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Guidelines for Measuring Air Infiltration Heat Exchange Effectiveness (IHEE)

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DISCLAIMER

Executive Summary

This report is presented to the Texas Higher Education Coordination Board as a deliverable under the Energy Research and Applications Program Project #227, which targeted reducing the design size of HVAC systems in houses since the actual air infiltration energy consumption is less than the design values due to air infiltration heat recovery in house components.

This report presents three methods of measuring the air infiltration heat recovery in buildings. The blower door method estimates the air infiltration heat recovery using a test which takes less than one hour, and gives information to the contractors making retrofit decisions. The co-heating method identifies the relationship between the infiltration heat recovery and the air flow rate using two or three nights of testing. This method has higher accuracy than the blower door method and is suitable for use by both contractors and researchers. Finally, the STAM (short term average method) investigates the relationship between air infiltration heat recovery and air flow rate, air flow direction, and solar radiation. This is a comprehensive method which is most suitable for use by researchers.

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Guidelines for Measuring Air Infiltration Heat Exchange Effectiveness (IHEE)

Introduction

The rate of air infiltration into buildings affects the energy consumption. It has been universally assumed when calculating the heating and cooling loads of buildings that the amount of energy required to heat (or cool) infiltration air is the same as that required to heat (or cool) outside air to the indoor conditions: this is the product of the specific enthalpy difference between indoor and outdoor conditions and the mass flow rate of the infiltration air. However, the actual air infiltration energy consumption can differ (generally smaller) from this value significantly depending on building structures and weather according to the studies performed by the authors [Claridge & Bhattacharrya 1989, Bhattacharrya & Claridge 1992, Liu & Claridge 1992 a, b, c] and other researchers [Timusk et al. 1986, 1992, Morisson et al. 1992 a, Virtanen et al. 1992, Adderland, 1985, Guo & Liu 1985]. To estimate the energy consumption correctly, the authors proposed the concept of air Infiltration Heat Exchange Effectiveness, which expresses the reduction of energy consumption as a fraction of the classical air infiltration energy consumption:

$$IHEE = \frac{Q_{classical} - Q_{actual}}{\dot{m}C_p(T_{room} - T_{out})} \tag{1}$$

where, $\dot{m}$ is the air infiltration rate (Kg/s), C_p is the specific heat of air (J/Kg K), T_{room} is the room air temperature (°C), and T_{out} is the ambient temperature (°C). $Q_{classical}$ is the energy consumption calculated using the classical method (W), which treats air infiltration, conduction, and solar radiation independently. Q_{actual} is the measured energy consumption.

Generally, $Q_{classical}$ is not same as Q_{actual} because of the interaction of heat conduction, solar radiation, and air infiltration in the building components [Liu and

Claridge 1992]. For example, when cold air leaks through walls from outside to inside, the air is partially warmed before it enters the room, while warm air may heat up the wall and reduce conduction loss as it leaks from inside to outside. This phenomenon is called air infiltration heat recovery. According to the definition of the IHEE in Equation 1, the actual energy consumption is less than the classical energy consumption when the IHEE is greater than zero; the actual energy consumption is larger than the classical values when the IHEE is less than zero. The higher the IHEE, the higher the air infiltration heat recovery is. Therefore, it is important to evaluate the IHEE to value the energy performance of buildings.

The classical method estimates heat conduction, solar radiation, and air infiltration energy consumption separately using the heat loss factor of buildings, air flow rate and weather parameters. However, the actual energy consumption not only depends on these parameters but also on geometric forms of air flow paths, locations and directions of air flow, and profiles of weather parameters and air flow rates [Liu 1992]. Therefore, the IHEE depends on the geometric form of air flow paths, the air flow directions, and the profile of weather parameters and the air flow rate. Clearly, it is impossible to get the complete relationship between the IHEE and all of these parameters with limited measurements. Consequently, this guide for measuring IHEE focuses on how to measure it for different purposes. The methods used vary according to the requirements for accuracy and completeness.

This report presents three methods of measuring the IHEE for buildings. The blower door method estimates the general level of the IHEE using a test of less than one hour, and gives information to infiltration contractors making retrofit decisions. The co-heating method identifies the relationship between the IHEE and air flow rate using two or three nights of testing. Finally, the STAM (short term average method) investigates the relationship between the IHEE and air flow rate, air flow direction, and solar radiation.

Blower Door Method

Purpose:

The blower door method roughly estimates the range of the IHEE values and provides information to the infiltration contractors making retrofit decisions.

Users:

This method is suitable for infiltration contractors to determine the potential for air infiltration retrofitting.

Equipment:

Blower door.

Procedures:

1. Perform blower door test following the ASTM E 779-87 standard. Note that the building pressure differences should be spaced equally, such as 10, 20, 30, 40 50 Pa.

2. Regress the air flow rates as a function of the pressure differences across the building envelope with the following formula:

$$Q = a\Delta P^n \tag{2}$$

3. If the exponent coefficient "n" is larger than 0.65, the building may have a IHEE value in the range of 0.5 to 0.9 (Appendix A). If "n" is less than 0.65, the air infiltration may be dominated by concentrated air flow, where the air flows through relative large holes. Therefore, the IHEE can be improved by sealing these big holes.

Fundamentals:

This method is based on the fact that airflow through big holes is turbulent flow. Therefore, the exponent value is expected to be close to 0.5 under fully turbulent conditions. Since IHEE values are extremely small for this large hole or concentrated flow, IHEE of buildings should be improved by sealing these holes. Note that the IHEE depends mainly on the structure of cracks rather than the number of the cracks. Therefore, a higher IHEE can occur in a very leaky building, where numerous small cracks present. Under this condition, the building energy consumption can be reduced by tightening the envelopes and reducing air infiltration rate to a suitable level.

Test Advantages:

1) weather independent; it can be performed at any time;

2) fast, it takes about 30 minutes to an hour; and

3) simple, the blower door is the only equipment needed.

Test Disadvantage:

It estimates the IHEE qualitatively rather than quantitatively.

Co-heating Method

Purpose:

This method has two options which can be used to develop the relationship between the IHEE and the infiltration rate using two or three nights of measurements. The fundamental theory of this method is given in Appendix B.

Users:

Infiltration contractors and researchers.

Equipment:

1) Co-heating system which controls room temperature at a constant value and measures the power inputs.

2) Tracer gas system; which measures the air infiltration rate (for option 1).

3) Blower door system (option 2).

Procedures (option 1):

1) Perform co-heating for at least two nights. The test should be started at 10 PM or earlier. During the test, the room temperature should be kept as constant as possible, while the ambient and room temperature, and the heat input should be measured at least once per hour. The air infiltration rate should be measured continuously, and the time average values should be available during the late night period.

A period during 1 am to 6 am should be chosen, when the ambient temperature is stable, and the average temperatures and the air flow rate are then determined over this period.

2) Identify the constant coefficients "a" and "b" using the following equation sets:

If two co-heating tests were performed, then:

$$\begin{bmatrix} 1 & -(\dot{m}_1 C_p)^2 \\ 1 & -(\dot{m}_2 C_p)^2 \end{bmatrix} \begin{bmatrix} X \\ b \end{bmatrix} = \begin{bmatrix} UA_1^* \\ UA_2^* \end{bmatrix} \tag{2}$$

If three co-heating tests were performed, then:

$$\begin{bmatrix} 1 & \dot{m}_1 C_p & (\dot{m}_1 C_p)^2 \\ 1 & \dot{m}_2 C_p & (\dot{m}_2 C_p)^2 \\ 1 & \dot{m}_2 C_p & (\dot{m}_2 C_p)^2 \end{bmatrix} \begin{bmatrix} X \\ a \\ b \end{bmatrix} = \begin{bmatrix} UA_1^* - \dot{m}_1 C_p \\ UA_2^* - \dot{m}_2 C_p \\ UA_3^* - \dot{m}_2 C_p \end{bmatrix} \tag{3}$$

Where: $\dot{m}$ is the air infiltration rate for the first test (Kg/s), C_p is the specific heat of air (J/Kg K), and UAs are defined as follows:

$$UA_i^* = \frac{Q_i}{(T_{r,i} - T_{a,i})} \tag{4}$$

where Q is the average heat input rate (W), T_r is the room temperature (°C), T_a is the ambient temperature (°C). Note that the subscripts 1, 2 and 3 refer to the number of the test.

3) Finally, the IHEE can be calculated under different air flow rates using the formula:

If two co-heating tests were performed, then:

$$IHEE = 1 + b\dot{m}C_p \tag{5}$$

If three co-heating tests were performed, then:

$$IHEE = a + b\dot{m}C_p \tag{6}$$

Note that this option estimates the IHEE under normal operating conditions. However, if the air flow rates do not vary enough from night to night to provide accurate coefficients a and b substantial estimation error may occur.

Procedures (option 2):

1) Before starting the tests, the mechanically ventilated holes, such as hood, chimney, and diffusers, should be sealed first.

2) Perform at least two co-heating tests with different air flow rate at nights using blower door (See procedure option 1). It is suggested that the air flow rate of the following test be at least 20% higher that of the previous test.

3) Identify the constant coefficients "a" and "b" using the following equation sets:

If two tests are carried out, then:

$$\begin{bmatrix} 1 & -(\dot{m}_1 C_p)^2 \\ 1 & -(\dot{m}_2 C_p)^2 \end{bmatrix} \begin{bmatrix} X \\ b \end{bmatrix} = \begin{bmatrix} UA_1^* - 0.5\dot{m}_1 C_p \\ UA_2^* - 0.5\dot{m}_2 C_p \end{bmatrix} \tag{7}$$

for two tests or

$$\begin{bmatrix} 1 & \dot{m}_1 C_p & (\dot{m}_1 C_p)^2 \\ 1 & \dot{m}_2 C_p & (\dot{m}_2 C_p)^2 \\ 1 & \dot{m}_2 C_p & (\dot{m}_2 C_p)^2 \end{bmatrix} \begin{bmatrix} x \\ a \\ b \end{bmatrix} = \begin{bmatrix} UA_1^* - \dot{m}_1 C_p \\ UA_2^* - \dot{m}_2 C_p \\ UA_3^* - \dot{m}_2 C_p \end{bmatrix} \tag{8}$$

for three tests.

where: $\dot{m}$ is the air infiltration rate for the first test (Kg/s), and C_p is the specific heat of air (J/Kg K). The UAs are defined as follows:

$$UA_i^* = \frac{Q_i}{(T_{r,i} - T_{a,i})} \tag{9}$$

where Q is the average heat input rate (W), T_r is the room temperature (°C), and T_a is the ambient temperature (°C). Note that the subscripts 1, 2 and 3 refer to the different tests.

3) Finally, the IHEE can be determined using the following equations:

If two co-heating tests were performed, then:

$$IHEE = 0.5 + b\dot{m}C_p \tag{10}$$

If three tests are performed, then:

$$IHEE = a + b\dot{m}C_p \tag{11}$$

Note that this option estimates the IHEE under pressurized building conditions and has higher accuracy. The estimated IHEE value may differ from that of option 1 because this option has air flow through envelope in only one direction while option 1 has air flow through the envelope in both directions (infiltration and exfiltration).

Under normal operating conditions, the IHEEs of buildings can be estimated as twice the value measured by option 2.

Advantages:

1) fast;

2) determine the relationship of the IHEE with air flow rate, which gives the possibility of estimating the IHEE at other air flow rates, and

3) little intrusion on the day time use of the building.

Disadvantage:

This method involved relatively complicated equipment compared with the blower door method.

STAM Method

Purpose:

The STAM stands for the short term average period method, which measures the IHEE of buildings accurately and investigates the impact of solar radiation and air flow direction on the IHEE.

Users:

Researchers.

Equipment:

The same equipment is needed as for the co-heating method.

Procedures:

1. Tighten the building by eliminating mechanical ventilation holes.

2. Determine the solar aperture using a three-day test. During this test, the room temperature is maintained as constant as possible using electrical heaters. Note that no mechanical air ventilation is provided. Meanwhile the room and ambient temperatures, the

solar radiation and the heat input are measured. Two "zero net effect" [Liu and Claridge 1993] periods should be chosen using STAM methods. The average temperature difference between inside and outside, the solar radiation and the heat input are then calculated over these two periods. Finally, the solar aperture is determined as:

$$A_{solar} = \frac{Q_1 \Delta T_2 - Q_2 \Delta T_1}{\Delta T_1 I_2 - \Delta T_2 I_1} \tag{12}$$

where A_{solar} is the solar aperture (m^2), Q is the average heat input rate (W), ΔT is the temperature difference between inside and outside (°C), and I is the average solar radiation (W/m^2) on the exterior surface of the building. Note that the index 1 refers to data from the first "zero net effect period", and index 2 refers to data from the second "zero net effect period".

3. Determine the UA using two days tests with different air flow rates. During the tests, the room temperature is maintained as constant as possible using electrical heaters. A constant air flow rate is required for each test, meanwhile the room and ambient temperatures, the solar radiation, the air flow rate and the heat input are measured. The measured data are then analyzed by the STAM and one "zero net effect" period should be chosen for each test. The average temperature difference between inside and outside, the solar radiation, the air flow rate and the heat input are then calculated over this period. Finally, the heat loss factor of the building is determined as:

$$UA = \frac{Q + A_{solar} I}{\Delta T} \tag{13}$$

Two or more similar tests are suggested. Note that the flow rate of the first test can be determined as that which creates a building pressure difference of 5 Pa; the air flow rate of the following test can be chosen at least 20% higher than the air flow rate of the previous test.

4. To determine the relationship of the IHEE with air flow rate. if two tests are performed, the coefficient "b" can be determined by the following equation:

$$\begin{bmatrix} 1 & -(\dot{m}_1 C_p)^2 \\ 1 & -(\dot{m}_2 C_p)^2 \end{bmatrix} \begin{bmatrix} X \\ b \end{bmatrix} = \begin{bmatrix} UA_1 - 0.5\dot{m}_1 C_p \\ UA_2 - 0.5\dot{m}_2 C_p \end{bmatrix} \qquad (14)$$

Finally, the IHEE can be estimated as:

$$IHEE = 0.5 + b\dot{m}C_p \qquad (15)$$

Advantages:

1) high accuracy;

2) takes account of solar effects; and

3) automatically accounts for thermal storage effects.

Disadvantages:

1) intrusion on building operation;

2) relatively long time is required;

3) complicated algorithm is required to treat the measurement results; and

4) relatively complicated equipment is required.

Conclusions

The blower door method estimates the IHEE level using a 30 minute to one hour test. Therefore, the infiltration contractor can use it to estimate the potential for infiltration retrofitting.

The co-heating method estimates the relationship between the IHEE and air flow rate using two or three nights of testing. This method is suitable for researchers and in special cases for retrofits.

The STAM method exploits the relationship between the IHEE and the air flow rate, and accounts for the influence of solar radiation. However, this method takes re more time and requires complicated equipment and advanced data analysis tools. It is most suitable for use by researchers.

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Appendix A

The blower door technique exploits the relationship between air flow through the building envelope and pressure difference across it. The common form of equation is a power-law relationship:

$$Q(\Delta P) = a\Delta P^n$$

where ΔP is the pressure difference (Pa), Q is the total infiltration (m^3/s), and n is the leakage exponent. The exponent is normally found to be between two physically meaningful values of n=1/2 (nozzle or orifice flow) and n=1 (laminar flow). Therefore, the exponent value can serve as a good indicator of leakage path characteristics. If exponent value approaches 0.5, the air flow path must be short, such as a nozzle or orifice. Consequently, there is a little chance for the air infiltration heat exchange and a smaller IHEE is expected under this condition. However, if the exponent value approaches 1, the air flow path, or the ratio of the length to the diameter should be relative larger. Consequently, the stronger air infiltration heat exchange presents, and a higher IHEE value is expected under this condition.

The relationship between IHEE and exponent coefficient has been investigated using an indoor test cell and an outdoor test cell. The measurement results are summarized in Table A-1.

This table shows clearly that IHEE increases with exponent n increases. The measurement results show that the IHEE may have a value in the range of 0.5 to 0.9 when the exponent n is about 0.65 or higher, and IHEE is very low when the exponent n approaches 0.5.

Note that the single flow refers to that the air either infiltrates or exfiltrates through the whole envelope, while the double flow refers to that part of the envelopes has infiltration and the other part has exfiltration. For the indoor cell test, the double flow introduced air diffusely through part of the wall. This accounts for the big difference between the single and the double flows. For the outdoor cell tests, the IHEE values for the double flow are two times of that for the single flow.

Table A-1: Summary of Measurement Results (IHEE vs exponent n)

Indoor Test Results		Outdoor Cell Results		Note
n	IHEE	n	IHEE	
0.51	0.10	0.52	0.30	Single flow
0.53	0.20	0.51	0.35	Single flow
0.71	0.43	0.65	0.47	Single flow
0.51	0.51	0.51	0.60	Double flow
0.52	0.52	0.52	0.70	Double flow
0.75	0.67	0.65	0.94	Double flow

It is worth to mention that the exponent n depends on both the air leakage structure and the pressure range of the blower door test. Therefore, it is suggested to perform the blower door test with pressure difference varies from 10 to 50 Pa.

Appendix B

The co-heating method estimates the relationship between IHEE and air flow rate with minimized thermal storage influence. The fundamental of this method is discussed the following.

If the room temperature is kept constant, the building energy balance equation is generally expressed as:

$$Q_h = \left[UA_0 + (1 - IHEE)\dot{m}C_p\right]\Delta T + Q_{ground} - Q_{solar} + Q_{storage} \quad \text{(B-1)}$$

Where, Q_h is the heat input from the heaters(W), UA_0 is the heat loss factor of building excluding the floor (W/K), $\dot{m}$ is the air flow rate (Kg/s), C_p is the specific heat of air (J/Kg K), ΔT is the temperature difference between inside and outside (°C), Q_{ground} is the heat flow rate to the ground (W), Q_{solar} is the solar energy contribution to the building (W), $Q_{storage}$ is the net heat gain or loss of the envelopes excluding floors and internal thermal mass (W), and IHEE is the air infiltration heat exchange effectiveness..

To divides both sides of equation by ΔT, it then follows:

$$UA^* = UA_0 + (1 - IHEE)\dot{m}C_p + UA_{ground} - UA_{solar} + UA_{storage} \quad \text{(B-2)}$$

where:

$$UA^* = \frac{Q_h}{\Delta T} \quad \text{(B-3)}$$

$$UA_{ground} = \frac{Q_{ground}}{\Delta T} \quad \text{(B-4)}$$

$$UA_{solar} = \frac{Q_{solar}}{\Delta T} \quad \text{(B-5)}$$

$$UA_{storage} = \frac{Q_{storage}}{\Delta T} \quad \text{(B-6)}$$

Note that if tests can be performed continuously in a two or three-day period, Q_{ground}, Q_{solar}, $Q_{storage}$, and ΔT may have similar values during similar period of day for all the tests respectively. Consequently, UA_{ground}, UA_{solar}, and $UA_{storage}$ can be treated as constant during this test period, when room temperature is kept constant, ambient temperature and solar radiations are relatively stable. To introduce this assumption, the energy balance equation is rearranged as:

$$UA^{*} = X + (1 - IHEE)\dot{m}C_p \tag{B-7}$$

where UA^{*} is the measured (W/K), and X is the summation of the UA_{ground}, $UA_{storage}$, and $-UA_{solar}$.

According to the experimental results [Claridge and Bhattachrryra] and theoretical analysis [Liu and Claridge 1992], the IHEE is strongly correlated with the air flow rate, and can be generally expressed as:

$$IHEE = a + b\frac{\dot{m}C_p}{UA_0} \tag{B-8}$$

Where "a" and "b" are two constants, which varies with air flow pattern and leakage configuration of buildings. Since, the UA_0 is a constant, and it is not necessary to identify it for measuring the IHEE. Therefore, the above equation is rewritten as the following:

$$IHEE = a + b\dot{m}C_p \tag{B-9}$$

Note that the constant "a" represents physically the value of IHEE when air flow rate approaches zero. Therefore, the constant "a" may be chosen according to air flow pattern and building leakage conditions. Consequently, different test options are developed according to the choice of constant 'a".

Option 1

If air infiltrates into the building through part of the envelope and exfiltrates through the other part, we call this flow pattern as double flow. Under double flow pattern, the IHEE has the maximum value of one when air flow rate approaches zero. Therefore, equation (B-9) can be written as:

$$IHEE = 1 + b\dot{m}C_p \tag{B-10}$$

To introduce equation (B-10) into (B-7), the energy balance equation then is:

$$UA^* = X - b(\dot{m}C_p)^2 \tag{B-11}$$

If two tests are performed, both constants "b" and "X" can be determined by Equation (B-12):

$$\begin{bmatrix} 1 & -(\dot{m}_1 C_p)^2 \\ 1 & -(\dot{m}_2 C_p)^2 \end{bmatrix} \begin{bmatrix} X \\ b \end{bmatrix} = \begin{bmatrix} UA_1^* \\ UA_2^* \end{bmatrix} \tag{B-12}$$

where subscript 1 refers to data from the first test, and 2 refers to data from the second test.

Note that since the tests require similar temperature and solar radiation conditions, the tests should be performed as close as possible. However, air flow rates may be very close under these conditions. Consequently, a small measurement error may result in significant estimation error of constant "b".

Option 2

In order to overcome the difficulty of air flow rate encountered in option 1, air is then supplied to (or exhausted from) buildings through a fan, air hence leaks out (or leaks in) through building envelopes, which is called the single flow. Under this pattern, the IHEE has the maximum value of 0.5 when air flow rate approaches zero. Therefore, the constant "a" in equation (B-9) is 0.5.

$$IHEE = 0.5 + b\dot{m}C_p \tag{B-13}$$

To introduce equation (B-13) into equation (B-7), we get:

$$UA^* - 0.5\dot{m}C_p = X - b(\dot{m}C_p)^2 \tag{B-14}$$

If two tests are performed, then the constant "b" can be determined by the equation (B-15).

$$\begin{bmatrix} 1 & -(\dot{m}_1C_p)^2 \\ 1 & -(\dot{m}_2C_p)^2 \end{bmatrix} \begin{bmatrix} X \\ b \end{bmatrix} = \begin{bmatrix} UA_1^* - 0.5\dot{m}_1C_p \\ UA_2^* - 0.5\dot{m}_2C_p \end{bmatrix} \tag{B-15}$$

This option estimates the IHEE under the controlled single flow condition, and measurement results serve as good indicator of the air infiltration heat recovery.

Option 3

Both option 1 and option 2 assume that building envelopes have the maximum IHEE value of 0.5 for the single flow pattern when air flow rate approaches zero. However, leaky buildings, where air flows through short paths, have IHEE values lower than 0.5. Therefore, treating constant "a" as an unknown may improve the IHEE estimation.

To introduce equation (B-9) to equation (B-7), it results in:

$$UA^* - \dot{m}C_p = X - a\dot{m}C_p - b(\dot{m}C_p)^2 \tag{B-16}$$

If three tests are performed and labeled as 1, 2, 3, then the constants can be determined by equation (B-17):

$$\begin{bmatrix} 1 & -\dot{m}_1C_p & -(\dot{m}_1C_p)^2 \\ 1 & -\dot{m}_2C_p & -(\dot{m}_2C_p)^2 \\ 1 & -\dot{m}_2C_p & -(\dot{m}_2C_p)^2 \end{bmatrix} \begin{bmatrix} X \\ a \\ b \end{bmatrix} = \begin{bmatrix} UA_1^* - \dot{m}_1C_p \\ UA_2^* - \dot{m}_2C_p \\ UA_3^* - \dot{m}_2C_p \end{bmatrix} \tag{B-17}$$

Note that this option can be performed under both the single flow and the double flow patterns. Although this option seems to give higher accuracy, it requires more tests, hence more time.

Appendix C

The co-heating method provides an easy way measuring the IHEE during night time. However, the IHEE is also influenced by the interaction of solar radiation and air infiltration. To cover the impact of solar radiation, a method is developed by simplifying the STAM.

The first step is to determine the solar aperture under the minimized air flow conditions. It is required to seal the big cracks and holes first, then control the room temperature as constant as possible over a three-day period, meanwhile , measure the ambient and the room temperature, the heat input , the solar radiation, and the air infiltration rate if possible. From this test, two "zero net effect" periods should be chosen at least using the STAM method.

The energy balance equation over a "zero net effect" period can be expressed as equation (C-1) because the net thermal gain is zero.

$$Q_h = \left[UA_0 + UA_{ground} + (1 - IHEE)\dot{m}C_p\right]\Delta T - A_{solar}I \qquad \text{(C-1)}$$

where, Q_h is the heat input (W), UA_0 is the heat loss factor of envelopes excluding the floor, UA_{ground} is the heat loss factor of the floor, IHEE is the air infiltration heat exchange effectiveness, $\dot{m}$ is the air flow rate (Kg/s), C_p is the specific heat of air (J/kg K), ΔT is temperature difference between inside and outside (°C), A_{solar} is the solar aperture (M^2), and I is the measured average solar radiation (W/m^2).

Although UA_{ground} varies slowly with time, it can be treated as a constant during a short period, such as a couple of days. The IHEE can also be regarded as constant if the air flow rate does not vary significantly under natural conditions. Therefore, the three terms within the bracket can be treated as constant, which is called as the overall heat loss factor of the building:

$$UA = UA_0 + UA_{ground} + (1 - IHEE)\dot{m}C_p \qquad \text{(C-2)}$$

To introduce equation (C-2) into equation (C-1), the energy balance equation is then:

$$Q_h = UA\Delta T - A_{solar}I \tag{C-3}$$

Finally, the solar aperture can be identified according to the measured average parameters over the two "zero net effect" periods as:

$$A_{solar} = \frac{Q_1\Delta T_2 - Q_2\Delta T_1}{\Delta T_1 I_2 - \Delta T_2 I_1} \tag{C-4}$$

where the index 1 refers to data from the first "zero net effect" period, and index 2 refers to data from the second "zero net effect" period.

Note that the solar aperture is an indicator of the ability to receive solar energy, and it varies with air infiltration rates and air flow patterns because infiltration carries more solar energy absorbed by surface to room while exfiltration rejects more solar energy to outside. However, the solar aperture identified by this test can be regarded as the standard value because it is identified under the normal operating condition..

The second step is to determine the heat loss factor under different air flow rates and flow patterns. It is suggested to depressurize the building first and perform two or three tests with different air flow rates, and then pressurize the building and perform another two or three tests. Each test takes two days. During the test, the room temperature is maintained as constant as possible using the electrical heaters. A constant air flow rate is given for each test. Meanwhile the building and ambient temperatures, the solar radiation, the air flow rate and the heat input are measured. The measured data are then analyzed by the STAM and one "zero net effect" period should be chosen. The average temperature difference between inside and outside, the solar radiation, the air flow rate and the heat input should be calculated over this period. Finally, the heat loss factor of building can be determined as:

$$UA = \frac{Q + A_{solar} I}{\Delta T} \tag{C-5}$$

Finally to determine the relationship of IHEE and air flow rate. If the test can be performed during a relative short period, then UA_{ground} can be treated as a constant. Consequently, equation (C-2) can be written as:

$$UA = X + (1 - IHEE)\dot{m}C_p \tag{C-6}$$

where UA is the measured heat loss factor of the building (W/K), X is a constant (W/K).

If the relationship between IHEE and air flow rate is assumed as:

$$IHEE = 0.5 + b\dot{m}C_p \tag{C-7}$$

Then equation (C-6) can be written as:

To introduce equation (B-13) to equation (B-7), we get:

$$UA - 0.5\dot{m}C_p = X - b(\dot{m}C_p)^2 \tag{C-8}$$

If two tests are performed, then the constant "b" can be determined by equation (C-9).

$$\begin{bmatrix} 1 & -(\dot{m}_1 C_p)^2 \\ 1 & -(\dot{m}_2 C_p)^2 \end{bmatrix} \begin{bmatrix} X \\ b \end{bmatrix} = \begin{bmatrix} UA_1 - 0.5\dot{m}_1 C_p \\ UA_2 - 0.5\dot{m}_2 C_p \end{bmatrix} \tag{C-9}$$

If the relationship between IHEE and air flow rate is assumed as:

$$IHEE = a + b\dot{m}C_p \tag{C-10}$$

Then equation (C-6) can be written as:

$$UA - \dot{m}C_p = X - a\dot{m}C_p - b(\dot{m}C_p)^2 \tag{C-11}$$

If three tests are performed and labeled as 1, 2, and 3, then the constants can be determined by equation (C-12):

$$\begin{bmatrix} 1 & m_1C_p & (m_1C_p)^2 \\ 1 & m_2C_p & (m_2C_p)^2 \\ 1 & m_2C_p & (m_2C_p)^2 \end{bmatrix} \begin{bmatrix} x \\ a \\ b \end{bmatrix} = \begin{bmatrix} UA_1 - \dot{m}_1C_p \\ UA_2 - \dot{m}_2C_p \\ UA_3 - \dot{m}_2C_p \end{bmatrix} \qquad \text{(C-12)}$$

The advantages of this method are 1) high accuracy; 2) accounts for solar effects; 3) automatically accounts for thermal storage effects; 4) most suitable for comprehensive study.

The disadvantages are 1) intrusion on building operation; 2) more time is required; 3) complicated algorithm is required to treat the measurement results; 4) relatively complicated equipment is required.