THE MEASURED ENERGY IMPACT OF INFILTRATION UNDER DYNAMIC CONDITIONS[1]

Mingsheng Liu and David E. Claridge
Energy Systems Laboratory
Texas A&M University

ABSTRACT

Energy consumption due to air infiltration is customarily assumed to equal the mass flow rate times the specific enthalpy difference between the inside and outside air. Anderlind showed theoretically that this represents an upper limit for the energy impact of infiltration with an idealized steady-state wall model. Claridge and Bhattacharyya found it to be 20% to 80% of the value customarily used in an indoor test cell and a frame wall under steady-state condition. However, in real buildings, the heat transfer process is a complicated non-linear process, and neither the temperature nor the air flow rate is constant. Therefore, the validity of the steady-state methodology should be proved for dynamic condition. As a preliminary step, dynamic tests were conducted by varying an indoor test cell temperature in a periodic manner for a variety of leakage configurations and air flow rates. The measurement results demonstrated that the cell envelope can be treated as a linear system, and the steady-state methodology or time-averaging technique can be used for the treatment of energy performance when a constant air flow rate is present.

INTRODUCTION

Air infiltration is defined as the uncontrolled flow of air through building components. It has received increasing attention since the 1970s because of the current energy situation, its great potential to save HVAC energy consumption, and indoor environmental problems.

Air infiltration studies have focused major attention on measurement and reduction of air flow rate and on developing models which predict this flow. Extensive development in these areas has been achieved by Charlesworth [1989] and Liddament [1986]. But the impact of air infiltration on energy consumption has received much less attention, although some excellent experimental and theoretical studies have been done. The energy performance of combined conduction and infiltration in double-frame windows was studied experimentally and substantial heat recovery was noted by Bursey and Green [1970]. The theoretical basis for the double-window heat recovery was reported by Guo and Liu [1985]. The analytical solution [Liu 1987] of the differential equation for the combined conduction and infiltration process in walls was developed for steady-state conditions. It was found that both conduction and infiltration energy consumption were quite different from those calculated by the design method. Anderlind [1985] provided another theoretical treatment which demonstrated that combined conduction and infiltration effects were a common phenomenon in walls and that energy saving potential existed. Several studies [Beyea et al. 1977, Harrje et al. 1979, Claridge et al. 1984] observed that attic temperatures were often higher than those calculated because of warm air leakage into attics. Another study [Claridge et al. 1985] found the overall energy consumption of several houses to be 50% lower than that calculated. All of these studies add insight into the heat transfer process in residential house components and show that the conduction and air infiltration energy consumptions are not simply additive as is normally assumed. However, all of these studies were limited to the scope of steady-state condition. Because the heat transfer of a wall is a complicated non-linear process under weather conditions where both temperature and air flow rate change with time, the validity of the steady-state methodology must be proved under dynamic conditions. The results and conclusions from the steady-state measurement must then be checked as to whether or not they can be extended to house components.

In order to validate the steady-state methodology under dynamic temperature condition, an indoor test cell was modified, a test methodology was developed, and the energy performance (heat loss factor, air infiltration energy consumption) was measured for four different air leakage configurations and different air flow rates under both dynamic and steady-state conditions. The validity of the steady-state methodology was checked by comparing the steady-state results with dynamic results. The test facility, test methodology, measurement results, and conclusions are reported in the following sections.

EQUIPMENT

The test cell was constructed using standard frame construction for the walls, ceiling, and floor surfaces. The construction of all surfaces was:

- 3/8 inch exterior plywood sheathing
- 2x4 studs
- R-11 fiberglass batt insulation between the studs
- 3/8 inch interior plywood sheathing

The external measurements of the test cell were 56.5 inches wide by 48 inches high by 96 inches long. Each surface was constructed separately, and then all six

Proceedings of the Eighth Symposium on Improving Building Systems in Hot and Humid Climates, Dallas, TX, May 13-14, 1992

surfaces were bolted together and caulked. One of the 56.5 inches by 48 inches end-walls contained a removeable 24-inch square window glazed with 3/8 inch Plexiglass and covered by polystyrene weather shield insulation.

The test cell had two concentrated holes: "A"-2 inches in diameter, and "P"-1/2 inch in diameter. Each wall also had two diffuse holes (one on the interior plywood panel, one on the exterior plywood panel) at diagonally opposite corners. The schematic of the hole position is shown in Figure 1. These holes served to simulate the following air leakage configurations: (1) diffuse wall: no holes open except "P" in the walls, air introduced through hole "P"; (2) quasi-diffuse wall: diffuse holes open, air introduced through hole "P"; (3) concentrated flow: air exhausted through hole "A", air introduced through hole "P"; and (4) double flow: walls configured as in case 2, but air introduced through the diffuse holes in two side walls, and leaked out through the others.

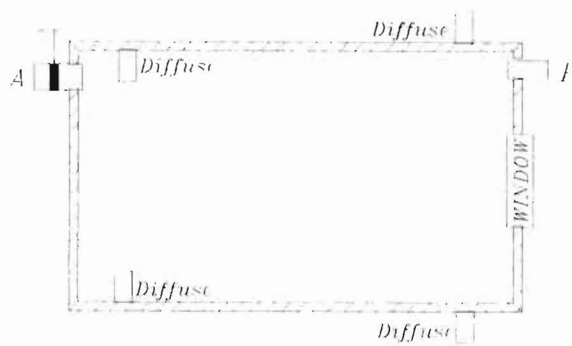

Figure 1: Schematic of Hole Positions

This test cell was initially built and used for the thermal performance measurement under steady-state conditions [Claridge et al. 1990]. The rota-meter used for flow measurement in the earlier tests was replaced by a calibrated orifice to permit essentially continuous measurement of air flow rate, and the internal heating system was modified to provide more uniform temperature distribution. The room temperature was measured by ten thermocouples surrounding the test cell, instead of only one, to provide a better record of mean room temperatures.

METHODOLOGY

The tests consisted of two phases: system calibration and normal tests. The system calibration investigated the systematic error and basic assumptions. The normal tests measured the thermal performance by following the standard test profile as shown in Figure 2.

The systematic error was defined as the non-zero output of the system with zero controlled inputs. Here, the output was the temperature difference between the test cell and room, and the inputs were air flow rate and heat input. The cell and room temperatures were measured continuously for a week and the room was illuminated continuously. The average temperature difference, defined as systematic error and expressed as δT, was calculated for this period (δT was 0.4^oC because the test cell surfaces received more radiation from lights than did the thermocouples).

A uniform distribution of the cell air temperature was assumed. This was initially checked by comparing the temperature at different positions when the heater was turned on and off repeatedly for two days.

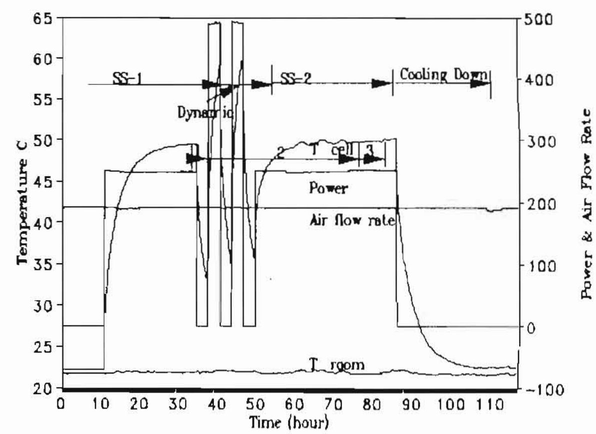

Figure 2: Schematic of Dynamic Test of Indoor Test Cell

The basic dynamic test profile imposed on the indoor cell is shown in Figure 2. The profile consisted of three periods: (1) a quasi-steady period (SS-1), where 250 watts heat input was supplied for 24 hours; (2) a dynamic period, where heat input was switched off and on at 3-hour intervals for a total of 15 hours; and (3) a second quasi-steady period (SS-2), where 250 watts heat input was supplied for 36 hours. The energy performance of the cell was then investigated under both steady and dynamic conditions.

The total heat loss factor of the test cell was calculated by the following formula:

$$UA = \frac{\sum_{i=1}^{k} Q(i) - UA_0\ \delta T}{\sum_{i=1}^{k} \Delta T(i)} \qquad (1)$$

Proceedings of the Eighth Symposium on Improving Building Systems in Hot and Humid Climates, Dallas, TX, May 13-14, 1992

$$UA_{classical} = UA_o + MC_p \quad (2)$$

where

UA	= total heat loss factor (conduction infiltration) (W/^{o}C)
Q	= heat input (W)
UA_o	= heat loss factor when air infiltration is not present(W/^{o}C)
δT	= systematic error of the system (^{o}C)
ΔT	= temperature difference between room and outside (^{o}C)
$UA_{classical}$	= calculated heat loss factor based on the design method
M	= air leakage rate (Kg/s)
Cp (J/Kg^{o}C)	= specific heat capacity of air
i	= time index.

Two steady-state periods, where the test cell temperature was stable, were chosen from SS-1 and SS-2. Then the UA was calculated from each of these periods. These UA values were called steady-state values because they were calculated from steady-state periods. The dynamic UA value was calculated from a period which started from the end of the steady-state period from SS-1 and ended at the start of the steady-state period from SS-2.

Subsequently, Infiltration Heat Exchange Effectiveness (IHEE or ε) and total energy recovery ratio due to air infiltration (β) were defined as:

$$IHEE = \frac{UA_{classical} - UA}{MC_p} \quad (3)$$

$$\beta = \frac{UA_{classical} - UA}{UA_{classical}} \quad (4)$$

IHEE presented the difference between the designed and actual heat loss factors as a fraction of MC_p. Because MC_p was regarded as the designed heat loss factor due to air infiltration, IHEE was also called air infiltration energy recovery. β presented the difference between the designed and actual heat loss factors as a fraction of the designed heat loss factor. Subsequently, β was regarded as the total energy saving ratio. If actual energy consumption was greater than the designed value when both infiltration and conduction were present, the IHEE and β would both be less than zero. If actual energy consumption was same as the designed value, the IHEE and β would both be zero. If the actual energy consumption was less than designed value, the IHEE and β would both be greater than zero. The larger the IHEE and β were, the more energy recovered by the air infiltration.

RESULTS

The measured IHEEs for case one from both steady-state and dynamic periods are shown as a function of non-dimensional air flow rate in Figure 3. The non-dimensional air flow rate (α) was defined as the ratio of air infiltration heat loss factor (MCp, energy consumption due to air infiltration only per degree temperature difference) to the conduction heat loss factor (UA_o, energy consumption due to conduction only per degree temperature difference). The results showed that IHEEs from the dynamic period were smaller than those from the first steady-state period but larger than those from the second steady-state period in 4 out of 5 tests. Figure 4 shows IHEE for different leakage configurations with a non-dimensional air flow rate of 0.2. The results showed that the IHEE from the dynamic period were in between IHEEs from the steady-state periods for the diffuse flow and double flow, the largest for the concentrated flow and the smallest for the quasi-diffuse flow. It appeared that IHEE decreased with time because the chronological order of the periods was the first steady-state period, the dynamic period, and then the second steady-state period. This time dependence was explained by the fact that the moisture content of the test cell decreased with time after the test started. The test cell had the highest moisture content during the first steady-state period, as it was heated up. The test cell had a lower moisture content during the dynamic period and second steady-state period. These moisture changes with time caused the variation of the IHEE.

The differences of the dynamic and steady-state IHEE were within the range of 3% to 12% when the air flow rate was the same. The error analysis conducted for this test showed the measurement error limit was from 15% to 34% when the non-dimensional air flow rate changed from 0.2 to 0.05. Therefore, the differences of IHEE values from the dynamic and steady-state periods were caused by either the time dependence of the test cell thermal performance or by the measurement error. Finally, it was concluded that the heat transfer of house envelopes could be treated as a linear process, and the steady-state methodology or time-averaging technique could be used without causing systematic error in the treatment of the thermal performance of the house envelope when a constant air flow rate was present.

Figure 3 shows that the IHEE varied from 0.60 to 0.45 when the non-dimensional air flow rate changed from 0.05 to 0.2 for the diffuse leakage configuration. Figure 4 shows that the IHEE was about 0.84 for the double flow, 0.25 for the concentrated flow, and 0.45 for the diffuse and quasi-diffuse flow when a non-dimensional air flow

Proceedings of the Eighth Symposium on Improving Building Systems in Hot and Humid Climates, Dallas, TX, May 13-14, 1992

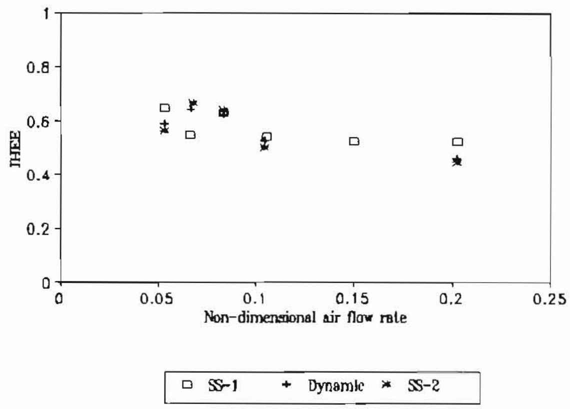

Figure 3: IHEE Comparison for the Diffuse Leakage Configuration
SS-1 = First steady-state period; Dynamic = Dynamic period; SS-2 = Second steady-state period;

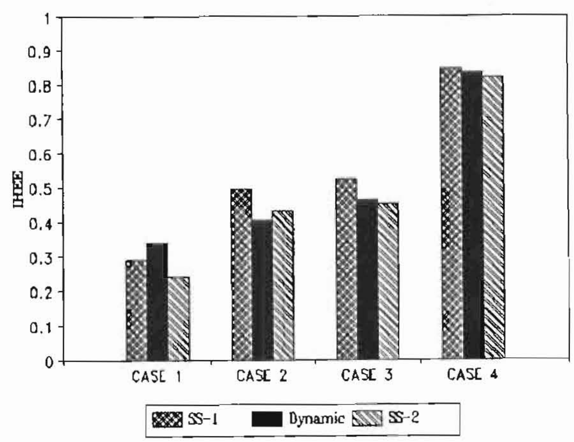

Figure 4: IHEE Comparison for Different Leakage Configurations
Case 1 = Concentrated flow; Case 2 = Diffuse flow; Case 3 = Quasi-diffuse flow; Case 4 = Double flow.

rate 0.2 was present. These numbers show that the actual air infiltration energy consumption was 25% to 84% lower than customarily assumed under the leakage configurations and air flow rate conditions.

Figure 5 shows both the UA and total energy saving ratios as a function of the non-dimensional air flow rate for the diffuse wall configuration. The results show that the measured UA values were always smaller than the classical values, and the difference increased with air flow rate increase. The total energy savings changed from 5% to 8% when the non-dimensional air flow rate varied from 0.05 to 0.2. The UA and energy saving ratio are shown in Figure 6 for four air leakage configurations with a non-dimensional air flow rate of 0.2. The energy saving ratios were about 5% for the concentrated flow (case 1), 8% for the diffuse and quasi-diffuse flow (case 2 and 3), and 14% for the double flow (case 4). These numbers show that the actual test cell energy consumption was 5% to 14% lower than customarily assumed under the leakage configuration and air flow rate conditions. In other word, the design method could overestimate the test cell energy consumption by 5% to 14% under the leakage configuration and air flow rate conditions.

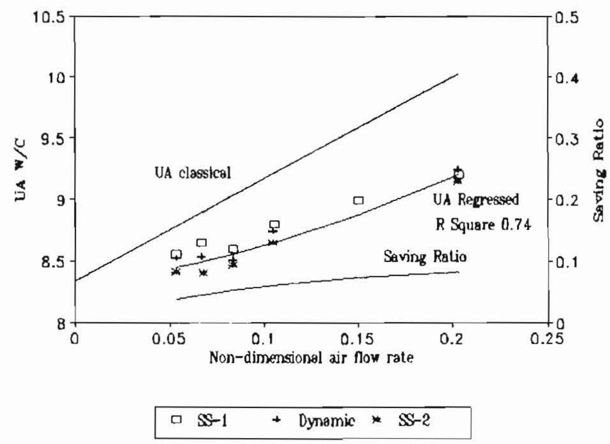

Figure 4: Heat Loss Factor Comparison for the Diffuse Leakage Configuration

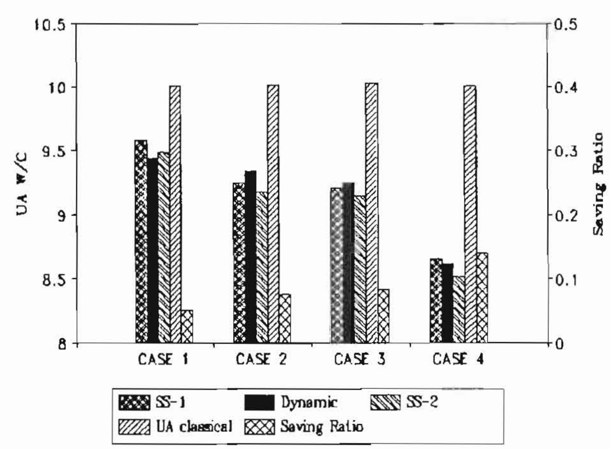

Figure 5: Heat Loss Factor Comparison for Different Leakage Configurations
Case 1 = Concentrated flow; Case 2 = Diffuse flow; Case 3 = Quasi-diffuse flow; Case 4 = Double flow.

Proceedings of the Eighth Symposium on Improving Building Systems in Hot and Humid Climates, Dallas, TX, May 13-14, 1992

It was observed that both IHEE and β (energy saving ratio) depended on air flow rate and leakage configuration. IHEE decreased with air flow rate increase, but β increased with air flow rate increase. Because a larger IHEE generally reflected a better heat exchange performance between solid wall materials and air, a higher IHEE meant a lower energy requirement for a test cell or house. However, both a higher air flow rate and a better heat exchange performance between solid materials and air could result in a higher total energy saving ratio. Subsequently, a higher energy saving ratio did not always represent a lower energy requirement for a test cell or house.

The results showed IHEE of 0.84 and β of 0.14 for the double flow and IHEE of 0.25 and β of 0.05 for the concentrated flow under same non-dimensional air flow rate of 0.2. These numbers show that the leakage configuration had a substantial energy impact on the test cell. It was inferred that a diffuse house (without big cracks or holes) could lead to much lower energy consumption without the sacrifice of fresh air.

Similar IHEE and β results were observed for cases 2 and 3. These numbers might demonstrate that the energy performance depends on the ratio of the area, which was affected by the air flow, to the air flow rate, because the quasi-diffuse leakage configuration had diffuse holes open. Therefore, a corner to corner flow might be present. However, the area affected by the air flow was the same for both the cases.

CONCLUSION

The air infiltration heat exchange effectiveness was measured in an indoor test cell under controlled dynamic temperature variations but with a constant air flow rate. The tests covered non-dimensional air flow rates from 0.05 to 0.20 for diffuse leakage configuration, along with three other configurations: quasi-diffuse, concentrated, and double flow (defined in Equipment section), with single non-dimensional air flow rate of 0.2.

The measurement results prove that the heat transfer of house envelopes can be treated as a linear process when a constant air flow rate is present. Subsequently, the steady-state methodology or time-averaging technique can be used without causing systematic error in the treatment of the thermal performance of house envelopes when a constant air flow rate is present.

The measurement found that a substantial air infiltration energy (25% to 84%) was recovered, and the actual energy consumption was much lower (5% to 14%) than customarily assumed under the leakage configurations and air flow rate conditions in the test cell.

The tests demonstrated that both IHEE and β (energy saving ratio) depend on the air flow rates, leakage configurations, and the ratio of area, which was affected by the air flow, to the air flow rate. IHEE decreased with the air flow rate increase, but β increased with the air flow rate increase. A diffuse leakage configuration can result in substantial energy savings when air infiltration is present. It was inferred that a diffuse house (without big cracks or holes) can lead to a much lower energy consumption without sacrificing fresh air.

Although the validity of the steady-state methodology is proved under indoor dynamic temperature conditions, further study is suggested because of additional dynamic effects present in outdoor conditions.

ACKNOWLEDGEMENTS

This work was supported by the Texas Higher Education Coordinating Board under Energy Research and Application Program (ERAP) project #227.

REFERENCES

Anderlind, G., 1985, "Energy Consumption Due to Air Infiltration," *Proc. of the 3rd ASHRAE/DOE/BTECC Conference on Thermal Performance of the Exterior Envelopes of Buildings*, Clearwater Beach, FL, 1985, pp. 201-208.

Beyea, J., Dutt, G. and Wotecki, T., 1977, "Critical Significance of Attics and Basements in the Energy Balance of Twin Rivers Townhouses," *Energy and Buildings*, Vol. 1, 1977, pp. 261-269.

Bhattacharyya, S. and Claridge D. E., 1992 "The Energy Impact of Air Leakage Through Insulated Wall," To be published in Solar Engineering 1992.

Bursey, T. and Green, G. H., 1970, "Combined Thermal and Air Leakage Performance of Double Windows," *ASHRAE Transactions*, 1970, Vol 73, pp. 215-226.

Charlesworth, P.S., 1988, "Air Exchange Rate and Airtightness Measurement Techniques -----An Application Guide," *Air Infiltration and Ventilation Centre,* Coventry, Great Britain, August, 1988.

Claridge, D. E., Jeon H., and Bida, M., 1984, "Performance Analysis of the Colorado 50/50 Retrofit Program," Vol. 1, Submitted to the Solar Energy Research Institute by the *University of Colorado, Dept. of*

Civil Engineering and Architecture Engineering, February, 1984.

Claridge, D. E., Jeon H., and Bida, M., 1985, " A Comparison of Traditional Degree-Day and Variable-Base Degree-Day Predication with Measured Consumption of 20 Houses in the Denver Area," *ASHRAE Transactions*, Vol. 91, part 2, 1985, pp. 865-874.

Claridge, D.E. and Bhattacharyya, S., 1990 "The Measured Energy Impact of Infiltration in a Test Cell," *Journal of Solar Energy Engineering*, Vol. 112, 1990, pp. 132-139.

Guo Jun, Liu Mingsheng, 1985, "The Energy Saving Effect of Double Frame Windows," *Proceedings of the CLIMA 2000 World Congress in Heating , Ventilating and Air-Conditioning*, Copenhagen, Denmark, August, 1985, Vol. 2.

Harrje, J., Dutt, G., and Beyea, J., 1979, "Locating and Elimating Obscure but Major Energy Losses in Residential Housing," *ASHRAE Transactions*, Vol. 85, part 2, 1979, pp. 521-59.

Liddament, M.W., 1986, "Air Infiltration Calculation Techniques ----An Applications Guide," *Air infiltration and Ventilation Centre*, Berkshire, Great Britain, June, 1986.

Liu Mingsheng, 1987 "Thermal Techniques in Buildings," *Harbin Architectural and Civil Engineering Institute Press*, 1987, pp. 3.85 - 3.90.