On the experimental validation of the infiltration model DOMVENT3D

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ABSTRACT

Buildings represent approximately 40% of global energy demand and heat loss induced by uncontrolled air leakage through the building fabric can represent up to one third of the heating load in a building. This leakage of air at ambient pressure levels, is known as air infiltration and can be measured by tracer gas means, however, the method is disruptive and invasive. Air infiltration models are a non-disruptive way to calculate predictive values for air infiltration in buildings. DOMVENT3D, is an infiltration model that predicts the infiltration rate from air permeability measurements quoted at 50 Pa. The model has been used to calculate the English housing stock infiltration rates, however, it has not been experimentally verified. The objective of this study is to compare DOMVENT3D's predictions with real measurements. Air permeability measurements using a blower door (50 Pa) and the Pulse method (4 Pa) were carried out in three domestic dwellings in Nottingham, U.K. DOMVENT3D was calibrated to predict infiltration from air permeability measurements taken at 4 Pa. This paper presents a comparison of results for both the blower door and pulse methods predicted values and real infiltration measurements. Initial results show discrepancies (from 34 to 107%) in the predictions between blower door and pulse methods and also with the real infiltration measurements. Nevertheless DOMVENT3D presented results close to the measurements. Further validation is needed before a final conclusion about the model is given.

KEYWORDS

Air infiltration, airtightness, infiltration modelling, permeability, heat loss

1 INTRODUCTION

Buildings represent approximately 40% of the global energy demand. The heat losses induced by the uncontrolled air leakage through the building fabric can represent up to one third of the building heating load (Etheridge , 2015). This uncontrolled leakage at ambient pressure levels is commonly known as air infiltration (h^{-1}).

Air infiltration is a parameter which is difficult to measure. The common method to measure air infiltration is by tracer gas means, however these are disruptive, invasive, costly and time consuming. The most used tracer gas methods are the constant concentration, constant emissions and concentration decay, out of which the last is the most used one. Hence, a practical way of obtaining the infiltration rate is by predicting it based on a measurement of building airtightness. Airtightness is the parameter that affects the most on air infiltration; and is defined as a flow of air passing through adventitious openings in the building envelope at a given pressure difference. Airtightness can be given as a rate of flow Q (m^3/s, kg/s), an air change rate n (h^{-1}), or an air permeability q ($m^3h^{-1}m^{-2}$), when normalised by building volume and envelope area.

The way to predict air infiltration is to use air infiltration predicting models. Models have changed over the years. The simplest models are the airtightness-infiltration ratios which have been questioned by their crude simplicity (Jones, et al., 2016). Simplified models have been used since the 1980's, the most widely used simplified models are the LBL (Sherman & Grimsrud, 1980) and the AIM-2 (Walker & Wilson, 1990) models, both created in North America. Through the years more complex models with improved accuracies were developed such as CONTAM (Dols, et al., 2000). In the UK, the infiltration predicting model DOMVENT3D (Jones, et al., 2013) has been used to predict the infiltration of the English housing stock, however it has not gone through experimental validation.

The objective of this paper is to field validate the predictions made by DOMVENT3D from measurements of airtightness quoted at 50 Pa. In addition, DOMVENT3D will be calibrated to give predictions from airtightness measurements quoted at 4 Pa. Both results (at 50 and 4 Pa of pressure difference) are compared herein to assess the feasibility of including different airtightness measuring methods in air infiltration prediction.

2 DOMVENT3D

DOMVENT3D is an infiltration model which is based on research undertaken by Lyberg (Lyberg, 1997) and Lowe (Lowe, 2000), which proved that superposition techniques used in simplified models are not physically correct.

DOMVENT3D is a modification from Lowe's (Lowe, 2000) model (DOMVENT2D). In this new model, flows from every façade are accounted for. It used the power law (equation 1) as governing equation to predict infiltration rate.

$$Q = C\Delta P^b \tag{1}$$

Where
Q is the air flow (m^3/s),
C is the flow coefficient ($m^3/h/Pa^n$),
ΔP is the differential pressure experienced (Pa), and,
b is the flow exponent (dimensionless) which varies from 0.5 to 1 (turbulent to laminar), typically taken as 0.66.

Lowe identified four zones in a building, windward and leeward exfiltration (a and b), and windward and leeward exfiltration (c and d), shown in Figure 1. Δh_0 is the differential of the mean heights of the neutral planes of each façade.

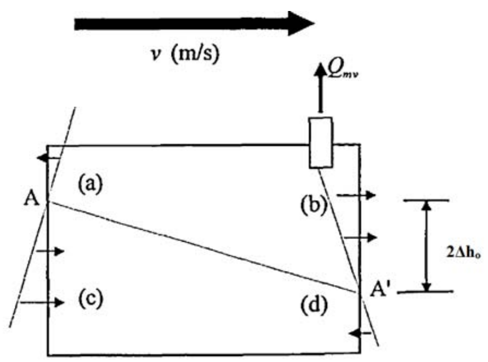

Figure 1. From (Lowe, 2000) Vertical cross section through dwelling, showing direction and magnitude of infiltration and exfiltration across envelope. AA' is the neutral plane.

Lowe formulated a single integral for each zone from Figure 1, and once solved, the resulting equations are as shown in equation 2.

$$Q_{inf} = \frac{LEC(\rho g\,\Delta T/T)^b}{n+1}\begin{bmatrix} +(h_0+\Delta h_0)^{b+1} \\ -(h_0+\Delta h_0-H)^{b+1}|_{h_0+\Delta h_0>H} \\ +(h_0-\Delta h_0)^{b+1}|_{\Delta h_0<h_0} \\ -(h_0-\Delta h_0-H)^{b+1}|_{h_0-\Delta h_0>H}\end{bmatrix} \quad (2)$$

L and *H* (*m*) are the length and height of the building respectively; *E* is the relative leakage area (dimensionless); *g* is the gravitational acceleration (m/s^2); ΔT is the temperature difference (K) and; h_0 (*m*) is the mean height of the neutral plane (no flow).

Jones (Jones, et al., 2013) modified the model when testing the effect of infiltration if party walls are considered fully permeable or impermeable. This model, named DOMVENT3D considers flow from every façade; the power law (equation 1) is applied to an infinitesimal section of a vertical façade. The flow rates ($\dot{Q}_f$) from DOMVENT3D can be simplified in equation 3.

$$\dot{Q}_f = E\alpha W\varepsilon(\rho_0-\rho_i)\{|(\rho_0-\rho_i)|g\}^b\begin{bmatrix} +\int_0^{minh_{0.H}}(h-h_0)^b dh \\ -\int_{maxh_{0.H}}^{H}(h-h_0)^b dh\end{bmatrix} \quad (3)$$

Where
α is taken as $(2/\bar{\rho})^b$, and $\bar{\rho}$ is the mean air density (indoor-outdoor) in kg/m^3,
ρ_o and ρ_i are the outdoor and indoor air densities respectively in kg/m^3,
W is the width of the façade (*m*) and,
h is the height of the selected opening (*m*).

The solution of the integrals in equation 3 leads to equations 4 and 5.

$$Q_1 = \frac{E\alpha W\varepsilon(\rho_0-\rho_i)}{b+1}\{|(\rho_0-\rho_i)|g\}^b\begin{bmatrix} +h_0^{b+1}|_{h_0>0} \\ -(h_0-H)^{b+1}|_{h_0>H}\end{bmatrix} \quad (4)$$

$$Q_2 = \frac{E\alpha W\varepsilon(\rho_0-\rho_i)}{b+1}\{|(\rho_0-\rho_i)|g\}^b\begin{bmatrix} +(H-h_0)^{b+1}|_{h_0<H} \\ -(-h_0)^{b+1}|_{h_0<0}\end{bmatrix} \quad (5)$$

DOMVENT3D predicts air infiltration in each façade using only two equations from 1, 4 and 5 depending on the air densities. The major shortcoming of the model is that is only valid for low rise buildings because it does not account for temperature stratification. The model, has been used to predict the infiltration rate of the English housing stock (Jones, et al., 2015). Nonetheless, it had not been field validated until this study.

3 AIRTIGHTNESS AND AIR INFILTRATION MEASURING

Air infiltration is the parameter needed to calculate the infiltration heat losses of a building. To obtain the infiltration rate of a building, first its airtightness has to be measured.

The steady pressurisation method, commonly known as "blower door" (Energy Conservatory, n.d.), is the most common way of measuring the airtightness of a building. The blower door test is implemented by creating a pressure difference across the building by pressurising or depressurising the building by a fan mounted in an existing doorway. This pressure difference, commonly between 10-60 Pa, is correlated to the airflow exchange rate. Results are quoted at 50 Pa; high pressures are used to minimize the noise of natural phenomena occurring at low pressure difference, namely wind and buoyancy effect. The method is well known, developed and standardised internationally (The British Standards Institution, 2015; American Society for Testing and Materials;, 2019). A picture of a typical blower door is give in Figure 2.

Despite the long development process that the blower door has gone through, some authors argue that measuring at high pressure differences create high uncertainty when extrapolating to the lower pressures (Cooper & Etheridge, 2007), and that measuring airtightness at low pressure should be more accurate. For this reason the Pulse method was developed; Pulse measures building airtightness at low pressure difference.

Pulse generates an instantaneous pressure rise in a building, whilst at the same time the variations in tank and building pressures are monitored and used to determine the airtightness. This pressure rise in the building is created by releasing air from a compressed air tank. The pressure rise in the building typically lies between 1 - 10 Pa. The method quotes the airtightness at 4 Pa (Cooper, et al., 2014). The latest PULSE-60 equipment is shown in Figure 3.

Despite the shorter time that has been developed, the Pulse has shown good repeatability and reproducibility; and, is considered as a future alternative of measuring airtightness (Cooper, et al., 2016; Zheng, et al., 2018; Zheng, et al., 2019).

Figure 2. Standard Minneapolis blower door unit (photo source: Wikimedia)

Figure 3. Latest version of the Pulse unit

On the other hand, to measure the air infiltration rate of a building directly, is through tracer gas methods. Different methods have been standardised, however, the concentration decay method is the one most frequently used due to its simplicity in operation and required equipment. The tracer gas concentration decay method is carried out by increasing the gas concentration, commonly carbon dioxide (CO_2), and monitoring its decay for a certain period.

Standards describe the minimum test period and the optimum conditions for a decay test (American Society for Testing and Materials, 2011; British Standards Distribution;, 2017).

In order to obtain the air infiltration rate (h^{-1}) from the tracer gas decay method, a plot of time vs natural logarithm of the average concentration graph is produced. The slope in the equation of the best fitting line from that regression is the average air infiltration rate; valid for that period and the encountered environmental conditions.

4 METHOD

Three houses in Nottingham, United Kingdom were tested with the objective of validating the infiltration model DOMVENT3D. Table 1 describes the characteristics of the houses tested.

Table 1. Description of dwellings

Dwelling	Date of test	Dwelling type	Main construction type	Volume (m^3)	Envelope area (m^2)
1	03/08/2018	Detached	Timber frame	188	227
2	16/08/2018	Detached	Solid	478	435
3	07/06/2018	Semi-detached	Solid	264	252

The first step was to measure the airtightness conditions of the houses, therefore blower door tests were carried out. A pressurisation and a depressurisation test were performed and the average result of both tests was reported. As an alternative three different Pulse tests were undertaken, with the average also reported.

All airtightness tests were carried out according to standard *BS EN ISO 9972:2015*(The British Standards Institution, 2015). This means that internal doors were left open, outdoor openings were closed, flues, vents, and trickle vents were sealed. These considerations applied for both, the blower door and the Pulse tests.

After the airtightness testing, the infiltration rate was measured using the tracer gas concentration decay method. Any sealing applied to the house was maintained. Before the test, the houses were divided in different zones according to volume and distribution of the house. One CO_2 sensor was placed in each zone; the sensors were connected to a data logger sampling every second. To ensure the right mixture of the gas fans were placed in every internal zone. Tracer gas was spread until the concentration was close to 5000 ppm. The concentration was left to decay for as long as possible, trying to comply with the minimum time specified in the standard ASTM designation E741-11. (American Society for Testing and Materials, 2011).

During the airtightness and tracer gas tests, the environmental conditions were measured. An ultrasonic anemometer was placed outside the tested dwelling. Meanwhile, a temperature sensor was placed in each internal zone (next to the CO_2 sensor) and next to the anemometer which was installed in an open outdoor area. Both the anemometer and the temperature sensors were connected to a data logger sampling every second throughout the test. A summary of the equipment used is listed in Table 2.

Table 2. Equipment

Airtightness measuring	Minneapolis blower door model 4. (BD-4) Pulse-60
Tracer gas	Carbon dioxide Sontay GS-CO2-1001 CO_2 sensors ±5%
Environmental	WindSonic Ultrasonic anemometer Temperature sensors PT100 RTD
Data logging	Datataker DT85 data logger
Other	Fans

DOMVENT3D model was re-coded using MATLAB; the input parameters included the dimensions of the dwellings, blower door test result, wind and temperature measurements. The output was the predicted air infiltration rate (h^{-1}). DOMVENT3D was designed to work with a pressure difference of 50 Pa, due to the assumption of using the blower door for airtightness tests. In order to use the Pulse method measurements as an input value, DOMVENT3D was recalibrated. Therefore a second set of predictions was made using the Pulse measurements.

The predictions given by DOMVENT3D using the blower door results were compared against the measured infiltration rates from the tracer gas test. In addition, the predictions using the Pulse measurements were compared with the measured infiltration rate and the DOMVENT3D predictions based on blower door measurements. Discussions were made according to the performance of the model and how the input values changed the predictions.

5 RESULTS AND DISCUSSION

Dwelling parameters (dwelling type, volume, envelope area), shielding conditions and terrain conditions have to be defined before entering to an infiltration model. Table 3 describes these parameters from the tested dwellings. The shielding conditions vary depending on the surroundings of the property and the natural and artificial barriers can obstruct the flow of wind or, change the microclimate. Terrain conditions are bound to the infrastructure in the area where the dwelling is located. In addition, the measured environmental factors are presented in Table 3. Wind speed, wind direction and temperature difference were measured while the airtightness and tracer gas tests were being carried out; an average value is reported. Finally, the exposed facades are presented, 0° represents the north orientation, moving clockwise, 90° represents the east orientations and so on.

Table 3. DOMVENT3D inputs.

Dwelling number	Shielding conditions	Terrain conditions	Wind speed (m/s)	Wind direction (°)	ΔT (K)	Dwelling type	Exposed Facades			
							0°	90°	180°	270°
1	Light	Suburban	1.080	250	3.69	Detached	✓	✓	✓	✓
2	Moderate	Suburban	0.712	216	3.40	Detached	✓	✓	✓	✓
3	Light	Suburban	1.700	195	1.71	Semi detached	✓	✗	✓	✓

Table 4 includes the measured air change rate (h^{-1}) obtained from blower door tests (average from pressurisation and depressurisation) quoted at 50 Pa; another important result of the airtightness tests is also the flow exponent (*b*); both are key parameters to input in the DOMVENT3D model.

As mentioned before, DOMVENT3D was calibrated to predict infiltration values from airtightness measurements quoted at 4 Pa. Table 4 includes the airtightness results obtained from Pulse tests in each dwelling.

Table 4. Air infiltration (n_1) and airtightness results from blower door (n_{50}, b_{50}) and Pulse (n_4, b_4).

Dwelling number	Air infiltration, n_1 (h^{-1})	Air infiltration uncertainty (h^{-1})	Blower door n_{50} (h^{-1})	Blower door b_{50}	Pulse n_4 (h^{-1})	Pulse b_4
1	0.1241	0.0019	5.3128	0.659	1.0098	0.707
2	0.0787	0.0036	3.5310	0.596	0.7167	0.675
3	0.1645	0.0020	5.7654	0.626	1.2267	0.604

The measured air infiltration given by the tracer gas method is included in table 4. An uncertainty of the data and the regression was calculated. It can be seen that all the tests have uncertainties lower than 5%.

Aided by information from Tables 1, 3 and 4, DOMVENT3D was able to predict infiltration rates for each dwelling. The results are presented in Table 5. The first column shows the predicted infiltration rates from blower door measurements, and, the second from Pulse measurements.

Table 5. DOMVENT3D air infiltration rate predictions (DVn_1).

Dwelling number	DOMVENT3D predictions from n_{50} (h^{-1})	DOMVENT3D predictions from n_4 (h^{-1})
1	0.2091	0.1941
2	0.1628	0.1289
3	0.2203	0.2346

There are discrepancies between DOMVENT3D's predicted values, however, except for property two (133%), the values are not large. Nevertheless, there is not a specific pattern, i. e. for property number one and two, the predicted values are higher when the n_{50} is used, whereas for property number three, the opposite occurs. This is probably due to the nature of the tests and their own uncertainties during the measurements.

In Table 6, the predicted values (*DVc*), using blower door and Pulse are given and each are separately taken into account with the tracer gas value (***n_1***) to provide a statistical standard error assuming a normal distribution for any results.

There are clear differences between the measured and predicted values, for the blower door the standard error reaches up to 18% and up to 14% for the Pulse. It can be seen that the discrepancies from property to property are smaller for the results obtained using the Pulse method (11-14%), though this does not mean that the Pulse method gives better predictions, but suggests the range of uncertainty of the predictions using this model is smaller when using measurements taken at 4 Pa. However, these results need to be validated by further tests in more properties.

Table 6. Standard error between measured and predicted infiltration values.

Dwelling number	n_1 (h^{-1})	Blower door (ΔP=50 Pa) DVn_1 (h^{-1})	Blower door (ΔP=50 Pa) Standard Error (h^{-1})	Blower door (ΔP=50 Pa) Standard Error (%)	Pulse (ΔP=4Pa) DVn_1 (h^{-1})	Pulse (ΔP=4Pa) Standard Error (h^{-1})	Pulse (ΔP=4Pa) Standard Error (%)
1	0.1241	0.2091	0.0301	14%	0.1941	0.0248	13%
2	0.0787	0.1628	0.0297	18%	0.1289	0.0177	14%
3	0.1645	0.2203	0.0197	9%	0.2346	0.0248	11%

Regarding the precision of DOMVENT3D's prediction, Table 7 shows the difference in percentage between the measurements of air infiltration and the predictions (based on both airtightness measurement methods).

Table 7. Percentage difference between measurements of air infiltration and DOMVENT3D's predictions.

Dwelling number	DVn₁ (ΔP=50 Pa) difference (%)	DVn₁ (ΔP=4 Pa) difference (%)
1	68%	56%
2	107%	64%
3	34%	43%
Average	**70%**	**54%**

As mentioned there are discrepancies between the predictions and measurements; it is important to remark that the environmental conditions during the airtightness measurements were used as the input to the infiltration model. This suggests that the measured and predicted infiltration rates are valid only for those scenarios. The differences between using a standard pressurisation method as an input for DOMVENT3D and tracer gas measurements, range from 34 to 107%. For the Pulse method the differences lie in a much tighter range (43-64%).

Despite the lower average difference obtained by the Pulse method, the results seem inconclusive. The difference in the third property is lower when predicting from the blower door than the Pulse. DOMVENT3D's predictions overall generate an error, nevertheless this error is smaller than when using infiltration ratios (Vega Pasos, et al., 2019) and modifying factors, as used in UK's legislation (Building Research Establishment, 2013). Therefore, for more accurate calculations of heat losses, infiltration models should be used.

Assuming that the Pulse method is as repeatable and accurate as the conventional pressurisation method, DOMVENT3D, or other infiltration model can be employed to predict infiltration rates. Nevertheless, this study is rather short (limited number of properties) for the capabilities of the model which has been used to predict full housing stocks. More properties in different climates in different seasons need to be studied in order to give a realistic validation of the results; and, to make conclusive statements about the model. A larger testing and modelling campaign is underway led by the authors, future results will be compared with the ones reported in this paper.

6 CONCLUSION

Three houses located in Nottingham, United Kingdom were used to validate the infiltration rate predictions given by the infiltration model DOMVENT3D. Airtightness tests using the pressurisation and the Pulse methods were carried out in those dwellings. In addition, the infiltration rate was measured using the tracer gas concentration decay method. Real measurements were used to compare against predictions. DOMVENT3D was also calibrated to produce an infiltration rate prediction when inputting airtightness measurements at 4 Pa (using Pulse). During those tests the environmental conditions were monitored. The test were considered as successful.

Results from the tracer gas tests delivered valid results with low uncertainty, therefore it was concluded that they were representative of the infiltration rate for that period. Input parameters were defined for each dwelling and logged into DOMVENT3D including the air change rate obtained from airtightness measurement methods.

DOMVENT3D predictions differed from 34% to 107% when using the blower door's measurements; and, from 43% to 64% when using the Pulse measurements. Despite these figures, it cannot be concluded that an airtightness measurement method is better than the other to predict infiltration rate, however, results suggested that the nature of Pulse (low pressure measurement), led to a lower uncertainty, or a more repeatable one. In addition, the Standard error between measurements and predictions was lower in general when using the Pulse method. Despite these, it is concluded that these results are only a first step to experimentally validating the model. This same method has to be used in a larger testing and modelling campaign including different dwellings, locations and environmental conditions.

Although the difference between measurements and predictions might seem large, in some cases, the model showed more accurate results than those ones obtained when using UK's legislation method. Finally, assuming that both airtightness testing techniques give accurate results, it can be concluded that they both can be used to measure airtightness and predict air infiltration rates.

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