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MEASURING AND MODELING RESIDENTIAL INFILTRATION

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SUMMARY

Air infiltration into residential buildings has a major effect on both heat loss and indoor air quality. In order to properly model infiltration, the impacts of wind, temperature, and mechanical systems must be assessed. Detailed infiltration and pressure measurements on four electrically heated homes in the Pacific Northwest region of the USA were made to determine these impacts.

Based on the measurements taken, improvements to existing infiltration models were proposed, and a simple model to incorporate the infiltration effects of exhaust and supply systems and unbalanced flows due to duct leakage was developed. The measured data agree closely with the theoretical model.

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INTRODUCTION

Air infiltration into residential buildings has a major effect on both heat loss and indoor air quality. Due to increased emphasis by home buyers, home builders, and electric utilities on energy efficiency, tighter homes are being constructed. Past assumptions that natural infiltration provides adequate ventilation for a home are no longer valid for modern energy-efficient homes. This concern has led to the development of minimum ventilation standards and requirements for mechanical ventilation systems.

In order to determine heating-season infiltration characteristics for all-electric homes in the Pacific Northwest region of the USA, detailed measurements were made on four homes in the Seattle area. These measurements were made to resolve several questions concerning the infiltration model developed at Lawrence Berkeley Laboratory (LBL) and described in reference [1]. The questionable areas concerned the effect of leakage distribution, the effect of wind on floor and ceiling pressures, and quantification of terrain and shielding effects. The superposition of natural and mechanical ventilation was also investigated.

TEST HOME MEASUREMENTS

The four homes selected for testing were preferentially chosen for the presence of a forced air distribution system, a mechanical ventilation system, and wind exposure. Measurement protocols were designed to quantify the infiltration impacts of ventilation systems, air handlers, and natural driving forces.

In each home, pressure differences across the floor and ceiling were measured, as well as across each exterior face on the first floor; in two-story homes an additional pressure across a second-story exterior wall was also measured. The living areas of each home were divided into two tracer zones. For two-story homes, each floor was a tracer zone, while for the single-story home, the master bedroom was a second zone. The attic, crawl space, and garage were also measured as separate zones to gain understanding of the flows through each of these areas and the leakage distribution of the house. The volumes and floor areas of each zone were measured, excluding exterior walls.

MEASURING INFILTRATION

Natural infiltration stems from two driving forces: wind-generated pressures on the building exterior and buoyancy pressures due to density differences between the interior and exterior. The two driving forces interact with each other and with the leakage characteristics of the building in a complex fashion. Also, the magnitude of the induced pressures is generally small.

Under typical Pacific Northwest heating-season conditions (a temperature difference of 12°C between indoors and outdoors), the buoyancy-induced (or stack) pressure across the floor or ceiling is about 1.2 Pa for a two-story home or 0.6 Pa for a one-story home. Assuming wall-averaged wind pressure coefficients of 0.5, a wind speed of 1.8 m/s produces a pressure of about 1 Pa across the walls.

Infiltration and interzonal flows were measured by using LBL's multitracer measurement system (MTMS), which injected constant quantities of tracer gases into the various zones and measured the concentration of each gas in each zone. Several injection and sampling points were included in each zone; each zone was also equipped with a continuously operating mixing fan and with temperature sensors. The MTMS made one complete cycle through the zones every 90 to 240 s, and temperatures were measured once per cycle. Using the MTMS injection and concentration measurements, a computer program calculated flows between each zone and the outside as well as flows between zones. To assess envelope leakage, blower doors were used to perform pressurization tests at each site. Flows through exhaust fans and supply and return grilles were measured with flow hoods and tracer gas tests.

The four homes in this study were relatively tight in terms of specific leakage area, air changes at 50 Pa, and natural infiltration. The leakage characteristics are summarized below.

Leakage characteristics of four homes

	Site 1	Site 2	Site 3	Site 4
Specific leakage area	3.88	5.30	5.36	2.61
ACH at 50 Pa	7.24	10.74	12.04	5.01
Stack Effect (ACH)	0.264	0.383	0.305	0.139
Wind Effect (ACH)	0.022	0.062	0.058	0.005
Natural Infil (ACH)	0.286	0.445	0.363	0.144

Stack-effect infiltration was dominant in these homes, ranging from 84 to 97% of the natural infiltration and from 58 to 70% of the total infiltration (including mechanical ventilation). Ventilated attics and crawl spaces had high infiltration rates: the attic rates ranged from 3.1 to 6.0 ACH, and the crawl space rates from 2.4 to 7.2 ACH. Infiltration in these areas was due almost entirely to wind, showing excellent correlation with wind speed.

MODELING INFILTRATION

Two infiltration models were compared[3] in this study; the LBL model previously identified and the Alberta Infiltration Model (AIM2) developed at the University of Alberta and described in reference [2]. AIM2 can be viewed as a simple extension of the LBL model, although it incorporates several refinements. Both models combine weather data and pressurization data from blower-door tests to predict infiltration due to stack and wind effects. To improve both the LBL and AIM2 model predictions, which base the stack effect on the full height of a home, an average stack height was used for all model runs. The average stack height is defined as the height of a column of warm air which displaces outdoor air, thus taking into consideration building construction that is partly below grade. This simple compensation method reduced stack effects predicted with the models by about 10%.

Each model's predictions were compared with actual infiltration measurements for periods when only natural infiltration was occurring. Although the two models have many similarities, they produced systematically different results. For all sites, the LBL model predicted combined wind and stack infiltration effects 30-60% greater than AIM2 predicted. While the magnitude of this difference appears large, the model predictions did bound the measurements. Detailed comparisons of predicted and measured infiltration do not indicate that either model is clearly superior. The differences in predictions stem primarily from the way the models use measurements of building tightness.

The standard method for characterizing tightness is to pressurize or depressurize the building by using a blower door and then to make flow measurements over a range of pressures from 15 to 70 Pa. The data generally appear to follow a power curve—called the leakage function of the building—with flow proportional to some power of pressure difference. Typically, the data from many thousands of field blower-door tests fit power curves quite well. Because of technical difficulties, however, such as interference from stack and wind effects, these tests are rarely done at pressures below 15 Pa, although the actual pressures across building envelopes are much lower. As measurements at the test homes indicate, naturally induced pressures are about 1-2 Pa (or less, if a home is somewhat sheltered from the wind.) Thus, leakage functions determined by tests at high pressure are being extrapolated far beyond the measurements on which the functions are based.

The LBL model uses the leakage function to predict the flow at 4 Pa and then uses a square-root law, while the AIM2 model uses the power curve from the pressurization test. The determination of which method, if either, should be used to extrapolate blower-door test data to lower pressures depends on the specific nature of the leaks in each home and cannot be predicted by theory. The key issue is the nature of the leakage function in real buildings at low pressures (0-4 Pa), and it now appears that field measurements under windless conditions are needed to resolve this issue.

Since mechanical systems can have large impacts on infiltration rates, a fan model that can be used with any natural infiltration model would help in the comparison of measured and modeled infiltration. This simplified fan model, described in reference [3], assumes that the total infiltration is the net fan flow when the net outward or inward flow (whichever is larger) due to all fans in operation is greater than twice the predicted natural infiltration rate. The added infiltration is then the net fan flow minus the predicted natural infiltration. When the net fan flow is less than twice the predicted natural infiltration rate, the added infiltration is one-half the net fan flow and the total infiltration is the sum of the natural infiltration and one-half of the net fan flow.

Air handlers and their associated ductwork systems interact with the natural infiltration in a more complex fashion. Three separate effects are involved: (1) duct leakage effects when the air handler is running, (2) increased natural infiltration due to duct leaks and envelope penetration leaks, and (3) induced infiltration due to closing of interior doors. Reference [3] presents details of this part of the model. Measured infiltration data were used to test the model, and excellent agreement was achieved.

COMPARISONS OF MEASURED AND MODELED INFILTRATION

Figure 1 shows the floor plan for the house at site 1, a two-story home with attached garage and vented crawl space. The home has six exhaust fans and a multiport mechanical ventilation system, and uses individually-controlled fan-forced wall heaters in each room for heat. Figure 2a compares measured and predicted (using the LBL model) natural infiltration; the predictions (which incorporate stack and wind effects) are seen to provide a reasonable lower bound to the measured infiltration. When the exhaust fan model is included in the predictions (Figure 2b), good agreement between measured and modeled infiltration is noted.

Figure 3 shows the floor plan for the house on site 4, a manufactured home with an electric furnace heating system. The furnace had a single return grille and multiple supply grilles. This home had three exhaust fans and two separate ventilation systems. The furnace ductwork was located under the home in the crawl space. Figure 4 compares the AIM2 wind and stack effect predicted infiltration with the measured infiltration (including ventilation and exhaust fan operation). As in Figure 2, the infiltration model provides a good lower bound for the measured infiltration.

The effect of air handler operation and door closing on the house pressures at site 2 is clearly shown in Figure 5. Shown are the air handler signal and the pressure difference across the envelope at the ceiling. At night, when the bedroom door is closed, the operation of the air handler depressurizes the house relative to the outside ambient pressure. This is caused by the buildup of air in the bedroom, which has no return duct. When the occupants open the bedroom door about 6:30 a.m., the depressurization no longer occurs. Closing this single bedroom door caused a major increase in infiltration.

CONCLUSIONS

The use of real-time multizone flow measurement of living zone plus attic, crawl space, and garage combined with concurrent pressure and temperature measurement is a powerful technique for understanding air flows in homes. The homes investigated in this study were found to be relatively tight, and stack-effect infiltration was dominant, ranging from 84 to 97% of the natural infiltration and 58 to 70% of total infiltration. The two infiltration models investigated bounded the measured natural infiltration; a simplified model for mechanical infiltration and duct leakage that was used in conjunction with the natural infiltration models provided excellent agreement with measurements.

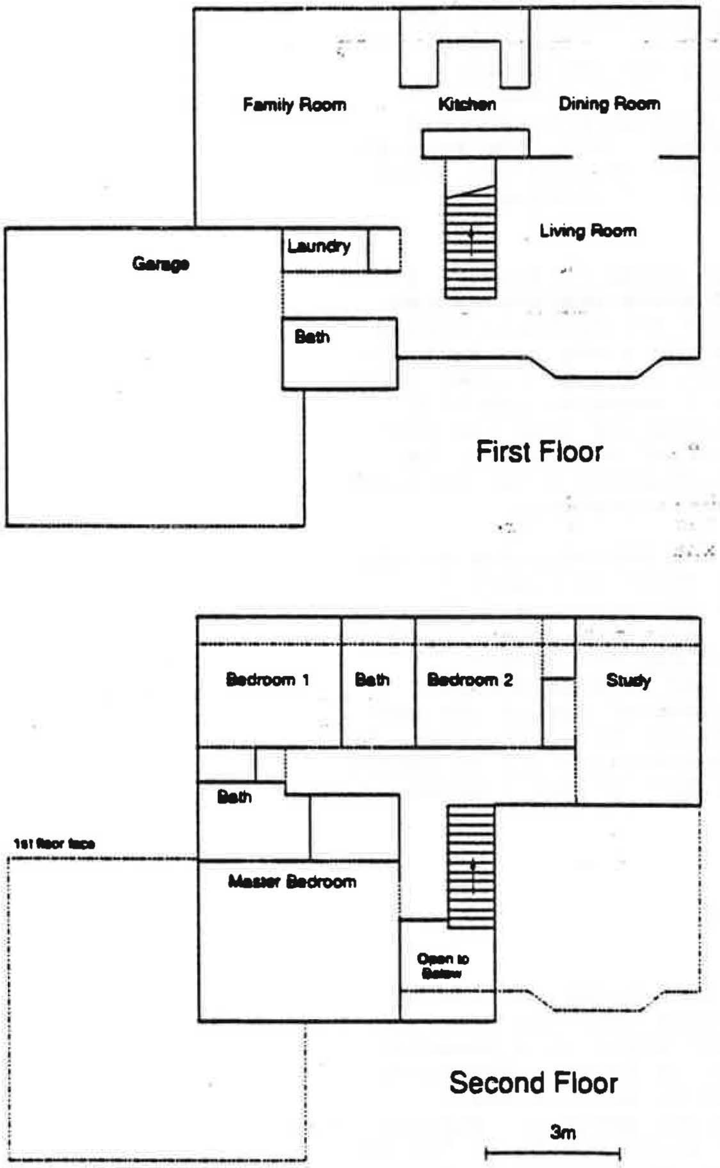

Fig. 1. Schematic floor plan of site 1.

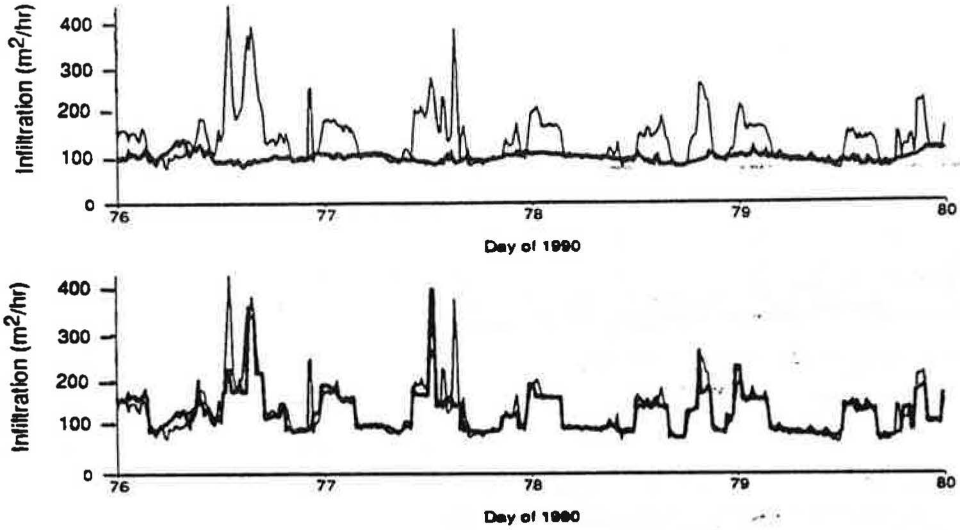

Fig 2. Comparison of measured and predicted infiltration at Site 1. The upper graph compares measured infiltration with predicted natural (wind and stack) infiltration (bold); the lower graph compares measured infiltration with predicted infiltration (bold), including the exhaust fan model.

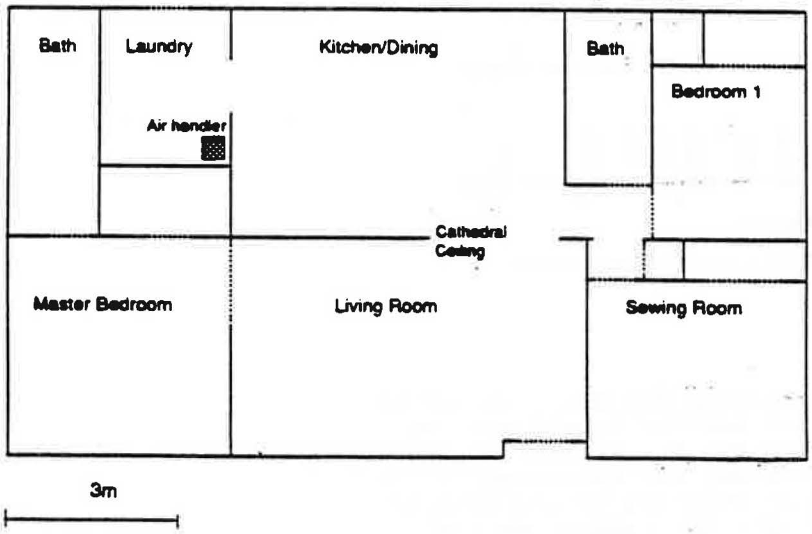

Fig. 3. Schematic floor plan of site 4.

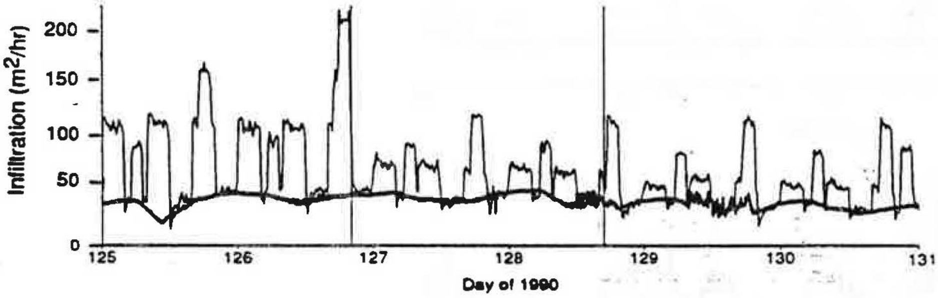

Fig. 4. Comparison of measured total infiltration with predicted natural (wind and stack effect) infiltration at site 4. The prediction forms an excellent lower bound for the measurements.

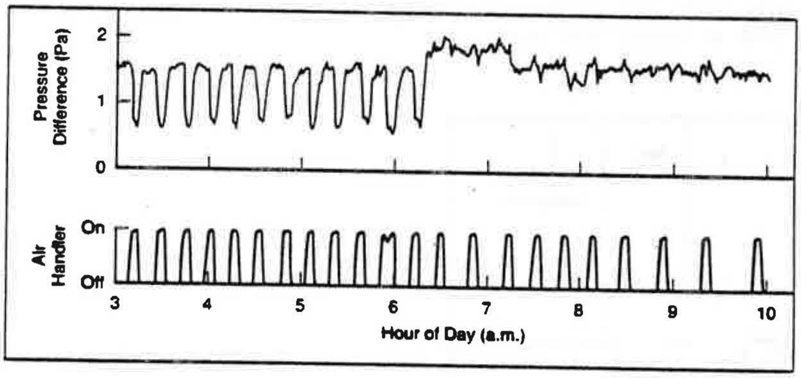

Fig. 5. Effect of air handler operation and door closing on house pressures. Shown are the air handler signal and the pressure difference across the envelope at the ceiling. At night, when the bedroom door is closed, the operation of the air handler depressurizes the house relative to the outside ambient pressure. The occupants open the bedroom door at 6:30 a.m., stabilizing the pressure in the house.

LITERATURE

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