ESTIMATION OF AIR INFILTRATION OF BUILDINGS BASED ON THE DEGREE OF AIR TIGHTNESS AND CLIMATIC DATA

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ABSTRACT
This study presents a simple method, developed for estimating annual air infiltration rates in single-family detached houses. The input data to this technique are: measured building air tightness, wind speeds, and the indoor-outdoors temperatures. Six test buildings of the same size, constructed of different building materials were involved in the study. The air tightness of these buildings was determined by using pressurisation method at 50 Pa pressure difference. Infiltration air change rates were measured by using tracer gas – concentration decay method and also calculated by using the developed technique. In addition, four other infiltration models were used to predict the air infiltration namely: LBL, Kronvall, ASHRAE, and CEN models. Measured and calculated/predicted infiltration results were compared. A very close correlation between the measured and the calculated results, obtained by using the developed technique and the other infiltration models was observed.

INDEX TERMS
Air infiltration, air leakage, air tightness, building envelope, and measurements

INTRODUCTION
The determination of the quantity of air infiltration in buildings is an important task complicated by the changing nature of wind speeds and direction, coupled with the buoyancy effect. As a result, approximation methods are still relied upon for calculating infiltration since exact methods are yet beyond practical capabilities.

Infiltration air change rate within a building (if considered as single zone) can be calculated provided that the following quantities are known or can be determined: wind speed and direction; indoor-outdoor temperatures; the size, position, and flow characteristics of all openings within the envelope. In practice however, it is almost impossible to have information on all these quantities and hence theoretical models developed for infiltration calculations normally make some simple assumptions of what happens in reality. These simplifying assumptions retain the main physical concepts but enable an acceptable mathematical interpretation of the airflow process to be formulated. Etheridge and Sandberg (1996) proposed that the chosen equation for prediction of airflows in buildings satisfy two requirements. First, it should closely describe the flow characteristics of the range of pressure differences normally encountered with ventilation (low pressures). Second, it should satisfy the range of pressure differences used for experimental measurements of leakage (high pressures). Several infiltration models exist; see for example, (Sherman and Grimsrud 1980, CEN 1997, Kronvall 1978, and ASHRAE 1989). These model are either based on the power law (Eqn. 1) or the quadratic law (Eqn. 2). The power law equation assumes that air flow

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through adventitious openings is a developing flow, which is a combination of laminar and turbulent flows due to the complex nature of the driving forces.

\[ Q = a (\Delta p)^\beta, \quad m^3 s^{-1} \]  

(1)

where, \( Q \) is the air flow rate (m\(^3\)/s), \( a \) is the power law flow coefficient (m\(^3\)/s at 1 Pa), \( \Delta p \) is the pressure difference (Pa), and \( \beta \) is the flow exponent (ranges in value from 0.5 for fully turbulent flow to 1 for laminar flow. Default value = 0.67 or 0.7). The quadratic equation (Etheridge 1977, 1987) is based on the relation between the air flow, \( Q \), and the pressure difference, \( \Delta p \). For real air flows, the quadratic equation can be written as

\[ Q = \frac{-b \pm \sqrt{b^2 - 4a(-\Delta p)}}{2a}, \quad m^3 s^{-1} \]  

(2)

where, \( a \) and \( b \) are constants that can be estimated from the power law curve fitting using expressions derived in Etheridge (1998). The power law has been widely used for measurement standards for building envelopes (ASTM 1982, ISO 1995) including ventilation standards ((ASHRAE 119 (1988), ASHRAE 136 (1993)). Walker, Wilson, and Sherman (1996) including Liddament (1987) report that the power law performs better than the quadratic equation. However, Etheridge and Sandberg (1996) give a detailed examination of the relative merits of the two equations where it is concluded that the quadratic equation should be used in preference to the power law.

Simple methods for predicting the quantity of uncontrolled air change in buildings are of crucial importance since infiltration/exfiltration affects both the energy performance and the indoor air quality of buildings. Most of infiltration models found in the literature require much input data that is not always available while others can give only annual infiltration average values. The method developed in this study requires minimum input data (i.e. air tightness, wind speeds, indoor-outdoor temperatures), simple to use, and it can be used to predict infiltration due to specific weather conditions including annual averages. The model is based on the power law equation as it is intended to make use of known or predefined building air tightness data (i.e. the hourly air changes at 50 Pa pressure difference) including measured wind speeds and indoor and outdoors temperature.

**METHODS**

**Formulation of the model**

Wind creates a pressure difference (\( \Delta p_w \)) across the building envelope that is given by the expression

\[ \Delta p_w = \frac{1}{2} \rho v^2 C_{pw} \]  

(3)

where, \( \rho \) is the air density (kg/m\(^3\)), \( v \) is the wind speed (m/s), and \( C_{pw} \) is the wind pressure coefficient. If the number of air changes per hour at 50 Pa pressure difference, \( (n_{50}) \), is known, infiltration per square meter of a wall in one hour, \( R_{50} \) (m\(^3\)/m\(^2\).h), can be predicted as

\[ R_{50} = n_{50} \cdot \frac{V}{A_{tot}} \]  

(4)
For a given pressure difference, \( \Delta p \), infiltration air change rate per square meter of the building envelope per hour, \( R \) (m\(^3\)/m\(^2\).h), can be determined by using the expression

\[
R = R_{50} \left( \frac{\Delta p}{50} \right)^{0.7} = \frac{V}{A_{tot}} n_{50} \left( \frac{\Delta p}{50} \right)^{0.7}
\] (5)

where \( V \) is the volume of the building (m\(^3\)) and \( A_{tot} \) is the total area of the leaking surfaces (m\(^2\)). Assuming that the pressure difference created by wind across a building envelope is equal to \( \Delta p_w \), infiltration air change due to wind \( (R_w) \) would be given by the expression:

\[
R_w = n_{50} \cdot \frac{V}{A_{tot}} \left( \frac{\Delta p_w}{50} \right)^{0.7}, \text{ m}^3\cdot\text{m}^{-2}\cdot\text{h}^{-1}
\] (6)

Assuming that infiltration due to wind occurs only through the leakage areas within the windward walls \( (A_{inf}) \) and exfiltration through the rest of leakage areas within the walls \( (A_{exfil}) \), the number of infiltration air changes per hour in a building due to wind will be given by the expression:

\[
n_w = \frac{R_w \cdot A_{inf}}{V} = n_{50} \cdot \frac{V}{A_{tot}} \frac{A_{inf}}{V} \left( \frac{\Delta p_w}{50} \right)^{0.7}
\]

Substituting (3) into (7) we obtain,

\[
n_w = n_{50} \cdot \frac{A_{inf}}{A_{tot}} \left( \frac{1}{2} C_{pw} \cdot n_{50} \cdot V \Delta h \right)^{0.7}, \text{ h}^{-1}
\]

Substituting 0.5 and 1.2 as values for \( C_{pw} \) and \( n \) respectively into (8) also assuming that infiltration takes place through one-third of the leaking surface area whereas exfiltration takes place through the remaining surface area (i.e. \( A_{inf} = 0.3 A_{tot} \)), equation (8) becomes

\[
n_w = 0.0084 n_{50} \cdot V^{1.4} \cdot n^{-1}, \text{ h}^{-1}
\] (9)

Equation (9) gives the number of infiltration air change rate \( (n_w) \) of buildings when wind speed \( (v) \) and building’s air tightness \( (n_{50}) \) are known. The pressure difference caused by the indoor-outdoors temperature difference \( (\Delta p_{stack}) \) is given by the expression

\[
\Delta p_{stack} = -273 \rho_o g \Delta h \left[ \frac{1}{T_{ext}} - \frac{1}{T_{int}} \right], \text{ Pa}
\] (10)

where \( \rho_o \) is the density of air at 0 °C (1.29 kg/m\(^3\)), \( g \) is gravitational force, \( \Delta h \) is a vertical distance between two leakage openings (assumed to be equal to two-third of the room height), \( T_{int} \) and \( T_{ext} \) are indoor and outdoors temperatures respectively. Substituting the values for \( \rho_o \) and \( g \) into (10), also based on (5) and (8), the number air changes per hour resulting from pressure differences due to stack effect would be given by the expression
Wind and stack effect act together to cause total air infiltration in a building. However, according to Liddament (1986) the respective air infiltration values resulting from wind and stack effect should be added in a quadrature to obtain the total infiltration. Hence adding (9) and (11) in a quadrature gives the total air infiltration, \( Q_{\text{inf(tot)}} \), through a building envelope as

\[
Q_{\text{inf(tot)}} = n_{50} \left[ 7.1 \times 10^{-5} \nu^{2.8} + 19.36 \Delta h^{1.4} \left( \frac{1}{T_{\text{ext}}} - \frac{1}{T_{\text{int}}} \right)^{1.4} \right]^{0.5}, \text{ h}^{-1}
\]

Equation (12) represents the formulated model for estimating buildings’ air infiltration.

**Test buildings**

The method was applied to determine air infiltration of six test buildings that were constructed in a moderately exposed parking area within the compound of Tampere University of Technology. The floor area of each test building was 2.4 x 2.4 m\(^2\) and the free floor to ceiling height was 2.6 m. Both the ceiling and the floor consisted of two layers of foamed polyurethane elements with overall thickness of 200 mm. All the buildings had two well-insulated outer doors fixed one after another and had no windows. During the tests the indoor air temperature was maintained constant at 20°C ± 1°C. Balanced mechanical ventilation systems with air-to-air heat recovery were used to ventilate the test buildings number 1, 3, and 5. The mechanical ventilation air change rates in the test buildings were set at 0.5 h\(^{-1}\).

**Air tightness measurements**

The air tightness of the test buildings was measured by using fan pressurisation method at a 50 Pa pressure difference. The Swedish Code of Practice (1988) gives recommendations regarding the level of air tightness. For detached single-unit dwellings and linked houses, air tightness equivalent to an hourly air leakage of three times the building’s volume (3 ach), at a pressure difference of 50 Pa is considered reasonable (Gusten 1989).

**Air infiltration measurements**

The infiltration air change rates of the test buildings were measured by using tracer gas technique (concentration decay method). Approximately 0.9 litre (approx. 60 ppm) of Sulphur hexafluoride (SF\(_6\)) gas was released into each test building at the beginning of the measurements. A mixing fan was used to continuously mix the air inside each building to create a uniform gas mixture throughout the tracer gas measurements. The decay in tracer gas concentration was automatically monitored over a period of 2 to 3 days by the help of an infrared gas analyser, MIRAN 1A, which was connected to a data logger. The measurements were taken both in winter and in summer weather conditions in order to study the effect of buoyancy. The average air infiltration flow rates, \( \overline{Q} \) (m\(^3\)h\(^{-1}\)), were calculated by using equation (13) (Etheridge and Sandberg 1996).

\[
\overline{Q} = V \frac{\ln \frac{C(t_1)}{C(t_2)}}{t_2 - t_1}, \text{ m}^3\text{h}^{-1}
\]
where, $V$ is the volume of the ventilated space in m$^3$, $C(t_1)$ and $C(t_2)$ are the percentage concentrations of the gas at time $t_1$ and $t_2$ in hours respectively, during the measurements.

**RESULTS**
The obtained air tightness measurement results were 0.93, 1.15, 11.1, 2.31, 1.2, and 3.28 h$^{-1}$ respectively for test buildings number 1, 2, 3, 4, 5, and 6. The measured and predicted infiltration air change rate results for winter and summer seasons are summarised in Table 2.

**Table 1.** Measured and predicted infiltration air change rates of the six test buildings for winter and summer seasons

<table>
<thead>
<tr>
<th>Test Building No.</th>
<th>Measured air infiltration rates (h$^{-1}$)</th>
<th>Predicted air infiltration rates (h$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Winter season</td>
<td>Summer season</td>
</tr>
<tr>
<td>1</td>
<td>0.016</td>
<td>0.01</td>
</tr>
<tr>
<td>2</td>
<td>0.031</td>
<td>0.028</td>
</tr>
<tr>
<td>3</td>
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<td>4</td>
<td>0.041</td>
<td>0.038</td>
</tr>
<tr>
<td>5</td>
<td>0.073</td>
<td>0.04</td>
</tr>
<tr>
<td>6</td>
<td>0.045</td>
<td>0.034</td>
</tr>
</tbody>
</table>

**DISCUSSIONS**
A very close similarity is observed between the measured and the predicted results. This could be a specific case for the tested buildings as they were very small and had no windows. With larger buildings, the case could be slightly different. On average, the difference between the measured infiltration rates for winter and summer conditions is 30% whereas for the predicted values, the difference is 41%. This shows the significance of the stack effect on buildings’ air infiltration. Comparisons between the calculation results of the formulated model and the other three infiltration models showed a good correlation except for the CEN model where only two objects lied within the ±20% region of the best-fit line.

**CONCLUSIONS**
A mathematical model for predicting air infiltration in buildings due natural conditions based on the degree of air tightness of the building envelope was developed. Comparisons of the results predicted by the formulated model and measurements showed a very close agreement. A close similarity was also evidenced in the comparisons among the infiltration results calculated by using the LBL, ASHRAE, and Kronvall models and those calculated by using the formulated model. It can be concluded that, the formulated infiltration model performs well and can be used for estimation of air infiltration of buildings. However, more field data is needed to ascertain the accuracy of the formulated model.

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**REFERENCES**


