

Modelling uniformly porous facades to predict dwelling infiltration rates

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BM Jones¹, RJ Lowe², M Davies¹, Z Chalabi³, P Das¹
and I Ridley⁴

Abstract

It is important to limit dwelling infiltration to reduce energy demand and help meet national climate change commitments while concurrently providing sufficient ventilation to deliver adequate indoor air quality. DOMVENT3D is a model of infiltration and exfiltration that assumes a linear pressure distribution over any number of uniformly porous facades and integrates the airflow rate in the vertical plane to predict the theoretically correct airflow rate through them. DOMVENT3D is a new development of an existing two-dimensional model of infiltration that provides more opportunities for investigating a greater number of dwellings than was previously possible. Initial testing suggests that DOMVENT3D is mathematically robust and is suitable for modelling a wide variety of dwelling types and geometries to assist engineers and policy makers.

Practical application: The modern building services engineer may be required to model airflow networks in a building to balance the conflicting needs of energy consumption reduction and occupant health. Limiting exfiltration is one method of reducing heat losses from a building and so there is a need to model it accurately. This article presents a new model of infiltration and exfiltration through a uniformly porous facade that can be incorporated within advanced complex airflow network tools or applied using a simple spreadsheet.

Keywords

Infiltration, air leakage, permeability, ventilation, modelling, dwelling, house, DOMVENT, CONTAM, AIDA

¹Bartlett School of Graduate Studies, University College London, Central House, 14 Upper Woburn Place, London, UK

²UCL Energy Institute, University College London, Central House, 14 Upper Woburn Place, London, UK

³London School of Hygiene & Tropical Medicine, 15-17 Tavistock Place, London, UK

⁴School of Property, Construction and Project Management, RMIT University, Melbourne, Victoria, Australia

Corresponding author:

BM Jones, Bartlett School of Graduate Studies, University College London, Central House, 14 Upper Woburn Place, London WC1H 0NN, UK.

Email: b.jones@ucl.ac.uk

Introduction

The infiltration of cold air and the concurrent exfiltration of conditioned air through adventitious openings in the thermal envelope of a dwelling can be a significant component of its heating load. Measuring infiltration is technically difficult, invasive and expensive and so it is often inferred from a measurement of air permeability, the rate of airflow through the fabric of a building measured at a steady high pressure difference, normally 50 Pa, when the effects of wind and buoyancy forces are effectively eliminated.¹ This inference is also problematic² and so there is a clear need to predict dwelling infiltration theoretically, which is both cheap (in the sense that no measurements are required) and computationally quick. There are two approaches commonly used to model infiltration. The first approach relies on the knowledge of the location of adventitious openings, known as air leakage paths (ALPs), their geometry or expected losses across them. Each ALP is specified explicitly and appropriate leakage characteristics are derived either from measurement or from appropriate sources in the literature for specific building components.³

However, it is suggested that 'there is insufficient data available in the literature to justify [anything] other than a uniform distribution'⁴ of porosity. The second approach to modelling infiltration uses an appropriate number of ALPs, equally spaced in the vertical plane to account for buoyancy driven flow and sized according to the dwelling's permeability. This is known as the multiple element approach⁵ and it is advised that 11 equally spaced ALPs is an adequate number.²

An elegant development of this approach, when the number of ALPs is large, is the method proposed by Lyberg⁶ and Lowe.⁷ The basic equations proposed by Lyberg are additionally used to model airflow through large openings⁵ but his formulation also handles airflow through envelopes with a wide range of properties; a brief discussion of the fundamental differences is given in 'Initial tests'. Lowe's two-

dimensional infiltration model, known as DOMVENT, assumes a linear pressure distribution over a uniformly porous facade and integrates the airflow rate in the vertical plane to predict the theoretically correct airflow rate through that facade. Deru and Burns⁸ have extended this work by defining equations for the situation where both infiltration and exfiltration occur simultaneously through a single facade driven by natural forces. However, the approach does not consider the effects of a mechanical system on facade infiltration and exfiltration rates. The simplicity of Lowe's DOMVENT model⁷ and its implementation using bespoke MATLAB⁹ code means that the calculation and post-processing time is significantly less than that for conventional airflow analysis tools, such as CONTAM¹⁰ and AIDA,³ two independent validated airflow analysis tools. These tools do not have an airflow path that specifically characterizes infiltration and so must follow the multi-element approach described here. The predictions of DOMVENT have been compared against those of established envelope flow models² and is used to investigate energy use and CO₂ emissions in dwellings⁷ and the relationship between permeability and infiltration in conjoined dwellings.² Thus, DOMVENT is a useful tool for undertaking the simulations necessary to investigate the infiltration one might expect to find in a dwelling subjected to varying weather conditions. However, the current formulation of DOMVENT described in the literature is exclusively for a cuboid dwelling with two identical exposed facades when internal and external temperatures are unequal. This constrains its application to the modelling of mid-terrace houses and some apartments. Mid-terrace houses account for only 19% of the English housing stock,¹¹ whereas end-terrace, semi-detached and detached houses account for 53% of the stock.¹¹ Accordingly, if one is also to have confidence in the predictions of infiltration in dwelling types that comprise the majority of the English stock, a more versatile form of DOMVENT is needed that is able to consider

any number of vertical facades with differing geometries.

This article addresses the limitations of DOMVENT by developing a three-dimensional model of infiltration and exfiltration known as DOMVENT3D. Here the term ‘3D’ implies the potential of the model to predict infiltration and exfiltration in three-dimensions even if it is not always applied in this way. In ‘Modelling infiltration’, the model is derived from first principles so that it can predict the infiltration rate of any dwelling with cuboid geometry. Uncertainties and limitations are discussed and the model is corroborated against the predictions of CONTAM. In ‘Applications’, suitable applications of DOMVENT3D are discussed.

Modelling infiltration

Consider a dwelling of height H (m), depth D (m) and width W (m), with one or more exposed facades (see Figure 1, which shows a cuboid representation of a dwelling, and Figure 2, which shows a cross-section through one of any number of vertical facades). When a building contains no mechanical ventilation system or a perfectly balanced mechanical ventilation system, mean infiltration and exfiltration rates are equal in magnitude and opposite in sign. They are a function of the geometry of the building, its local environment and the prevailing meteorological conditions. When an unbalanced mechanical ventilation system is present, the

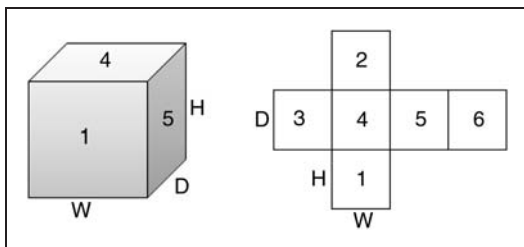


Figure 1. Cuboid dwelling of height H , width W and depth D . Facades 1 and 2, dwelling front and back; facades 3 and 5, sides (exposed if detached or internal if terraced); facades 4 and 6, ceiling and floor.

rates of infiltration and exfiltration are generally unbalanced.

A general model

Most models of infiltration and exfiltration use a power law relationship between the pressure difference Δp (Pa), across an adventitious opening, known as an ALP, and the volume flow rate \dot{Q} (m^3/s) of air where

$$\dot{Q} = C|\Delta p|^b \varepsilon(\Delta p) \quad (1)$$

Here, b is the flow exponent and C is a flow coefficient ($\text{m}^3/\text{s}/\text{Pa}^b$). The flow direction function $\varepsilon(x) = 1$ if $x > 0$, $\varepsilon(x) = -1$ if $x < 0$ or $\varepsilon(x) = 0$ if $x = 0$. Airflow into the building is positive in sign whereas airflow out is negative. Etheridge¹ states that a dwelling can be treated as a single-zone space by assuming that its rooms are interconnected and all internal doors are open. Then, the net flow through a system of ALPs in the thermal envelope of a building is zero and is described by the continuity equation

$$\dot{Q}_m + \sum_{i=1}^j \dot{Q}_i = 0 \quad (2)$$

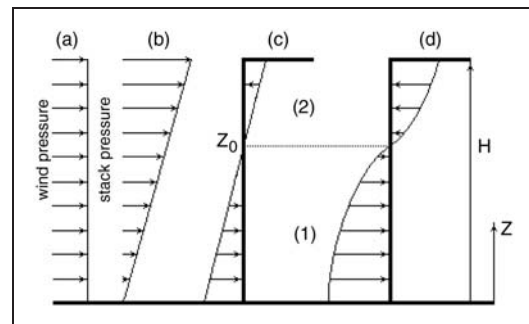


Figure 2. Vertical cross-section through a facade of height H , under pressure from: (a) action of the wind and (b) stack pressure. The resulting (c) linear pressure distribution gives an (d) airflow distribution with areas of (1) infiltration and (2) exfiltration, separated by a neutral point z_0 .

where \dot{Q}_i is the airflow rate through the i^{th} ALP of a total of j and \dot{Q}_m is the total airflow through a mechanical ventilation system, such as an extractor fan.

The modelling of specific ALPs is appropriate if their locations are known but in most cases they are not. In the absence of a priori knowledge on their locations, it is common to assume that a vertical wall or facade is uniformly porous.^{2,4} The vertical pressure distribution over the facade of a building is a function of the action of the wind, the difference between internal and external air densities, known as the stack pressure, and a change in internal pressure that occurs to balance mass through all openings in the building (see Figure 2 (a)–(c)). Accordingly, the pressure difference across a point on the facade at a height z (m) above floor level is given by¹

$$\Delta p(z) = \frac{1}{2} \rho_E u^2 c_p - (\rho_E - \rho_I) g z - p_I \quad (3)$$

where p_I is the internal air pressure relative to atmospheric pressure (gauge), u is the wind speed at height H , ρ_E is the external air density (kg/m^3), ρ_I is the internal air density (kg/m^3), g is the gravitation acceleration (m/s^2) and c_p is the dimensionless facade pressure coefficient. The first two terms on the right hand side of the equation are depicted in Figure 2 by gradients (a) and (b), where z varies between $z=0$ and $z=H$ and all other terms are constant.

A number of ALPs are defined in the vertical plane to model a uniform distribution of porosity of any number of facades. The airflow rate through and pressure difference across each ALP is defined by equations (1) and (3), respectively. The two equations are solved by varying p_I so that equation (2) is satisfied. Accordingly, for j ALPs, $j+1$ equations are required.

DOMVENT3D: An integrating infiltration model

When z is a variable and all other parameters are constant, the pressure difference across the

facade varies linearly with z and equation (3) has one root or equilibrium point. The height at which the root occurs is known as the neutral height z_0 (m). When $\Delta p(z_0) = 0$, an expression for z_0 is given by⁵

$$z_0 = \frac{\frac{1}{2} \rho_E u^2 c_p - p_I}{(\rho_E - \rho_I) g} \quad (4)$$

Equation (4) shows that as p_I increases, z_0 decreases, and vice versa. Accordingly, an extract fan can reduce p_I below atmospheric pressure and increase z_0 above the height of the building so that all exposed facades provide infiltration.

The pressure difference over a facade can also be described with reference to z_0 thus

$$\Delta p(z) = -(\rho_E - \rho_I) g (z - z_0). \quad (5)$$

When $0 < z_0 < H$, both infiltration and exfiltration occur simultaneously through a facade; otherwise, when $0 > z_0 > H$, only infiltration or exfiltration occurs.

If equation (1) is now assumed to be the flow rate through an infinitesimal section dz (m) of a facade in the vertical plane due to a pressure difference across it, it can be rewritten to describe the total volume flow rate of air through the facade, \dot{Q}_f (m^3/s)

$$\dot{Q}_f = C \varepsilon (\Delta p) \int_0^H (|\Delta p|)^b dz \quad (6)$$

Now, C can be expressed as

$$C = EaW \quad (7)$$

where E is the dimensionless relative leakage area (akin to a discharge coefficient) and W (m) is the facade width. Note that W is interchangeable with dwelling depth D (m), when the side facade of a dwelling is modelled (see Figure 1, facades 3 and 5). The flow exponent b normally has a value³ in the range of 0.6–0.7, although it is often taken as 0.5³ to simplify the analysis, a corresponds to $\left(\frac{2}{\rho}\right)^b$. By adopting

the Boussinesq approximation,¹ $\sim n \downarrow$ is the mean of the internal and external air densities. To calculate the total mass flow rate of air through the facade \dot{M}_f (kg/s), set $a = \bar{\rho} \left(\frac{2}{e\bar{\rho}} \right)$, so that when $b=0.5$, then $a = (2\bar{\rho})^{0.5}$. This corrects a mathematical error in Lowe's article⁷ but it does not affect its predictions and conclusions.

Lowe⁷ states that equation (1) can be rewritten to show that the dwelling air leakage rate, \dot{Q}_{50} (m³/s), at a pressure differential of 50 Pa and is given by

$$\dot{Q}_{50} = EaA_{50}(50)^b = \dot{Q}_m. \quad (8)$$

Here, A_{50} is the permeable area of the envelope at a pressure differential of 50 Pa, which can vary according to dwelling type² and is a function of all or some of H , W and D ; see Jones et al.² for a full discussion of A_{50} .

Equations (5), (6) and (7) are combined so that \dot{Q}_f is now given by

$$\dot{Q}_f = EaW\varepsilon(\rho_E - \rho_I) \{ |(\rho_E - \rho_I)|g \}^b \left[\begin{array}{l} + \int_0^{\min(z_0, H)} (z - z_0)^b dz \\ - \int_{\max(z_0, 0)}^H (z - z_0)^b dz \end{array} \right] \quad (9)$$

Note that for simplicity, the flow function input is reduced to the difference between the air densities because the difference between these parameters governs the airflow direction. Each of the integral limits of equation (9) are taken to be zero if the lower limit of integration exceeds the upper. The integration of equation (9) describes both infiltration and exfiltration (see Figure 2) and can be split into two separate equations whose sum is equal to \dot{Q}_f

$$\dot{Q}_1 = \frac{EaW\varepsilon(\rho_E - \rho_I)}{b+1} \{ |(\rho_E - \rho_I)|g \}^b \left[\begin{array}{l} + z_0^{b+1} \Big|_{z_0 > 0} \\ - (z_0 - H)^{b+1} \Big|_{z_0 > H} \end{array} \right] \quad (10)$$

$$\dot{Q}_2 = \frac{EaW\varepsilon(\rho_I - \rho_E)}{b+1} \{ |(\rho_E - \rho_I)|g \}^b \left[\begin{array}{l} + (H - z_0)^{b+1} \Big|_{z_0 < H} \\ - (-z_0)^{b+1} \Big|_{z_0 < 0} \end{array} \right] \quad (11)$$

when $\rho_I < \rho_E$, then \dot{Q}_1 and \dot{Q}_2 describe infiltration and exfiltration, respectively. When $\rho_I > \rho_E$, then \dot{Q}_1 and \dot{Q}_2 describe exfiltration and infiltration, respectively. When $\rho_I = \rho_E$, then equations (10) and (11) equal zero and must be replaced by a single ALP using equation (1). It is now possible to model airflow through multiple vertical facades of varying geometries (where H , D and W are not equal) by stating equations (1), (10) and (11) for each, thus making the model fully three dimensional.

Ordinarily, equations (1), (2), (10) and (11) are solved numerically but there are three situations when an explicit solution is possible for a naturally ventilated cuboid dwelling whose external facades are of equal height. First, when $u=0$ m/s and infiltration is solely attributable to buoyancy forces, $z_0 = H/2$ m. Second, when a building has two exposed facades, the mean of the neutral heights on the windward and leeward facades equal $H/2$ m. Finally, a single-sided dwelling has a neutral height of $z_0 = H/2$ m for all environmental conditions. These situations are true because: (a) an average value of air density is used in equation (7) and (b) the permeability of the exposed facades is considered to be uniformly distributed and so the area of exposed facades that provide infiltration must equal the area of exposed facades that provide exfiltration.

DOMVENT3D only requires three equations to model the airflow rate through a uniformly porous facade and a maximum of two equations are required at one time. This represents a considerable simplification of the multiple element approach and a development of the original DOMVENT model.

Model limitations

The application of equation (1) to airflow through a single ALP and to airflow through a whole building, characterised by a number of ALPs, is an approximation. The coefficients that describe the airflow through such a building are, in reality, not always constant but the assumption of constant values is not a significant obstacle to the use of this fundamental equation in the way proposed by Lyberg.⁶ Furthermore, the power law relationship described by equation (1) is the most widely used method of interpolating between measurements of air leakage rates² and so is used here. It is noted that the quadratic relationship is considered to be more accurate at operational pressure differences¹ and so a future version of DOMVENT3D may incorporate this approach.

Equation (3) assumes that p_I and ρ_E are uniform and u and c_p are not a function of z when $z \leq H$. These assumptions restrict equation (2) to low-rise buildings. Here, Liddament¹² suggests that mean pressure coefficients are appropriate for low-rise buildings of up to three storeys and so this limit is adhered to here. The authors are unaware of any empirical evidence of temperature distributions in dwellings that could be used to add another density term to equation (3) to accurately describe stratification. Moreover, the consideration of stratification increases the computational complexity of the model. Thus, it is acknowledged that although ignoring the effects of stratification introduces uncertainty into the model, it is nevertheless considered to be an acceptable trade-off between model complexity and prediction accuracy.⁵

Initial tests

The theory that underpins this article can handle envelopes in which flow varies continuously from turbulent ($b=0.5$) to laminar ($b=1$); see equation (1). It can therefore be configured for comparison against the two-way single-opening ventilation element (TWSO) that is used to model airflow through large doors and windows by CONTAM,¹⁰ a validated multi-zone

ventilation and pollutant transport model. The TWSO requires input of the width of the opening, height and discharge coefficient, C_d (akin to E , the relative leakage area). The flow exponent is fixed at $b=0.5$ and the minimum value of C_d is 10^{-3} . These restrictions make the TWSO unsuitable for modelling a porous facade because b is too small—for adventitious cracks³ b is between 0.6 and 0.7—and C_d is too big; for example,² $E=1.64 \times 10^{-4}$ for an archetypal apartment with a permeability of $10 \text{ m}^3/\text{h}/\text{m}^2$. Nevertheless, a numerical corroboration of DOMVENT3D against the TWSO element is possible and so a single DOMVENT facade and TWSO element are modelled when C_d , E , W and H are set to unity, $b=0.5$, $g=9.81 \text{ m/s}^2$ and $u=0 \text{ m/s}$. The internal and external air temperatures are $T_I=292.15 \text{ K}$ and $T_E=282.15 \text{ K}$, respectively. The air density is given by $\rho = P/RT$ where atmospheric pressure $P=101325 \text{ Pa}$ and the gas constant, $R=287.055 \text{ J}/(\text{kg K})$, so that $\rho_E=1.251 \text{ kg}/\text{m}^3$ and $\rho_I=1.208 \text{ kg}/\text{m}^3$. These calculations of air density are almost identical to those of CONTAM and the mass flow rate (kg/s) of air predicted by DOMVENT3D, using equations (2), (5), (7), (10) and (11), is 0.07% above that of CONTAM. Next, two facades are considered when $T_I=292.15 \text{ K}$ and $T_E=282.15 \text{ K}$ and a wind pressure is applied to each facade that is equal in magnitude and opposite in sign so that $0.5\rho_E c_p u^2 = \pm 1 \text{ Pa}$. The airflow rate predicted by DOMVENT3D is 0.02% above that of CONTAM.

The differences between the predictions of CONTAM and DOMVENT3D for both buoyancy-driven flow and combined wind- and buoyancy-driven flow are negligible and so can be said to be in agreement.

Applications

When comparing DOMVENT3D to most models of infiltration, its consideration of the physics is relatively complex because it assumes a linear pressure distribution over a uniformly porous facade and integrates the airflow rate in

the vertical plane to predict the theoretically correct airflow rate through that facade; yet, its application is simple. Thus, DOMVENT3D can be used to make many predictions quickly, making it an ideal tool for predicting the infiltration rates one might expect in a stock of buildings in reasonable computational time. DOMVENT3D's limitations (see 'Model limitations') constrain its application to the evaluation of low-rise buildings, such as houses. In England, there are some 22.3 million dwellings,¹¹ yet the number of measurements of dwelling air permeability made in the existing stock is limited.^{13,14} Although the air leakage testing of all new dwelling developments is now mandatory, 88% of the stock was built before 1990¹¹ when tests were not required. Therefore, the government formulates its policy on the retrofitting of energy efficiency measures designed to meet climate change mitigation commitments using a limited quantity of data. A forthcoming article by the authors uses DOMVENT3D to investigate infiltration rates in English dwellings following a study of infiltration rates in the U.S. housing stock using CONTAM.⁴ The latter study⁴ assumes uniform porosity, which means that it applied the multiple element approach, although this is not stated. Accordingly, the accuracy of their predictions could be improved if the TWSO element is amended to allow $1 \geq b \geq 0.5$ and a C_d or E value that is at least an order of magnitude smaller than is currently acceptable.

ALPs in horizontal facades (floors and ceilings) can be defined by equations (1) and (3) and incorporated within DOMVENT3D using equation (2). When a simple single zone airflow model is required, equations (10) and (11) can be easily incorporated within AIDA³ or placed into an Excel spreadsheet and solved using its 'Goal Seek' command.

To demonstrate the potential of DOMVENT3D, it is used to estimate the range of infiltration rates one might expect to find in a typical UK detached house¹⁵ located in open, rural and urban terrain. The house has

dimensions $W=6$ m, $D=8$ m, and $H=4.8$ m, a volume of 230.4 m³, an envelope area of 230.4 m² and an air permeability of 10 m³/h/m². The house has a loft and a suspended floor and so the entire thermal envelope is assumed to be permeable at a pressure differential of 50 Pa. A typical flow exponent³ of $b=0.66$ is applied and so, using equation (8), the relative leakage area is calculated to be $E=1.52 \times 10^{-4}$ when $\bar{\rho}=1.225$ kg/m³. Distributions of pressure coefficients for the vertical surfaces of a cuboid building with less than three stories are given by Liddament¹² and are applied for open, rural and urban terrain. The floor and ceiling are assumed to be completely shielded from the effects of the wind. The greatest infiltration rates are predicted by DOMVENT3D with the wind normal to the front of the house and so this angle of incidence is used to generate an infiltration rate performance envelope for temperature differences of 5 , 10 and 15 K following Liddament¹² (see Figure 3). Figure 3 shows that the infiltration rate is dominated by the difference between internal and external temperatures for building height wind speeds of up to ~ 4 m/s and thereafter the wind is the dominant driving force. Accordingly, in a climate where the mean building height wind speed is less than 4 m/s and the temperature differential is less than 15 K, the infiltration rate of this detached house is likely to be buoyancy driven and to be less than 0.5 air changes per hour (ac/h) on average. This is significant because 0.5 ac/h is the threshold ventilation rate (recommended by many European countries) above which negative health effects reduce.² Figure 3 suggests that this house could require additional purpose provided ventilation, which when applied with other mitigating measures¹⁵ would help to reduce risks to the health of its occupants. This type of finding should be of interest to both engineers and policy makers.

Conclusions

This article presents a brief analysis of approaches used to model infiltration in low-rise

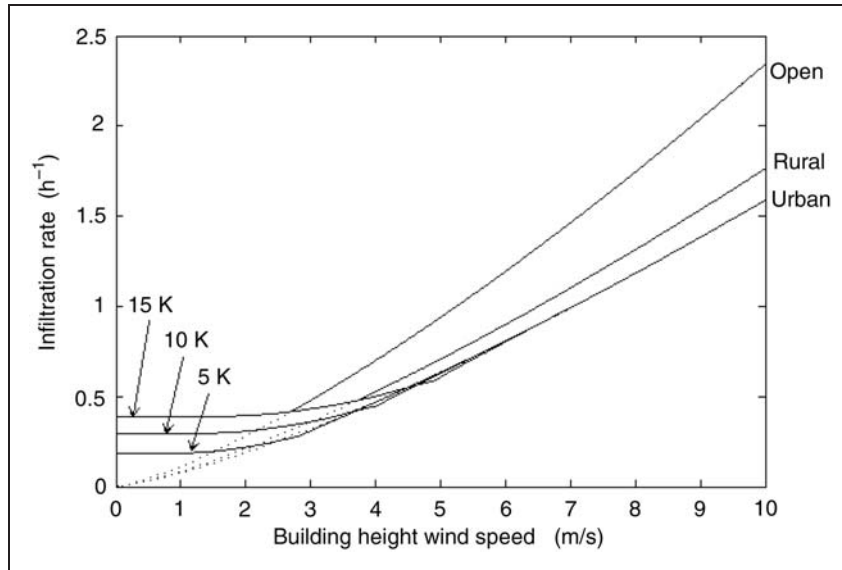


Figure 3. Infiltration rate (h^{-1}) envelope of a typical detached house located in open, rural and urban terrain for temperature differences of 5, 10 and 15 K.

buildings, such as dwellings, and describes a new general model of infiltration known as DOMVENT3D. The theory that underpins this article can handle any number of facades where airflow through them varies continuously from turbulent to laminar and the pressure differences across them are caused by both mechanical and natural forces. The model was tested against CONTAM with encouraging results. It is shown that two simple modifications to CONTAM's TWSO ventilation element would allow it to make improved predictions of infiltration rates. Finally, with increased confidence in its predictions, it is proposed to use DOMVENT3D to investigate the infiltration rates one might expect to find in UK houses and thus to help policy makers make informed decisions on the installation of energy efficiency measures in houses.

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References

1. Etheridge DW. *Natural ventilation of buildings: theory, measurement and design*. New York: John Wiley and Sons, 2012.
2. Jones BM, Das P, Chalabi Z, et al. The effect of party wall permeability on estimations of infiltration from air leakage. *Int J Vent* 2013; 12(1): 17–29.
3. Orme M and Leksmono N. *Ventilation modelling data guide – GU05*. Brussels, Belgium: Air Infiltration and Ventilation Centre, 2002.
4. Persily A, Musser A and Emmerich SJ. Modeled infiltration rate distributions for U.S. housing. *Indoor Air* 2010; 20(6): 473–485.
5. Li Y, Delsante A and Symons J. Prediction of natural ventilation in buildings with large openings. *Build Environ* 2000; 35(3): 191–206.
6. Lyberg M. Basic air infiltration. *Build Environ* 1997; 32(2): 95–100.
7. Lowe RJ. Ventilation strategy, energy use and CO₂ emissions in dwellings – a theoretical approach. *Build Serv Eng Res Technol* 2000; 21(3): 179–185.
8. Deru MP and Burns PJ. Infiltration and natural ventilation model for whole building energy simulation of residential buildings. *ASHRAE Trans* 2003; 109(2): 801–811.

9. MathWorks. *MATLAB® version 7.12.0.635 (R2011a)*. Natick, MA: The MathWorks Inc, 2011.
10. Walton GN and Dols WS. *CONTAMW 3.1 User guide and program documentation*. Gaithersburg, MD: NISTIR 7251, 2013.
11. DCLG. English housing survey: headline report 2009-10. London, Department for Communities and Local Government, 2011.
12. Liddament MW. *GU03: a guide to energy efficient ventilation*. Brussels, Belgium: Air Infiltration and Ventilation Centre, 1996.
13. Stephen R. *Airtightness in UK dwellings: BRE's test results and their significance*. BRE Report 359. Garston, Watford: Building Research Establishment, 1998.
14. Pan W. Relationships between air-tightness and its influencing factors of post-2006 new-build dwellings in the UK. *Build Environ* 2010; 45(11): 2387–2399.
15. Shrubsole C, Ridley I, Biddulph P, et al. Indoor PM2.5 exposure in London's domestic stock: modelling current and future exposures following energy efficient refurbishment. *Atmos Environ* 2012; 62(0): 336–343.