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Assessment of infiltration heat recovery and its impact on energy consumption for residential buildings

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ABSTRACT

Infiltration is a major contributor to the energy consumption of buildings, particularly in homes where it accounts for one-third of the heating and cooling loads. Traditionally, infiltration is calculated independent of the building envelope performance, however, it has been established that a thermal coupling exists between the infiltration and conduction heat transfer of the building envelope. This effect is known as infiltration heat recovery (IHR). Experiments have shown that infiltration heat recovery can typically reduce the infiltration thermal load by 10–20%.

Currently, whole-building energy simulation tools do not account for the effect of infiltration heat recovery on heating and cooling loads. In this paper, five steady-state IHR models are described to account for the thermal interaction between infiltration air and building envelope components. In particular, inter-model and experimental comparisons are carried out to assess the prediction accuracy of five IHR models. In addition, the results from a series of sensitivity analyses are presented, including an evaluation of the predictions for heating energy use associated with four audited homes obtained from whole-building energy simulation analysis with implemented infiltration heat recovery models.

Experimental comparison of the IHR models reveal that the predictions from all the five models are consistent and are within 2% when 1-D flow and heat transfer conditions are considered. When implementing IHR models to a whole-building simulation environment, a reduction of 5–30% in heating consumption is found for four audited residential homes.

1. Introduction

In the United States, residential buildings account for 21% of the nation's entire energy consumption [1]. About 91% of homes in the United States were built before the year 2000 [2]. Major steps can be taken to reduce the nation's energy consumption through the development and implementation of home energy efficiency strategies and technologies. Building energy simulation (BES) tools provide the analysis needed to predict building energy consumption. However, discrepancies between energy predictions of these tools and measured energy consumption can have significant impact, particularly the implications of residential retrofit projects. Since the 1980s, the development of BES tools has provided capabilities to capture the energy performance of new technologies and construction methods used in homes. With more emphasis on improving the energy efficiency of existing homes, BES models are considered to capture the performance of older, poorly insulated, leaky homes. However, most widely used simulation tools do not capture accurately important phenomena common in existing residential buildings.

Building description and occupant behavior are important to characterize a home energy model. However, an extremely large data set is needed to accurately quantify these characteristics, one which has not yet been identified. On the other hand, the building physics of energy simulation engines is well documented, and any changes and improvements made to building physics can be well quantified for future comparison. A number of issues have been identified [3] that can provide potential improvements to simulation tools. Detailed sensitivity analyses studies were performed on these issues to determine their impact on space heating and cooling in different climates [3], to effectively build a roadmap to improve upon existing simulation tools. After an evaluation of impact and feasibility, infiltration heat recovery was found to be the modeling issue that would provide the most potential improvement in energy simulation [3].

In this paper, models capable of estimating the level of infiltration heat recovery within the building envelope are described and compared against experimental data. Although infiltration heat recovery (IHR) has previously been identified and evaluated, it has not been implemented effectively into any BES tool. The results of this exercise are presented. In addition, the predictions of these models implemented within a whole-building energy simulation tool against measured data obtained for four audited homes are

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Nomenclature

A	area of the wall (m^2)
Bi	Biot number (–)
BLC	building load coefficient (W/°C)
c_p	specific heat of air (W/kg °C)
d	thickness of the wall (m)
f	infiltration heat recovery factor (–)
h	convective heat transfer coefficient at the wall surface (W/m^2 °C)
j	wall participation factor (–)
k	thermal conductivity of the wall material (W/m °C)
$\dot{m}$	mass air infiltration flow rate (kg/s)
n	air infiltration flow exponent (–)
Pe	Peclet number (–)
q	heat flux (W/m^2 °C)
$Q_{conduction}$	classical conduction thermal load (W)
$Q_{infiltration}$	classical infiltration thermal load (W)
$Q_{recovery}$	conduction-infiltration coupled thermal load (W)
r	ratio of wall heat transfer loads obtained with recovery vs. no recovery (–)
T	temperature (°C)
U	U-value of the wall (W/m^2 °C)
x	space location within the wall (m)
$X_{concentrated}$	fraction of concentrated air flow (–)
$X_{diffuse}$	fraction of diffuse air flow (–)

Subscripts

exf	exfiltration
i	inside
inf	infiltration
o	outside

presented. First, a literature review is presented to discuss previous studies on infiltration heat recovery. Second, the IHR models are presented. Finally, the predictions of the models against measured data are discussed.

2. Literature review

Thermal load associated with air infiltrating through the building envelope is traditionally calculated as the air leakage mass flow rate multiplied by the difference in enthalpy between the inside and outside air. This calculation approach ignores any thermal interaction between air flow and transmission losses resulting typically to over predict heating and/or cooling thermal loads for buildings. Past analytical and experimental work has identified that some thermal interactions between air infiltration and heat conduction exist within building envelope components, including walls and roofs. When accounting for this phenomenon, which has been referred to as infiltration heat recovery or IHR [3–11], the prediction accuracy of building thermal loads can be improved through a reduction in heat transfer to the conditioned space. The benefits of coupled heat and air flows have been investigated to improve the energy efficiency of several building energy systems [12–18].

The temperature gradient within a wall subject to air infiltration or exfiltration depends on the direction and velocity of air flow as well as the indoor–outdoor temperature difference as illustrated in Fig. 1. The thermal load associated with infiltration changes with the overall wall temperature, and heat conduction is closely dependent on the temperature gradient across the wall section. Anderlind developed a simplified model to evaluate the thermal coupling between heat conduction and air infiltration within a wall assuming that the infiltration is evenly distributed over the wall area [4]. Further developments of the Anderlind model have been proposed to more accurately capture the impact of IHR in a residential building envelope [8–11].

As illustrated in Fig. 1, the temperature gradient within a wall subject to air flow deviates from the linear temperature gradient (black) typical in steady-state heat transfer. Using the local thermal equilibrium (LTE) assumption, the temperature variation within the wall can be derived to define both the conditions of the wall and infiltrating air [10,17]. In addition to the temperature variation, the heat flux at any wall section can be estimated [4,8,17,19]:

$$q_{walltotal(x)} = -k\frac{dT}{dx} - \dot{m}C_p(T_{(x)} - T_{ref}) \tag{1}$$

with,

$$T(x) = T_o + (T_i - T_o) \times \frac{Bi_oBi_ie^{-Pe} - Bi_oBi_ie^{-Pe\frac{x}{d}} - Bi_ie^{-Pe}Pe}{Bi_oe^{-Pe} + Bi_oBi_ie^{-Pe} - Bi_oBi_i - Bi_ie^{-Pe}Pe} \tag{2}$$

and,

$$Pe = \frac{\dot{m}C_p}{UA} \tag{3}$$

$$Bi = \frac{h \times d}{k} = \frac{h}{U} \tag{4}$$

To evaluate the impact of IHR on the thermal load of conditioned spaces, a simple two-wall room model is defined, accounting for heat conduction and air flow as illustrated in Fig. 2. The top and bottom surfaces of the room model are assumed to be adiabatic. Both exterior walls have no fenestration and allow one dimensional heat transfer and mass flow for air infiltration and exfiltration. In the wall with air exfiltration, the Peclet number is set to be negative and the temperature is denoted T^* so that $T^*(x)$ is obtained from Eq. (2) by replacing Pe by $-Pe$. To quantify the thermal load to the space, $Q_{recovery}$, the indoor wall surface is set as the boundary conditions of the model, where $x = 0$:

$$Q_{recovery} = -\frac{Ak}{2} \times \left[\frac{dT}{dx_{(x=0)}} - \frac{dT^*}{dx_{(x=0)}}\right] + \frac{AkPe}{2d} \times [T_{(x=0)} - T^*_{(x=0)}] \tag{5}$$

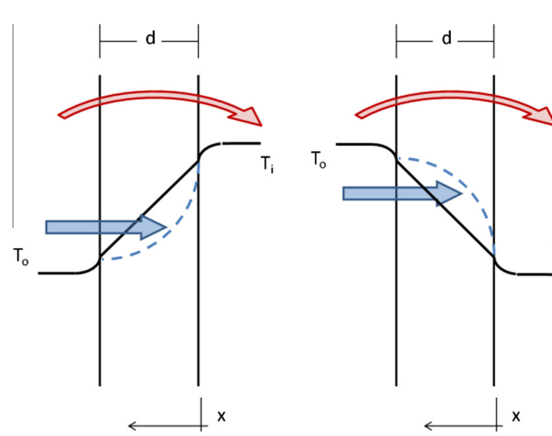

Fig. 1. Impact from air flow on wall temperature distribution.