

Measurement of infiltration heat recovery in a test cell with high flow rates

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Abstract

Infiltration heat recovery is the process that occurs when a building envelope acts as a heat exchanger for infiltrating air. This heat recovery process results in a reduced heat loss compared to predictions that use only flow rate and the total difference in enthalpy between inside and outside air. A series of experiments show the relationship between infiltration flow rate and heat loss in a test cell, with an emphasis on the high flow rate regime. A 3.5-m³ test cell was built with standard light-frame construction and one removable panel, to allow testing of wall sections with different engineered flow path lengths. Experiments were conducted with two different wall sections and at six different infiltration flow rates. Experimentally determined heat recovery factors are compared to computational fluid dynamics and agree to within approximately 15%.

Keywords

Infiltration, heat recovery, air leakage, building envelope, building energy use

Introduction

Infiltration is the uncontrolled process by which air leaks into the conditioned space of a building. A close relative of infiltration is exfiltration, the opposite process where conditioned air leaks out of a building. Infiltration can occur through seams in windows, doors, or ductwork, through open chimneys, cracks, or any other part of a building envelope that is not sealed tight. There are two primary causes of infiltration, and their relative importance depends on the type of building in question.

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In buildings that are less than three stories high, the primary cause of infiltration is usually wind. Wind blowing on the sides of a building induces a pressure gradient across the building envelope. This pressure gradient can drive air into the building on the windward side and out of the building on the leeward side, and can result in substantial energy losses. In taller buildings, the primary cause of infiltration is usually the stack effect. During the heating season, warm air inside the building rises—creating a positive inside pressure—and this air is forced out from the top. The lost volume is then replaced by cooler air entering the building from the bottom, resulting in a continuous flow through the building. During the cooling season the flow path is reversed, but the effect remains the same. Younes et al. (2011) provide a thorough review of air infiltration in buildings.

It is not very difficult to determine how much energy it takes to heat or cool a building—looking at the monthly electric bill usually does the trick. Determining the breakdown of this energy consumption between different thermal processes, however, can be quite difficult. Current estimates for residential homes put the average conductive losses at around 60% and the infiltration losses at 40% (Caffey, 1979). Probably the most common way for this to be determined is by performing a blower door test to find the typical leakage rate throughout the house. This flow rate is then multiplied by the enthalpy difference between the inside and outside air, thus determining the infiltration loss component (ASHRAE, 1989). In a building with no forced ventilation, the remainder of the loss is assumed to be conductive.

As noted, the energy impact of infiltration has traditionally been assumed to be equal to the product of the infiltration flow rate and the enthalpy difference between inside and outside air. This conclusion, however, is only true in cases where air enters a building without incurring any changes as it travels across the building envelope. If air is allowed to absorb energy from the building envelope as it passes through, effectively recycling conductive heat losses, the loss due to infiltration is reduced. The modified impact of infiltration will incorporate the enthalpy of the air that actually enters the conditioned space—warmed by heat from the wall—rather than the enthalpy of the outside air (Bhattacharyya S and Claridge DE, 1995; Sherman and Walker, 2001).

Although the direct benefit of exploring infiltration heat recovery is an improved energy audit, there are many indirect benefits that make this topic worth exploring. Building energy audits are performed by engineers who desire information that will allow them to make buildings and building processes more efficient. Better information can affect the sizing of heating, ventilation, and air conditioning (HVAC) systems, result in healthier buildings due to known and controllable ventilation rates, lead to optimal distribution of insulation due to improved information on conductive losses, and may give us clues about the possibility of dynamic insulation—where ventilation systems are replaced with walls that “breathe” to provide thermally conditioned fresh air in a system directly integrated with the building structure. All of these scenarios make for a building that needs less power to provide the necessary level of comfort, thus lowering costs and improving the environment.

One of the first experiments on the relationship between infiltration and heat loss was by Claridge and Bhattacharyya (1990). Claridge and Bhattacharyya studied the heat exchange between infiltrating air and an insulated test cell. It was found that heat conducting through the envelope of a building can warm the air that is leaking into that building, resulting in an infiltration energy loss that is less than the enthalpy difference between the inside and outside air. The degree to which energy is exchanged, or the infiltration heat exchange effectiveness ϵ , was found to be a strong function of three variables: flow rate, flow path length, and hole size. These experiments were carried out for dimensionless flow rates α ranging from 0.05 to 0.25 where

$$\alpha = \frac{\dot{m}c_p}{(UA)_0} \quad (1)$$

and m is the mass flow rate of air, c_p is specific heat, and $(UA)_0$ is the steady-state conductive heat transfer coefficient.

More recently, Buchanan and Sherman (2000) published a comprehensive numerical analysis of this heat exchange, using both two-dimensional (2D) and three-dimensional (3D) simulations, and used the 1990 experimental data to validate their results. Although other work on infiltration has been done since 1990, much of it has been tangential—relating instead to things like airflow within buildings, proper ventilation rates, or whole-building thermal performance—and cannot be applied to the general scenario of heat recovery presented by Buchanan and Sherman. A problem explicitly stated in this report is that Claridge and Bhattacharyya provide the only experimental data that they could find that represent infiltration in its simplest form, and that this data only cover a small portion of the realistic scenarios that their equations apply to. Claridge and Bhattacharyya reported data for $\alpha < 0.25$, yet Buchanan and Sherman calculated heat exchange effectivenesses for α as high as 4.5.

It is important to note that Claridge and Bhattacharyya worked with a small test cell, with a large surface area to volume ratio, and engineered leakage paths. In Buchanan and Sherman, the simplest models describe airflow through an ideal, impermeable wall with certain prescribed pathways. Both of these cases are far from being directly applicable to a real infiltration situation, but their idealized findings are very important in describing the potential of infiltration heat recovery and the specific factors that influence it. Because each infiltration situation is so unique, a lot can be gained from an experiment that, although unrealistic, is general enough to isolate principles that are applicable to all situations.

This research serves the purpose of filling the gap in experimental data noted by Buchanan and Sherman by performing experiments, with methodology resembling that of Claridge and Bhattacharyya, to see if the results from Buchanan and Sherman hold true under all conditions. The key variable that was extended in this new experiment was the airflow rate. Values for α ranged from 1.1 to 3.3, covering the greater part of the range predicted by the computational fluid dynamics (CFD) simulation. These high flow rates are possible in certain areas of many buildings and can realistically account for a large portion of a building's overall infiltration.

Experiment

The experiment was performed in a test cell—an insulated box, approximately 1.2 m wide \times 1.2 m high \times 2.4 m long. The walls are made from standard frame construction for all six sides: 1/4 in (6.4 mm) gypsum wallboard, 2 \times 4 (3.81 \times 8.89 cm) studs, and R-11 fiberglass batt insulation. One endwall is removable to provide an entrance into the test cell. All cracks were tightly sealed to prevent as much uncontrolled leakage as possible.

Inside the test cell is a heat gun and a thermometer. The heat supplied to the test cell is measured through the power input supplied to the heat gun. A manometer measures the difference between the interior and exterior pressure, and a Pitot tube is used to measure flow rate. A Shop-Vac is used to create the static pressure difference between the test cell and the environment.

Infiltration routes were modeled after the walls simulated by Buchanan and Sherman. All holes were 1 cm high slots. The endwall section contains a set of off-set holes, Section I, and later a set of adjacent holes, Section II (see Figure 1). Tests were performed without insulation in the wall cavity.

The goal of this experiment was to obtain steady-state measurements of the test cell temperature, T_i , that result from a given heat input, q_{in} , at a variety of known flow rates. Besides these variables, we must also know the steady-state conductive heat loss coefficient, $(UA)_0$, and the temperatures of incoming air, T_{in} , and the test cell surroundings, T_0 .

The first step is to determine experimentally the steady-state conductive heat loss coefficient. This is done by sealing the test cell and recording the steady-state heat input and interior and exterior temperatures. $(UA)_0$ is calculated as follows

$$(UA)_0 = \frac{q_{in}}{(T_i - T_0)} \quad (2)$$

The heat loss coefficient $(UA)_0$ is used to determine the heat lost due to conduction out of the test cell when it cannot be determined explicitly because of convective losses. Assuming that infiltration does not drastically change the temperature profile in the cell walls, this is present during all infiltration tests.

The final step is to perform the infiltration tests themselves. For each of the desired configurations, the test cell was heated to approximately 15°C above ambient and the desired flow rate was attained. The temperature distribution within the test cell was found to be relatively uniform. After reaching steady-state conditions, the critical heat input that corresponds to the given flow rate was recorded. In these experiments, mass flow rates vary between 0.01 and 0.03 kg/s.

Results

The experimentally measured value of UA , the steady-state conductive heat transfer coefficient, is 12.02 W/°C. This agrees in a general sense with predicted values,

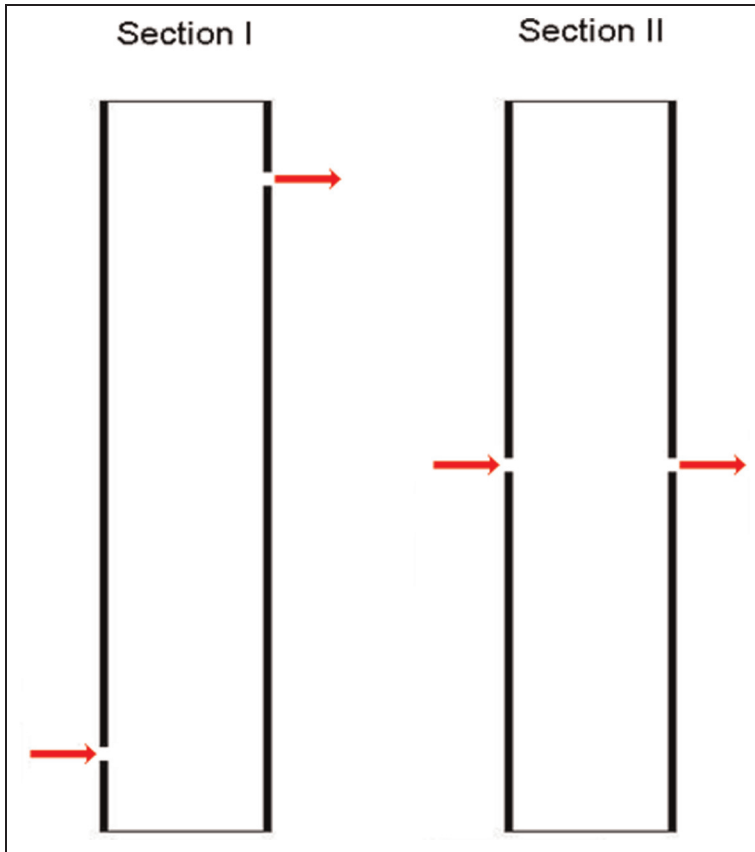


Figure 1. Wall sections used in infiltration tests to represent two different leakage paths.

which will vary based on the approximations made during calculation. This value is used to determine the conductive heat losses, Q_0 , for each infiltration test, where

$$Q_0 = (UA)_0 \Delta T \quad (3)$$

As in previous studies of infiltration heat exchange, our key parameter is the heat recovery factor, expressed as a dimensionless term, ε , and defined by

$$\varepsilon = 1 - \frac{Q - Q_0}{Q_{inf}} = \frac{Q - (UA)_0 \Delta T}{\dot{m} c_p \Delta T} \quad (4)$$

where Q is the total measured heat input to the test cell. This parameter is particularly useful because it compares the actual, measured infiltration loss in the numerator (assuming all nonconductive heat losses are due to infiltration) to the

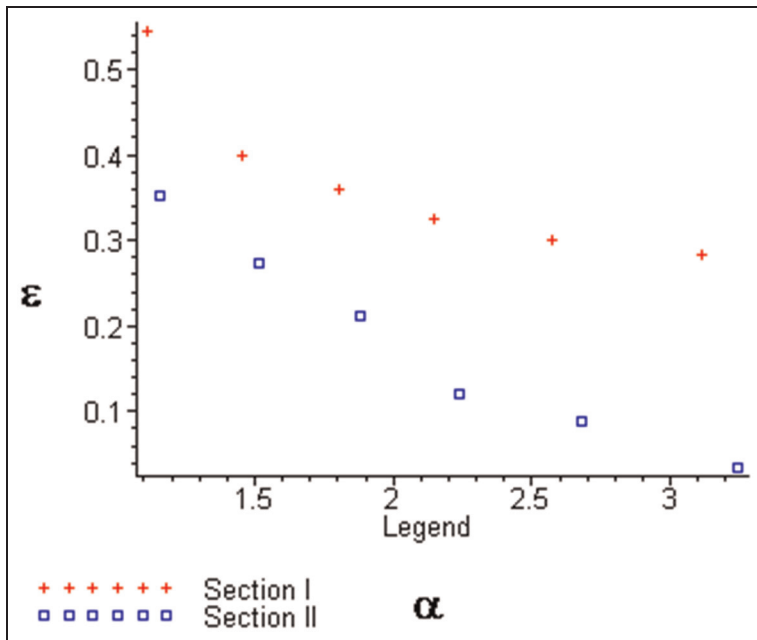


Figure 2. Results from wall Section I, +, and Section II, □. The plot shows the dimensionless heat recovery factor ε as a function of dimensionless flow rate α .

infiltration loss predicted by traditional methods, using the total inside–outside enthalpy difference, in the denominator. This number will be 0 when there are no measured infiltration losses, and will be unity when the measured losses match the predicted losses. In a controlled setting such as this experiment, ε should not be less than 0. This case, when the true losses are greater than the predicted losses, would most likely be the result of uneven temperature distributions in or around the test cell.

As mentioned earlier, the heat recovery factor is expressed as a function of a dimensionless flow rate α , defined by equation (1), which normalizes the flow rate compared to the thermal size of the test cell. In many discussions of infiltration, a common flow parameter is air changes per hour or ACH. Because of the small size of the test cell relative to the actual volume flow rate, ACH is not a good unit of measure for the current experiment.

Results for the two wall configurations are shown in Figure 2. From Section I, which represented a longer leakage path through the wall cross section, we see that ε ranges from 0.28 to 0.59 over flow rates α that range from 1.1 to 3.1. Section II, where the leakage path was shorter, shows a range of ε of 0.03 to 0.36 over α ranging from 1.3 to 3.3. In both cases, the presence of infiltration heat recovery is clear (no heat recovery would mean $\varepsilon = 0$). Also, it is clear that the magnitude of this

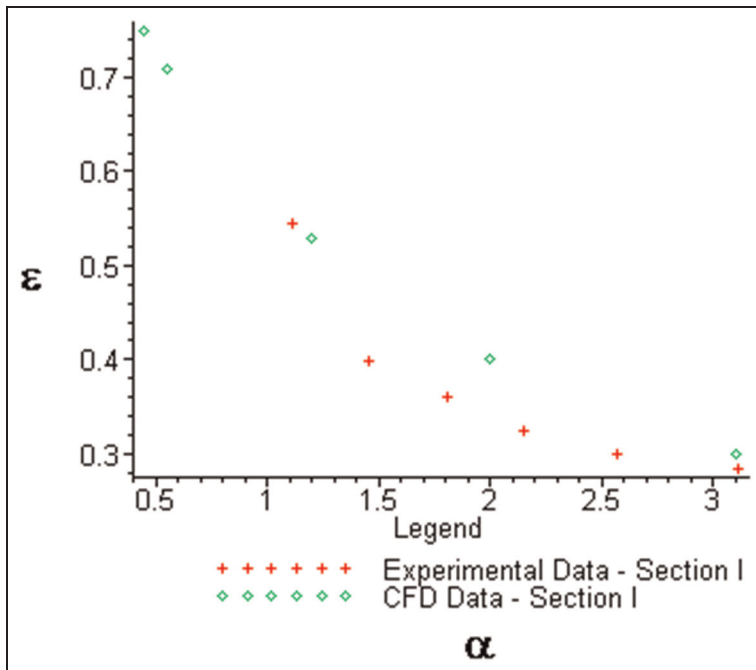


Figure 3. Comparison of experimental data with CFD for Section I. CFD: computational fluid dynamics.

heat recovery is dependent on the flow rate of the air. This dependence appears to be stronger at low flow rates, and then becomes increasingly weak as flow rates increase and ϵ approaches 0.

Close comparisons should not be made between the results from the two wall sections, other than the observation that increasing the length of the flow path through the wall section appears to increase the amount of heat recovery at a given flow rate. It is likely that geometric variables do not scale in the same way as the flow rate, a difficulty which will be discussed further (Figures 3 and 4).

Discussion

The results of this experiment compare favorably with the values predicted under similar conditions by Buchanan and Sherman (2000). For Section I, experimental values are within 10% of the Buchanan and Sherman data, with most experimental data points falling a little below CFD predictions. For Section II, the agreement is not quite as good, with an average percent difference of around 15%. Again, experimental values were generally a little lower than predicted values. In

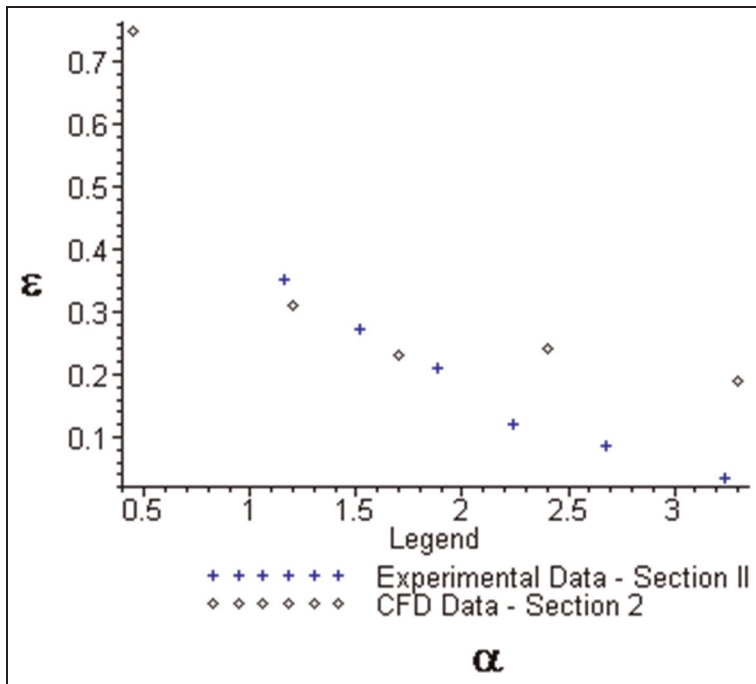


Figure 4. Comparison of experimental data with CFD for Section II. CFD: computational fluid dynamics.

both experiments, this was more evident at higher flow rates than at lower flow rates.

Claridge and Bhattacharyya (1990) observed that $\varepsilon(\alpha) = \varepsilon(0) + m\alpha$, or that ε was a linear function of α over the flow rates examined. The present experimental data, as well as the available CFD data, appear to disagree. If we assume that the wall can be represented by a single flow heat exchanger model and that the temperature distribution in the wall remains constant, in the ideal case $\varepsilon(0) = 1$ and $\varepsilon(\infty) = 0$. Over the currently available flow regime, this seems to be a more likely model. Observations suggest that these limits are probably accurate, with ε as a decaying function of α between the extremes.

If we assume that the infiltration heat recovery parameter tends to unity as the flow rate approaches 0 regardless of geometry, this observation may suggest that the lower heat recovery factors (with respect to CFD data) observed at high flow rates can be explained by differences in structural or flow geometry, which are only uncovered over a certain flow range. This also forms the key question that needs to be answered by further research: find ε as a function of geometry as well as flow rate, and then determine where values of α observed in real buildings fall in

this spectrum. Because the magnitude of neither range is clear, doubts about infiltration heat recovery must move from questions of existence to questions of impact.

As noted by Claridge and Bhattacharyya, results show that infiltration heat recovery is higher at lower flow rates, and lower at higher flow rates. Because this is inversely proportional to the actual energy losses (infiltration heat loss will be higher when the mass flow rate is higher), the true energy savings may not be significant in many cases, inhibiting the potential impact of infiltration heat recovery.

Because of scaling issues, it appears that it will be very difficult to answer subsequent questions about infiltration heat recovery using the same type of experiment done here. Buchanan and Sherman have created models that invoke an “effective area” as a means of estimating the impact of geometry on heat recovery. A method like this may provide a simple and effective means of estimating infiltration heat recovery, but flow complexities that can result from even minor geometric differences can change the shape and magnitude of the ε - α curve in a number of ways that are hard to predict. My suggestion for future experiments is to involve a building or building components directly, rather than running a controlled, indoor simulation. Key variables should be things that are directly relevant to building construction, like the tightness of the seal around a window pane, the total length of external seams, or number of times a door is opened and closed. When studying buildings, the greatest difficulty is often the inability to generalize, but all buildings are constructed using the same set of components and a finite number of methods. Information provided from an experiment that varies “features” rather than geometry would be more applicable, even if precision is still lacking.

The hope for continued research is to create a more accurate method for determining thermal energy losses from a building, one that yields the proper allocation of conductive and convective losses. With this tool, engineers will be able improve the efficiency of many kinds of existing systems, with each modification resulting in lower consumer costs, less energy use, and a cleaner environment.

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