increases. The author suggested that this was caused by the two vertical branches of a natural convection cell acting as a counter-flow heat exchanger. As the heat exchanger becomes longer, the heat transfer area between the two branches increases, and the convective heat link

carried by the counter-flow heat exchanger decreases. Bejan and Anderson (1981) further expanded upon this concept in a study that examined the heat transfer across rectangular enclosures divided by a vertical impermeable partition. The study determined that a partition dividing the enclosure in half (i.e. doubling its aspect ratio) had the effect of reducing the enclosure's heat transfer rate by approximately 63%.

1.4. Coupling radiation and natural convection in rectangular enclosures

Analytical studies by numerous researchers (Balaji and Venkateshan, 1993; Kim and Viskanta, 1984; Sen and Sarkar, 1995; Sharma et al., 2007) have shown that adding surface radiation to rectangular enclosure models tends to dampen natural convection and produce net heat transfer results that are difficult to predict.

Specifically, Balaji and Venkateshan (1993) disproved the notion that simple formulae could be used to sum independent natural convection and radiative heat flows. Even at very low wall emissivities and temperature gradients, the authors were able to show that radiation plays a “dual role”, reducing the convective component—a phenomenon they referred to as “convective drop”—while adding heat transfer of its own. Depending on the parameters of a given enclosure, the relative values of convection and radiation will vary, allowing heat transfers to vary up to 10%, either above or below the value found when considering convection alone.

Much of the convective drop described in this study may be attributed to an equilibration of fluid temperatures within the enclosure and the resultant reduction in the Nusselt number. At low wall emissivities (<0.23 for Balaji and Venkateshan), the additional radiative heat transfer is insufficient to overcome the convective drop and net heat transfer is lower than predicted by convection alone. As wall emissivities rise, however, radiative heat transfer becomes a much more significant mechanism and overall heat transfer is greater than that predicted by convection alone. Ultimately, the authors stressed that accurate predictions of heat transfer in enclosures could not be achieved unless radiation and convection were coupled.

Research has shown that practitioners cannot simply sum the resistances of layered thermal envelopes (Powell et al., 1989), nor can they simply sum the heat transfer from different heat

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