Infiltration simulation in a detached house – empirical model validation

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SUMMARY

This study discusses the empirical validation of a multi-zone infiltration model of an existing two-storey detached house in the cold Finnish climate. Empirical validation was performed by comparing simulated and measured pressure conditions of the building during a three-week test period in the heating season. The simulations were carried out using a dynamic simulation tool, IDA-ICE, which combines whole-building energy simulation and infiltration modelling. The initial data of the building model were obtained with extensive field measurements including the measurements of airtightness and leakage distribution of the envelope and performance of a ventilation system. According to the results, pressure conditions are slightly negative on the first floor and positive on the second due to the stack effect in the heating season. The empirical validation shows that the correspondence between the simulated and measured pressure conditions is good and the studied building model can be used for the infiltration and energy analyses.

INTRODUCTION

This study is part of the cooperation project between two Finnish universities; Tampere University of Technology and Helsinki University of Technology. In this project, called Tightness, indoor air and energy efficiency of residential buildings (AISE), extensive field measurements are being carried out in 159 dwellings with massive and lightweight structures consisting of flats and detached houses during the period 2005 – 2007. This study is concentrated on the infiltration modelling of one measured detached house. Infiltration, defined as uncontrolled air flows through a building envelope, depends on the air permeability of the structures and the pressure difference between indoor and outdoor air. The pressure difference is caused by wind, temperature difference over an envelope, and balance of the ventilation system. Wind conditions are strongly dependent on the building site and temperature-driven pressure difference is significant in a cold climate during the heating season. The objective of the study is to perform an empirical validation of the detailed multi-zone simulation model, including leakage distribution and other important parameters, with the intention of using the validated model for infiltration and energy analyses.

METHODS

Building description

The object of the study is a detached house comprising two floors (Figure 1). The house is situated in the metropolitan area of Helsinki and was built in 2000. The net floor area of the
building is 172 m². The structures of the house are wood-frame construction provided with a plastic vapour barrier and the base floor of the house is a concrete slab on the ground. The level of thermal insulation of the house fulfils the requirements of the Finnish building code [1] and the house is equipped with a mechanical supply and exhaust ventilation system with heat recovery.

Figure 1 The object of the study is a typical Finnish detached house.

The method of construction, the ventilation system and the tightness of the modelling object corresponds to the typical detached house defined by the national project “Moisture-proof healthy detached house” [2], where 102 newly built timber-framed detached houses were measured in Finland during 2002-2004. Airtightness of the building envelope equals the mean level of the measured 102 detached houses.

Measurements

Initial data of the simulation model were collected by means of field measurements of the building. The following factors were measured:

- Ventilation
- Tightness of the envelope
- Leakage distribution
- Pressure and thermal conditions.

The measurements of the ventilation air flow rates, tightness and leakage distribution of the building were carried out using a single-shot measurement. Supply and return air flow rates were measured at the low (3/8) speed of the air-handling unit, which is the normal use of ventilation in the studied building during wintertime. The measured air change rate of the building was 0.3 ach and the ratio of the supply and return air flow rates was 0.93, affecting a slight negative pressure in the building. The measured air change rate is lower than the minimum requirement of the Finnish building code (0.5 ach) [3] and also slightly lower than the typical mean air change rate of the detached houses (0.41 ach) in wintertime when equipped with mechanical supply and exhaust ventilation system [4].

The tightness of the building was measured using a fan pressurization method. To measure the air leakage of the envelope, all the exterior openings – windows and doors – were closed and ventilation ducts and chimney were sealed; a leakage air change rate per hour at 50 Pa of pressure difference was measured. The leakage air flow rate was divided by the internal volume of the building to get the building leakage rate n₅₀; the resultant was 3.9 ach. The distribution of the leakage openings was studied using two-phase infrared-camera imaging of the envelope of the building [5]. The imaging was performed inside the building in a normal
and 50 Pa under pressure conditions. The study was carried out during the heating season when the indoor and outdoor temperature difference was 25°C. According to an estimated vertical leakage distribution shown in Table 1, most of the leakage routes are at a junction of the roof and an intermediate floor; the routes are quite evenly distributed between the first and second floor.

Table 1 Vertical leakage distribution of the building based on the infrared camera imaging

<table>
<thead>
<tr>
<th>Place of the leakage routes</th>
<th>Leakage distribution, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>2nd floor</td>
<td></td>
</tr>
<tr>
<td>Junction of roof</td>
<td>36</td>
</tr>
<tr>
<td>Upper edge of window frame</td>
<td>4</td>
</tr>
<tr>
<td>Lower edge of window frame</td>
<td>4</td>
</tr>
<tr>
<td>Junction of intermediate floor</td>
<td>2</td>
</tr>
<tr>
<td>1st floor</td>
<td></td>
</tr>
<tr>
<td>Junction of intermediate floor</td>
<td>21</td>
</tr>
<tr>
<td>Upper edge of window</td>
<td>0</td>
</tr>
<tr>
<td>Lower edge of window frame</td>
<td>24</td>
</tr>
<tr>
<td>Junction of base floor</td>
<td>10</td>
</tr>
</tbody>
</table>

Pressure and thermal conditions of the building were measured during a three-week period in the heating season. Occupants were living normally in the building during the follow-up measurements, which were carried out between 4th and 24th of March 2005. Pressure and temperature data were collected with loggers using a 5-minute time-step. The pressure difference over the envelope was measured on the first and second floor of the building. The measuring points were at one façade of the detached house; the principle of the measurement is shown in Figure 2.

![Figure 2 Measurement of the pressure conditions of the building.](image)

Indoor air temperatures of the building were measured in a living room on the first floor and in a bedroom on the second floor. The outdoor air temperature was also measured next to the detached house during the follow-up measurements. The measured outdoor air temperature is shown in Figure 3; it is -7.1°C on average. The three-week period was very cold for Southern Finland, emphasizing the temperature-driven pressure difference over the building envelope.
The dynamic simulation model

The building model was done using IDA indoor Climate and Energy 3.0 (IDA-ICE) building simulation software. This software allows the modelling of a multi-zone building, HVAC-systems, internal and solar loads, outdoor climate, etc. and provides simultaneous dynamic simulation of heat transfer and air flows. It is a suitable tool for the simulation of thermal comfort, indoor air quality, infiltration and energy consumption in complex buildings. A modular simulation application, IDA simulation environment and IDA-ICE, has originally been developed by the Division of Building Services Engineering, KTH, and the Swedish Institute of Applied Mathematics, ITM [6,7]. Today the application is commercial tool owned by EQUA AB. IDA ICE has reached high levels of penetration among practitioners and researchers in Sweden and Finland.

The building model of the measured detached house comprises three different zones on the first and second floor (see Figure 4); the floors are connected by means of a staircase. Air flow between the zones, two floors and outdoors caused by the pressure differences is simulated by means of the principle of nodal network (see Figure 5.), where flow paths, cracks or openings between the zones or outdoors are described as flow resistances.

Figure 3 Measured outdoor temperature next to the detached house during follow-up measurements.

Figure 4 Profile of the 3-D plot showing the first floor (a) and the second (b) of the IDA-ICE building model. The figures are generated with the IDA-ICE 4.0 alpha version.
The building model was simulated using the hourly weather data of the three-week measurement period. The measured outdoor temperature data was used and the other required data, for example, wind velocity and direction and solar radiation properties, were taken from the weather station of Helsinki-Vantaa airport. Wind conditions of the environment were simulated using the wind-profile equation [8]

\[
U(h) = U_m \cdot k \cdot \left( \frac{h}{h_m} \right)^a, \quad (1)
\]

where \(U(h)\) is wind speed at height \(h\) and \(U_m\) is wind speed measured in open country at the weather station, \(h\) is height from the surface of the ground, \(h_m\) is height of the measurement equipment and parameters \(k\) and \(a\) are terrain-dependent constants. The simulated building is in a typical Finnish suburban area with closely built houses where the height of adjacent buildings is approximately the same as the simulated one. The wind-profile equation was simulated with the values of the parameters \((k = 0.67\) and \(a = 0.25)\). Wind-induced pressure conditions were simulated using constant wind-pressure coefficients defined at 45° intervals of a wind direction. The values of the wind-pressure coefficients used in the simulation were approximate values for typical detached houses with a height of up to three storeys [9]. Wind pressure outside the building façades was determined with the equation

\[
P_w = \frac{1}{2} \rho \cdot c_w \cdot U^2, \quad (2)
\]

where \(\rho\) is outdoor air density and \(c_w\) is the wind pressure coefficient and \(U\) is the local wind velocity defined by Equation (1). The air infiltration is calculated for every façade; the connection between the indoor and the outdoor climate, as well as the connection between the zones, is simulated using bi-directional leakage openings, which are so-called flow resistances of the kind shown in Figure 5. The leakage openings were distributed over the building model according to the measured leakage distribution shown in Table 1. Air flow through the leakage opening is simulated in the building model with the widely used empirical power law equation [10]

\[
Q = C \cdot \Delta P^n, \quad (3)
\]
where C is a flow coefficient that is related to the size of the opening and ΔP is the pressure difference across the opening, n is a flow exponent characterizing the flow regime. The flow exponent varies in value from 0.5 for fully turbulent flow to 1.0 for completely laminar flow. The total value of the flow coefficient and the mean value of the exponent for the whole building envelope were determined by the pressurization test.

RESULTS

The results of the three-week empirical validation period are discussed below. The simulated pressure conditions of the first and second floor of the detached house are compared against the measurement results. The simulated pressure differences over the envelope were logged from the building model at the same façade and the same height from the ground as in the measurements; the thermal conditions inside the building model correspond to the measured conditions.

According to the measurements and the simulation, the pressure difference is slightly negative on average on the first floor and positive on the second floor, see Figure 6 (a and b). The model gives some intermittent peaks of the negative pressure that clearly deviate from the measured pressure, but the correspondence is good on average. The pressure difference as a function of temperature difference between indoor and outdoor air is shown in Figure 6 (c and d). Almost completely parallel linear fits of the measured and simulated points show that the pressure difference decreases with an increasing temperature difference on the first floor and that the pressure difference is almost constant on the second floor. The different correlation between the pressure and the temperature differences on the first and second floor is a result of many factors, such as the stack effect, the ratio of the ventilation air flows, and the performance of air handling unit at the low outdoor air temperatures.
Figure 6 Measured and simulated pressure conditions of the detached house during the three-week measurement period from 4\textsuperscript{th} to 24\textsuperscript{th} of March 2005. The pressure difference over the envelope on the first and second floor are shown as a function of time (a and b) and as a function of temperature difference between indoors and outdoors (c and d).

The measured and simulated average indoor air temperatures and pressure differences of the validation period are almost equal (see Table 2). The set point of heating in the building model is chosen so that the average indoor air temperatures are as close to the measurement result as possible. Indoor air temperatures of the building are rather low, especially on the second floor, due to the occupant’s way of life.

Table 2 Measured and simulated average indoor air temperatures and pressure differences across the envelope during the validation period.

<table>
<thead>
<tr>
<th>Method</th>
<th>Indoor air temperature, °C</th>
<th>Pressure difference, Pa</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1\textsuperscript{st} floor</td>
<td>2\textsuperscript{nd} floor</td>
</tr>
<tr>
<td>Measurement</td>
<td>19.7</td>
<td>17.0</td>
</tr>
<tr>
<td>Simulation</td>
<td>19.8</td>
<td>17.0</td>
</tr>
</tbody>
</table>

DISCUSSION

The empirical validation of the studied building model shows that the simulated pressure conditions are in good agreement with the measurements. Because of this agreement, the multi-zone model can be used for the infiltration and energy analyses in the cold Finnish climate. Simulated pressure conditions of the building model seem to be realistic, even if the calculation of the wind-induced pressure conditions was simplified. The wind data used in the simulation was taken from the airport’s weather station; the wind-pressure coefficients were approximate values for typical low-rise buildings in the sheltered environment and the values were not based on the measurements or CFD-calculations of the studied building. The empirical validation of the model was carried out for the cold period of the winter season when the buoyancy-driven pressure difference was emphasized and the studied building was situated in the sheltered suburban area where wind conditions were not strong. It is obvious that an accurate modelling of the leakage distribution is important, especially when buoyancy-driven pressure is significant.

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REFERENCES


