HEAT RECOVERY IN BUILDING ENVELOPES

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ABSTRACT

Infiltration has traditionally been assumed to contribute to the energy load of a building by an amount equal to the product of the infiltration flow rate and the enthalpy difference between inside and outside. Some studies have indicated that application of such a simple formula may produce an unreasonably high contribution because of heat recovery within the building envelope. The major objective of this study was to provide an improved prediction of the energy load due to infiltration by introducing a correction factor that multiplies the expression for the conventional load. This paper discusses simplified analytical modeling and CFD simulations that examine infiltration heat recovery (IHR) in an attempt to quantify the magnitude of this effect for typical building envelopes. For comparison, we will also briefly examine the results of some full-scale field measurements IHR based on infiltration rates and energy use in real buildings. The results of this work showed that for houses with insulated walls the heat recovery is negligible due to the small fraction of the envelope that participates in heat exchange with the infiltrating air. However; there is the potential for IHR to have a significant effect for higher participation dynamic walls/ceilings or uninsulated walls. This result implies that the existing methods for evaluating infiltration related building loads provide adequate results for typical buildings.

KEYWORDS

Infiltration, heat recovery, modeling, field measurement, CFD.

INTRODUCTION

This paper summarizes efforts over the past three years of researchers in the U.S. and Canada to estimate the effect of Infiltration Heat Recovery (IHR) on typical houses. IHR occurs when infiltrating (or exfiltrating) air passes through a building envelope and exchanges heat with the envelope materials as it does so. This tends to reduce the effect of the infiltrating air on the energy used to condition the house because the air entering the house will not be at the outdoor conditions and air leaving the house tends to make the interior surface of the house closer to indoor temperature, thus reducing heat transfer through the envelope. Essentially, the house envelope acts as a heat-exchanger for infiltrating and exfiltrating air, with the net effect of reducing the energy impact of the air flow.

Several previous studies (e.g., Clare and Etheridge (2001) and Brunsell (1995)) have focused on houses and envelope systems that deliberately set out to maximize the IHR. These studies have shown that a carefully designed and constructed house can significantly reduce the energy impacts of ventilation air. However, given that very few houses have been built in this fashion, the current studies were undertaken to see if standard algorithms for calculating energy effects of infiltration were significantly over-estimating the impact of IHR. This study of IHR was divided

into several parts. The goal of first part was to develop a better understanding of IHR and develop a simplified model to estimate IHR effects on infiltration related energy. In parallel with this effort we performed CFD simulations of IHR to systematically vary the governing parameters to identify the most important aspects of the problem and estimate the magnitude of potential impacts under idealized conditions. The second part of the study was to conduct full scale laboratory tests of heavily instrumented walls to verify the CFD results and obtain further insight. Lastly, field tests were performed in a house to see if IHR could be estimated for a typical insulated building envelope.

SIMPLIFIED MODEL

The traditional approach to estimating the energy impact of air infiltration is given by:

$$q = mCp\Delta T \tag{1}$$

where q is the infiltration heat load, m is the mass flow of air, Cp is the specific heat of air and ΔT is the indoor to outdoor temperature difference. IHR acts to reduce this effect and so we use the idea of heat recovery effectiveness (ε) to estimate the true effect of this air flow.

$$q = (1 - \varepsilon)mCp\Delta T \tag{2}$$

The simplified IHR model is derived from a steady-state one-dimensional coupled heat and mass transfer analysis. The model is a function of the Peclet number (Pe) that is the ratio of infiltration (mass flow (m) and specific heat (Cp)) to conduction (conductivity (U)) and surface area (A)):

$$Pe = \frac{mCp}{UA} \tag{3}$$

$$Pe_{inf} = Pe/f_{inf} \qquad Pe_{exf} = Pe/f_{exf} \tag{4}$$

Higher infiltration rates increase the Peclet number - and houses are generally in the range of $0.1 < Pe < 1.0$. Equation 3 assumes perfect coupling between conduction heat transfer and the air leakage. The effective Peclet number (Pe_{inf} and Pe_{exf}) is determined by dividing the whole whose Peclet number by the participation – the fraction of the building envelope actively engaged in the heat transfer process between the building envelope and the air flow. This participation is treated separately for infiltration and exfiltration. The participation, f, is not simply the physical area through which the infiltrating/exfiltrating area flows. It is adjusted to account for other effects on heat transfer through the envelope, such as: specific air flow paths (i.e., direction of air flow with respect to the heat flow), the contribution of air flow in and out of boundary layers, and the interaction of solar heating of the wall exterior with exterior boundary layer flows (if all the air entering a leak comes from this warmed boundary layer then this has the effect of increasing IHR). Another factor is the actual flow path in real walls, where the air does not spread out over the entire interior wall cavity and only small fraction (say 10%) of the wall has air flow through its cavities.

Then ε is determined from the sum of the infiltration and exfiltration components (for details of this derivation see Sherman and Walker (2001)):

$$\varepsilon = \frac{1}{Pe_{inf}} - \frac{1}{e^{Pe_{inf}} - 1} + \frac{1}{Pe_{exf}} - \frac{1}{e^{Pe_{exf}} - 1} \qquad (5)$$

The effect of infiltration on IHR can be estimated from the infiltration rate, the UA of the house and an estimate of the participation. The participation is the most difficult parameter to estimate. Figure 1 shows the IHR effectiveness using this simplified model. It shows that, as expected, the IHR is greater at low flow rates and at higher participation. At low flows, the air spends mode time traversing the building envelope and therefore more heat transfer occurs. However, at these low flows, the contribution of infiltration to total building load is small. Figure 2 shows estimates of the effect of IHR on total building load. The result is that there is an optimum range over which IHR has its biggest potential effects. At low flows, the contribution to building load is not significant and at high flows there is little heat recovery.
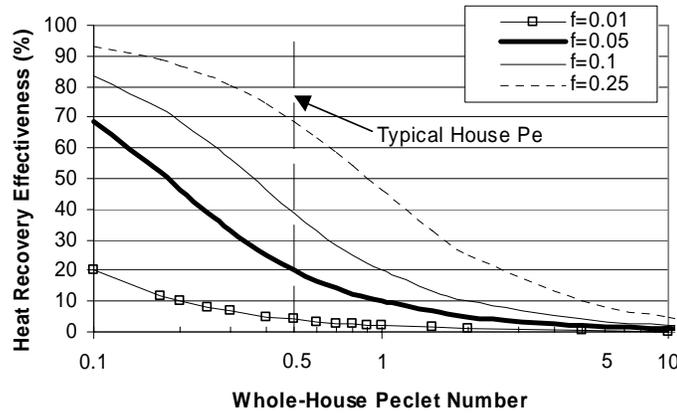

Figure 1: Heat recovery factor calculated with the simplified model using equal participations. The upper curve (with f = 0.5) is the theoretical maximum.
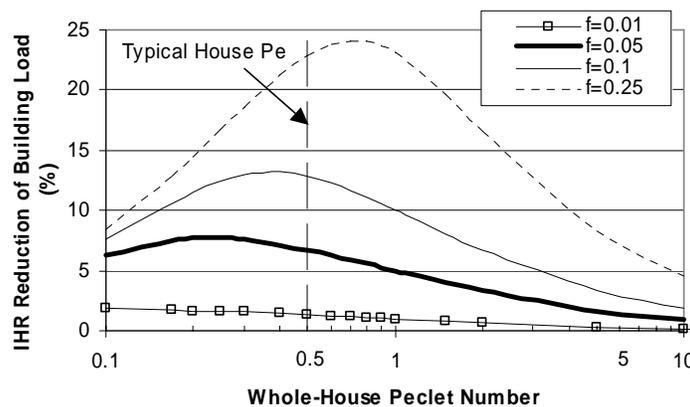

Figure 2. Reduction of building load using equal participations. The typical house Pe is for the case where one third of the building load is due to infiltration with no heat recovery.

CFD EXPERIMENTS

The CFD simulations were performed using the commercial STAR-CD code. The modeled wall sections were all 2.5 m high, and used standard (50 mm × 100 mm) stud sizes and wall sheathing. Three leak locations were used: straight through, hi entry/low exit and low entry/high exit. The simulations were repeated with the wall cavity filled with glass fiber insulation and with no insulation, for a total of six different wall systems. Because the previous studies showed that boundary layers may be significant, simulations were done both with and without a boundary layer. More details of the simulations can be found in Abadie et al. (2002).

The CFD simulations showed that the boundary layers had a big effect: they increased ε by about 0.2. For the infiltrating wall (with outside temperature less then inside temperature) this is because the air entering the leak from the boundary layer is warmer than ambient air (reducing the effective temperature difference for convection heat transfer) and the air leaving the leak enters the interior boundary layer – thus cooling the interior surface and reducing conduction through the wall. Similarly, air leaving the house is sucked from the interior wall boundary layer air that is below room temperature (again reducing the effective convection temperature difference), and the exfiltrating warmer air is entrained into the exterior boundary layer and reduces conduction losses through the wall.

These simulations were only two-dimensional so all the leaks must be thought of as slots. This has an important effect on interpretation of the simulation results. In a slots application, the boundary layer flows must interact with the flow in and out of the leaks, and all the boundary layer is affected. However for a three-dimensional hole only a small fraction of the boundary layer interacts with the air flow. The estimate of participation must account for these three and two-dimensional differences for different leaks. Another aspect of boundary layer interaction that still remains to be investigated is the effect of boundary layers on horizontal surfaces – in particular house ceilings. For horizontal surfaces we do not get the development of natural convection boundary layers as seen for the vertical surfaces and so theses boundary layer effects may be diminished. One last comment on the boundary layer effects is that building exteriors are exposed to atmospheric turbulence (even at low mean wind speeds and highly sheltered environments) that will tend to break-up the formation of natural convection boundary layers. The magnitude of this effect is unknown.

Other general observations from the CFD results are: ε is in the range of 0.1 to 1.0 for typical house Pe and is greater than 0.5 for all the low-high leak combinations; the straight through flow path exhibits considerably less IHR than for the low-high combinations (due to the reduced transit time and area affected by the air flow); and empty cavities at the same Pe as insulated cavities have about the same ε (albeit at about an order of magnitude less pressure difference). The results of simulations for infiltrating and exfiltrating walls were combined to determine the overall effect for a house. The results of these calculations showed a reduction in total building load due to IHR in the range of 3% to 13% for insulated walls.

LABORATORY TESTS

The laboratory tests were performed in environmental chambers at the University of Alberta (see Ackerman et al. (2003)). Two full scale wood frame test panels were constructed with

gypsum and oriented strand board (OSB) sheathing. The stud cavities were all filled with glass fiber batt insulation. Each panel was 2.5 m high and three stud spaces wide. The two panels differed in their leak site location: the first panel had a high slot opening in the gypsum board and a low slot opening the OSB face, and the second panel had circular (15 mm diameter) openings at half way up the panel in the two sheathing surfaces. The central stud space was instrumented and was carefully sealed from the other two stud spaces. Thermocouples were mounted on the interior and exterior surfaces of the sheathing and at three intermediate locations through the insulation. Temperature measurements were made at about thirty locations on the test panel.

The panels were mounted in the door of an environmental chamber. The environmental chamber was used to control the cold-side temperatures over a range of 0°C to -30°C, while warm side temperatures were maintained between 20 and 22°C. A pump was used to supply air at fixed rates (0 to 30 L/s) through the openings, which represented flows up to about 1/3 of and air change per hour for a house. This air was supplied via a mass flow controller and was conditioned to be at the same temperature as the ambient air. The air flow into the panel was via a plenum placed over the leak. Use of this plenum meant that boundary layer effects were not present in the air entering the test panel (although there remains the boundary layer interaction for air leaving the panel). This is key issue when interpreting the IHR results because Buchanan and Sherman (2000) and Sherman and Walker (2001) showed that the effect of the boundary layer can be significant.

The resulting temperature profiles gave significant insight on how the leak location can affect the air-flow pattern in the cavity and the resulting effective participation. The high/low slots resulted in "tilted" temperature profiles within the cavity. For cold air entering the cavity the temperature isotherms were moved away from the cold wall at the air entry point and toward the warm wall at the exit slot. Although the temperature profiles throughout the cavity were changed, because the air flow is largely parallel to the isotherms for most of the height of the cavity, the effect on heat transfer to and from the air flow is reduced. The effective area of influence of the slots (an indicator of the participation) was therefore on the order of the stud cavity depth. Similarly, the temperature profiles showed that the influence of the straight through round holes was confined to the center third of the panel. For the straight through holes, the change in flow rate had very little effect on the region of influence. The tests for this panel were repeated with the insulation removed and natural convection loops within the panel were clearly observed. As the flow rates and temperature differences were altered the natural convection loops tended to form different stable patterns with different numbers of loops. Also, the higher air flow rates induced flows within the cavity such that the loops in the cavity were split into two – one above and one below the hole. This multiplicity of natural convection conditions for the empty cavity is probably one of the reasons why the CFD code had problems reaching a solution under similar conditions.

FIELD TESTS

The field tests (see Ackerman et al. (2003)) were performed in an unoccupied house at the Alberta Home Heating Research Facility (AHHRF) located in Edmonton, Alberta, Canada. The house is of standard wood frame construction and the walls are filled with glass fiber insulation. The house was operated in three modes: normal envelope leakage, added holes (to approximately

double the leakage area of the envelope) and added holes with mechanical depressurization. Several hundred hours of infiltration and energy use data were recorded in each modes.

Without accounting for IHR, the infiltration contribution to building load was about 10% for modes one and two and about double this with the depressurization fan operating. In all three modes the effect of IHR was too small to measure. This implies that the background envelope leakage and the added straight through holes have limited participation for an insulated building envelope. This is about what would be expected based on the laboratory test results, where the straight through openings in an insulated wall can be estimated to have a zone of influence about equal to the wall thickness. The influence of all the added holes combined was only about 1% of the envelope surface area, which clearly limits the potential for IHR to have a significant effect on total building load (see Figure 2 for f=0.01, i.e., 1% participation).

SUMMARY

A combination of analytic modeling, CFD simulations, laboratory tests and field evaluations have shown that IHR is not significant for typical wood frame house construction with insulated cavities. The key reason for this is that little of the building envelope participates in IHR. Houses designed specifically to have high participation with dynamic walls and ceilings, or have empty wall cavities (no insulation) have a much greater IHR potential.

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