THE RELATIONSHIP BETWEEN PERMEABILITY AND INFILTRATION IN CONJOINED DWELLINGS

Benjamin Jones[*1], Payel Das[1], Zaid Chalabi[1,2], Michael Davies[1], Ian Hamilton[1], Robert Lowe[1], James Milner[2], Ian Ridley[3], Clive Shrubsole[1], and Paul Wilkinson[2]

1 Bartlett School of Graduate Studies
University College London
Central House, 14 Upper Woburn Place,
London, WC1H 0NN, United Kingdom
**Corresponding author: b.jones@ucl.ac.uk*

2 London School of Hygiene & Tropical Medicine
15-17 Tavistock Place
London, WC1H 9SH, United Kingdom

3 School of Property, Construction and Project Management
RMIT University, GPO Box 2467
Melbourne, VIC 3001 Australia

ABSTRACT

The importance of adventitious air leakage under normal operational conditions and its reduction in order to save energy is highlighted by the relvant building standards of many countries. This operational leakage is often inferred via the measurement of air permeability, a physical property of a building that indicates the resistance of its fabric to airflow. A building's permeability is the measure of airflow rate through its envelope at a constant pressure differential of 50 Pascals. However, operational pressure differences are dynamic and typically an order of magnitude lower than 50 Pascals. Thus there is much uncertainty when using a value of permeability in an attempt to predict operational air leakage.

Powerful simulation tools can model the ventilation rates found in a building in great detail, yet these complex modelling tools contrast with the much simpler tools that are used frequently to estimate annual energy consumption for space heating in dwellings. For example, some building codes assume a simple fixed relationship between air permeability measured at 50 Pascals and mean background infiltration during the heating season; the so-called *rule-of-20*.

This paper evaluates afresh this rule-of-thumb. Firstly, a theoretical model of adventitious air leakage for a dwelling is presented. Secondly, the predictions of the model are compared against those of CONTAM, and AIDA, validated airflow analysis tools, for an identical building and environmental conditions. Thirdly, the model is used to predict the mean infiltration rate and the corresponding energy required to replace heat lost via air operation infiltration during the heating season for an apartment and a terraced house located in 14 different UK cities. Finally, the predictions of the model are used to develop a relationship between the adventitious air leakage under pressure, operational infiltration, and energy consumption during the heating season. The relationship is used to discuss the validity, accuracy, and applicability of the *rule-of-20* and its use by simple modelling approaches such as the UK's Standard Assessment Procedure.

KEYWORDS

Infiltration, permeability, energy, dwelling, modelling, CONTAM, AIDA

INTRODUCTION

The ingress of cold air through adventitious openings can be a significant component of a dwelling's heating load. In the UK, for example, this has been recognised by a relevant standard for new dwellings[1]. However, measuring infiltration is technically difficult, invasive, and expensive. Accordingly, infiltration is often inferred from a measurement of permeability, the airflow through the fabric of a building, made at a steady high pressure difference, normally 50Pa, when the effects of wind and buoyancy forces are effectively eliminated[2]. Permeability is often scaled by the volume of the building or an area, such as envelope area in Finland or the UK, where it is known as the air leakage index (ALI), or in Denmark where permeability is scaled by heated floor area[2]. Because operational pressure differences are dynamic and normally an order of magnitude lower, at around 4Pa[2], the metric of permeability is only a physical property of a building that indicates the resistance of its fabric. Thus there is much uncertainty when using a value of permeability in an attempt to predict operational air leakage. The airflow rate at 50Pa, $\dot{Q}_{50}$ (m^3/s), must be converted to an infiltration rate, $\dot{Q}_4$ (m^3/s), at 4Pa, and although there are several approaches[3] for converting $\dot{Q}_{50}$ to $\dot{Q}_4$ the most common *rule-of-thumb* for dwellings[4] is given as

$$\dot{Q}_{50}/\dot{Q}_4 = 20. \qquad (1)$$

Equation (1) is often known as the *rule-of-20*, *Sherman's ratio*, or the *leakage-infiltration ratio*[4]. The figure of 20 must not be viewed as fixed and should be scaled according to a variety of factors such as dwelling height, shielding, air leakage path size, and climate [4]. In the UK, the Standard Assessment Procedure (SAP) is the government's method for assessing and comparing the energy and environmental performance of dwellings used to make energy and environmental policy decisions. As a starting point SAP applies Equation (1) (using a fixed value of 20) to obtain an initial rate of air leakage from measured permeability. It then adds extra air leakage if chimneys, flues, and fans are present in a dwelling. This revised figure of air leakage is scaled if local shielding and mechanical ventilation are present. Other building codes make similar assumptions[5].

However, the relevant literature reveals that little attention has been given to any scaling that should be applied to take account of the permeability of party walls. Measurements of airflow through party walls separating a series of terraced houses and apartments have indicated that such flows can be a significant component of total air leakage rate – up to 30%[6]. In the UK, for example, ~80% of the housing stock shares at least one wall with another dwelling[7]. This paper thus addresses this issue via a modelling based approach.

In this paper, a conjoined dwelling, such as an apartment, is assumed to be joined to four immediately adjacent apartments and a semi-infinite number of other apartments in both the vertical and horizontal planes. In the horizontal plane each dwelling is a mirror image of its adjacent apartment, whereas in the vertical plane each dwelling is identical to that located above and below it. Under operational conditions, and with all purpose-provided openings sealed, one does not expect to observe airflow between adjacent dwellings through permeable party walls because they are all assumed to experience identical environmetal conditions and thus have the same internal pressure. Therefore, airflow is only expected through external façades. Conversely, when undertaking a blower door test in a conjoined dwelling of interest one cannot expect adjacent dwellings to be undertaking a similar test simultaneously and so two limiting assumptions about the permeability of party walls can be made: (A1) party walls are permeable and so airflow to adjacent dwellings through them is observed; or (A2), party walls are impermeable and so no airflow to adjacent dwellings is observed. Accordingly, this paper asks the questions: what are the consequences of these two limiting assumtions of permeability and how do they affect Equation (1)? To answer them, a theoretical study is undertaken using a simple but useful model of infiltration.

INTERIM: A 2D INTEGRATING INFILTRATION MODEL

In the absence of knowledge of the location of air leakage paths (ALPs), we start by assuming that a wall is uniformly porous. The modelling of wind driven infiltration using an envelope flow model is simple because a single flow path, representative of all ALPs, is placed at an arbitrary height on each façade. Modelling buoyancy is more problematic, but guidance on the number and location of ALPs is given by the AIVC[8] which states that "*the simplest approach would be to assign a high positioned and low positioned leakage path to each façade*." However, they also note that "*we have found that 11 vertical holes, equally spaced, are required to model the stack flow though a uniformly porous wall to an accuracy of 3-4%*", although no evidence is given showing why 11 ALPs is an optimum number. The greatest error occurs when buoyancy forces are introduced into an infiltration model and so we propose a framework in which the pressure difference across each section of the thermal envelope of a dwelling are estimated explicitly and the resulting airflow rates integrated over the whole envelope to give a total ventilation rate. This approach offers a coherent starting point to investigate infiltration and so is utilized here. We directly apply the work of Lowe[9] whose 2D Integrating Infiltration Model is herein known as 'INTERIM'. Full details of the model are given in by Lowe in reference [9].

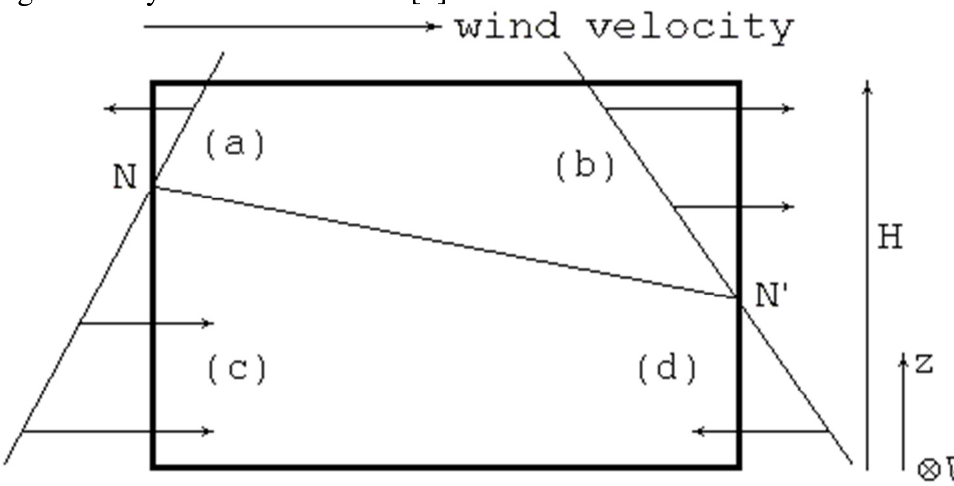

Figure 1: Vertical cross section through a dwelling showing stack pressure gradients on the windward and leeward façades and airflow modes: (a) windward exfiltration; (b) leeward exfiltration; (c) windward infiltration; (d) leeward infiltration. Line NN' is the neutral plane within the dwelling whose vertical deviation is caused by the action of wind around the dwelling. W is the dwelling width extending into the page.

A dwelling can be treated as a single-zone space by assuming that its rooms are interconnected and all internal doors are open[2]. Then, mass conservation ensures that the net mass flow rate $\dot{M}_{net}$ (kg/s) of air through the thermal envelope of a dwelling of height H (m) is zero, and is given by:

$$\dot{M}_{net} = \int WEF(|\Delta p|)\varepsilon(\Delta p)dz = 0 \quad (2)$$

where W is the dwelling width, E is the dimensionless relative leakage area, F is a flow function (kgm^{-2}s^{-1}), Δp (Pa) is the pressure difference across an infinitesimal section dz (m) of the thermal envelope in the vertical plane, and the flow direction function $\varepsilon(x) = 1$ if x>0 or -1 if x<0. The model assumes that the roof and ground floor are airtight and so infiltration only occurs through two opposite façades, and that each façade is uniformly porous. Figure 1 shows the stack pressure gradients on the windward and leeward façades and the neutral points (N and N') where there is no airflow through the envelope. The heights of N and N' (above ground) are affected by the action of the wind around the dwelling. Air flows into the dwelling below the neutral points and out above them, giving up to four airflow modes: (a) windward exfiltration; (b) leeward exfiltration; (c) windward infiltration; (d) leeward infiltration.

The flow function of Equation (2) has the form

$$F = a(|\Delta p|)^b \quad (3)$$

where b is the flow exponent with a value in the range of 0.6-0.7[8], although it is often taken as 0.5 to simplify the analysis when a corresponds to $(2\rho)^{0.5}$. The permeability of a building is normally recorded at a pressure differential of 50Pa and under these conditions Equation (2) becomes

$$\dot{M}_{50} = EaA_{50}(50)^b \quad (4)$$

where A_{50} (m^2) is the area of the envelope able to transfer mass at 50Pa. When permeability assumption A(1) is applied $A_{50} = A_{env}$, the area of the dwelling envelope. When permeability assumption A(2) is applied $A_{50} = A_{exp}$, the total area of the exposed façades. Equation (4) is used to calculate E for the whole dwelling.

MODEL VALIDATION

INTERIM is used to answer the questions posed by this paper by predicting infiltration through the thermal envelope of a number of dwellings. Therefore, it is important to have confidence in the predictions of INTERIM and so they are compared against those of established envelope flow models. The first is CONTAM, a validated multi-zone ventilation and pollutant transport model[10], and the second is the AIDA algorithm, a simple single-zone ventilation model[8]. Both models assume a power law relationship between volume flow rate of air through the i^{th} of j ALPs and the pressure difference accross it

$$\dot{Q}_i = C_i(\Delta p)^b \quad (5)$$

where C_i ($m^3 s^{-1} Pa^{-b}$) is a flow coefficient. Full descriptions of the models are given in their respective references and so are not repeated here. However, all of the models discussed here assume that energy and mass conservation is observed, flow characteristics are constant in the mean, the zone is perfectly mixed, and internal air velocities are negligible and do not affect the internal hydrostatic pressure[2].

To help compare the predictions of the models the dimensions of an archetypal apartment are used[11], see Table 1. The apartment has a floor area and height of $54.6m^2$ and 2.6m, respectively, two exposed façades oriented north-south each with an area of $20.3m^2$, an envelope area of $186.2m^2$, and an air leakage index (ALI) of $10m^3/h/m^2$, the maximum permissible for a new UK dwelling[12]. Accordingly, using permeability assumption A(1), $E=1.63\times10^{-4}$ and a standard flow coefficient for each exposed façade is calculated to be $C=10\times2.6\times7.8/(50^{0.66}\times3600)=0.0043 m^3 s^{-1} Pa^{-b}$, where the flow exponent b=0.66, a typical value for ALPs[8]. Windward and leeward façade pressure coefficients, c_p, are 0.603 and −0.452, respectively, and are specifically for a long wall[13]. Air density is $1.21kg/m^3$. Predictions are made for two conditions: wind only, and buoyancy only.

To model the wind only scenario using CONTAM and AIDA, a single ALP is placed at the centre of each façade and u is varied from 1 to 5m/s. When compared to INTERIM for all wind speeds, the predictions of CONTAM are 0.23% lower at all wind speeds, whereas the predictions of AIDA are 0.04% higher. These models predict wind pressure in the same way and so one would not expect to see big differences between their predictions. Variation may be attributed to the different numerical solving techniques and rounding errors.

Dwelling Parameter	Apartment	Terraced House
Width, height, depth (m)	7.8, 2.6, 7	6.2, 5.6, 10.5
Envelope area, A_{env} (m^2)	186.2	317.24
Total exposed façade area, A_{exp} (m^2)	40.56	69.44
Air Leakage Index ($m^3/h/m^2$)	10	10
ACH_{50} (h^{-1})	13.1	8.7
Relative leakage area $E_{A(1)}$, $E_{A(2)}$	1.63×10^{-4}, 7.49×10^{-4}	1.63×10^{-4}, 7.46×10^{-4}
Wind scaling height (m)	5.4	5.6

Table 1. Properties of an archetypal apartment[11] and terraced house[14].

The buoyancy only scenario is also modelled using CONTAM and AIDA where 2 to 11 equally spaced ALPs are placed at heights $z=0$m to $z=H$m at intervals of $H(j-1)^{-1}$ metres (where recall j is the number of ALPs) The internal temperature T_{int} (°C) is 19°C, a mean of recommended internal temperatures for a UK dwelling in winter[15], and the façade flow coefficient for each path is the façade flow coefficient divided by the number of paths present. When compared to INTERIM, for ΔT=10°C, the predictions made with 2 paths using CONTAM are 71% higher, whereas the predictions of AIDA are 68% higher. This overestimation by the modelling tools in relation to INTERIM is expected because the distance between the paths is the maximum possible and is equal to H. Therefore, increasing the number of paths systematically to 11, and reducing their separation, decreases the difference between the predictions of CONTAM and AIDA and those of INTERIM, see Figure 2. When compared to INTERIM for a temperature difference of 10°C, the predictions made with 11 paths using CONTAM are 8.8% higher, whereas the predictions of AIDA are 5.9% higher. Although more exhaustive testing would be beneficial, this inter-model comparison demonstrates reassuring agreement between their predictions.

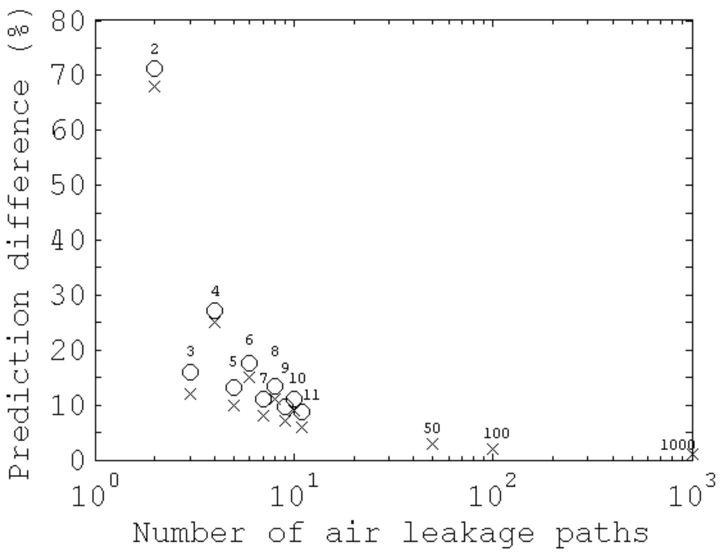

Figure 2: Percentage difference between the predictions of CONTAM and AIDA and INTERIM for a varying number of ALPs. ×, AIDA; ○, CONTAM; Number of ALPs. Wind velocity, 0 m/s; ΔT=10°C; H=2.6 m.

Based on the increased confidence in the predictions of INTERIM and as an interesting aside, we ask the question: what is the optimum number of ALPs when modelling infiltration using an envelope flow model? For this study, the data input of ALPs into CONTAM is done manually whereas data input into AIDA is automated. Using AIDA the number of ALPs on each façade is increased successively to 50, 100, and 1000, and its predictions are reduced to 2.6%, 1.8% and 1.22%, respectively, above those of INTERIM. This analysis suggests the difference between the predictions of the models reduce as the number of paths located on each façade approaches infinity asymptotically, but with diminishing returns, see Figure 2. However, for all practical purposes, 11 paths is close enough to infinity for a reasonably accurate prediction of buoyancy driven infiltration using a conventional envelope flow model such as CONTAM or AIDA.

Figure 2 shows that an odd number of ALPs gives better agreement than an immediately higher even number. An odd spacing places an ALP at the neutral height where the pressure difference across it and airflow through it is zero. Thus, the porosity of the wall reduces and better agreement is achieved, albeit artificially. Increasing the number of paths reduces the effect of this anomaly.

MODEL APPLICATION

The simplicity of the INTERIM model means that calculation time is significantly less than that for a CONTAM or AIDA model with a large number of ALPs. INTERIM is thus a useful tool for undertaking the simulations necessary to investigate the infiltration one might expect to find in a conjoined dwelling subjected to varying climatic conditions. The CIBSE Test Reference Year (TRY) weather data set[16] is a synthesised typical weather year suitable for analysing the environmental performance of buildings in the UK. Data exists for 14 locations, both coastal and inland, varying in latitude from 50.35°N to 55.95°N and longitude from 6.22°W to 1.36°E. Accordingly, these data are applied to the archetypal apartment (now considered to be located on the 1st floor) between 1st October and 1st March, thus simulating the heating season when purpose-provided ventilation is at a minimum. The rate of heat loss (W) via infiltration is given by

$$H(t) = \dot{M}_{inf} c \Delta T \tag{6}$$

where c is the specific heat capacity of air is (c=1 kJ kg^{-1}K^{-1}) and ΔT (K) is the difference between the internal and external air temperatures. ΔT is evaluated with internal air temperature T_{int}=19°C when external air temperature T_{ext}≤16°C. Otherwise, following Lowe[9]

$$T_{int} = T_{ext} + 3e^{-(T_{ext}-16)/3} \tag{7}$$

to account for the tendency of T_{int} to increase at the beginning and end of the heating season as T_{ext} rises. Equation (7) employs a *base temperature*[15] of 16°C; this is chosen because the heating system of an average UK dwelling begins to operate when $T_{ext} \leq T_{int} - 3$°C[17]. Accordingly, the rate of heat loss is not recorded when T_{ext}>16°C because it is assumed that the heating system is off. Heat loss (kW) is estimated over periods of t=1 hour and so it is easily converted to the total energy lost by operational air leakage (kWh).

Wind speed is scaled for an urban environment using the power law formula with a coefficient of 0.35 and an exponent of 0.25[18]. Façade wind pressure coefficients are varied according to the wind direction using the distribution described previously. The relative leakage area is varied according to the two permeability assumptions so that under A(1), $A_{50}=A_{env}$; and under A(2) $A_{50}=A_{exp}$. Therefore, $E_{A(1)}=1.63\times10^{-4}$ and $E_{A(2)}=7.49\times10^{-4}$, respectively. All other variables are identical to those given in Table 1.

Table 2 gives the predicted mean, median, and standard deviation (σ) infiltration rate in air changes per hour (ACH) in an archetypal apartment during the heating season for the two limiting permeability assumptions in each city and overall. Also given is total heat loss (kWh) for each city and the overall mean value. For this example, if permeable party walls are assumed, the infiltration rate is below 0.5ACH, which is recommended by many European countries as a threshold ventilation rate above which some negative health effects reduce[19]. Under these circumstances, additional purpose-provided ventilation would be required. If impermeable party walls are assumed, the opposite is true, highlighting the importance of the assumption about the behaviour of party walls. Table 2 also shows when party walls are considered to be permeable the ratio of airflow rates at pressure to those under operational conditions is much greater than that given in Equation (1), whereas when party walls are considered to be impermeable the ratio is very close to that given in Equation (1). This suggests that Equation (1) was originally formulated from measurements made in dwellings that either had no party walls or impermeable party walls, and required little scaling. A rough sensitivity analysis of the model shows that rotating the apartment through 90° increases average infiltration rates by 7% and so the simulations obtained here stand.

Location	Assumption A(1): Permeable party walls				Assumption A(2): Impermeable party walls			
	mean ACH	**median ACH**	**σ ACH**	**total heat loss**	**mean ACH**	**median ACH**	**σ ACH**	**total heat loss**
Belfast	0.16	0.13	0.11	470	0.74	0.60	0.52	2156
Birmingham	0.14	0.10	0.10	385	0.63	0.45	0.47	1767
Cardiff	0.15	0.12	0.11	401	0.68	0.55	0.49	1839
Edinburgh	0.14	0.10	0.12	421	0.66	0.45	0.55	1931
Glasgow	0.15	0.09	0.12	441	0.68	0.44	0.56	2025
Leeds	0.10	0.07	0.07	283	0.46	0.32	0.33	1299
London	0.12	0.09	0.09	305	0.57	0.39	0.42	1401
Manchester	0.14	0.10	0.11	395	0.66	0.47	0.51	1812
Newcastle	0.11	0.08	0.09	326	0.52	0.36	0.39	1496
Norwich	0.15	0.11	0.12	415	0.69	0.50	0.55	1904
Nottingham	0.13	0.10	0.09	391	0.60	0.46	0.42	1794
Plymouth	0.20	0.15	0.16	442	0.90	0.69	0.76	2030
Southampton	0.08	0.06	0.05	216	0.37	0.29	0.25	991
Swindon	0.16	0.12	0.13	471	0.75	0.57	0.58	2161
TOTAL	**0.14**	0.10	0.11	mean 357	**0.64**	0.44	0.52	mean 1640
$\dot{Q}_{50}:\dot{Q}_4$	**94.4**				**20.6**			

Table 2. Predicted infiltration air changes per hour (h^{-1}) and total heat loss (kWh) during heating season in an archetypal apartment for two limiting permeability assumptions. Permeability, $10\,m^3/h/m^2$; A_{env}:A_{exp}, 4.59.

Location	Assumption A(1): Permeable party walls				Assumption A(2): Impermeable party walls			
	mean ACH	**median ACH**	**σ ACH**	**total heat loss**	**mean ACH**	**median ACH**	**σ ACH**	**total heat loss**
Belfast	0.12	0.09	0.07	879	0.53	0.40	0.32	4015
Birmingham	0.10	0.08	0.06	748	0.46	0.34	0.28	3419
Cardiff	0.11	0.08	0.07	746	0.49	0.37	0.30	3408
Edinburgh	0.11	0.08	0.07	823	0.49	0.34	0.34	3760
Glasgow	0.11	0.08	0.08	867	0.50	0.35	0.34	3960
Leeds	0.08	0.07	0.04	582	0.36	0.30	0.19	2657
London	0.09	0.07	0.06	599	0.42	0.32	0.26	2736
Manchester	0.10	0.08	0.07	754	0.48	0.34	0.31	3443
Newcastle	0.09	0.07	0.05	646	0.39	0.31	0.23	2950
Norwich	0.11	0.08	0.08	786	0.50	0.35	0.34	3591
Nottingham	0.10	0.08	0.05	753	0.44	0.34	0.25	3439
Plymouth	0.14	0.10	0.11	813	0.63	0.45	0.48	3713
Southampton	0.07	0.06	0.03	473	0.30	0.27	0.14	2162
Swindon	0.12	0.08	0.08	876	0.53	0.38	0.36	4000
TOTAL	**0.10**	0.07	0.07	mean 690	**0.47**	0.34	0.32	mean 3150
$\dot{Q}_{50}:\dot{Q}_4$	**85.4**				**18.7**			

Table 3. Predicted infiltration air changes per hour (h^{-1}) and total heat loss (kWh) during heating season in an archetypal terraced house for two limiting permeability assumptions. Permeability, $10\,m^3/h/m^2$; A_{env}:A_{exp}, 4.57.

INTERIM is now used to assess the infiltration rate of a terraced house[14], using the properties given in Table 1 and CIBSE weather data. In a similar pattern to that of the apartment, the mean infiltration rate during the heating season is predicted to be $0.1h^{-1}$ when party walls are considered permeable, and $0.47h^{-1}$ when they are not, see Table 3. The leakage-infiltration ratios are predicted to be 85.4 and 18.7, respectively. Rotating the terrace through 90°C increases the infiltration rate by 5%. Accordingly, these predictions for an archetypal terrace house confirm the patterns of infiltration behaviour identified by the analysis of an archetypal apartment.

Consideration of Equation (4) demonstrates that the predictions made by INTERIM for the two party wall permeability assumptions are related by a simple ratio of the two effective leakage areas $E_{A(2)}$: $E_{A(1)}$, and by the exposed façade area to envelope areas A_{env}:A_{exp}; they both give the same value. Accordingly, the predictions made assuming permeable party walls can easily be scaled to identify those for impermeable part walls. For example, converting from the predicted mean ACH for the apartment for permeable party walls (see Table 2) to that for impermeable party walls is $ACH_{A(2)}=ACH_{A(1)}(A_{env}:A_{exp})=0.14(186.2/40.56)=0.64h^{-1}$. This means that Equation (1) can be amended according to one's knowledge of party wall permeability. The ability to scale infiltration rate means that it is also possible to scale predictions of total energy loss.

There are several consequences of these findings. If permeability assumption A(1) is true and party walls are indeed permeable, then conjoined dwellings do not experience the rate of operational infiltration predicted by Equation (1). Accordingly, annual energy lost via operational air leakage is also less than one might expect, see Tables 2 and 3. The payback period of retrofitted energy efficient measures (required to mitigate greenhouse gas emissions) designed to increase the air tightness of a conjoined dwellings would increase dramatically. The lower than expected airflow rates could also have health consequences by allowing the build-up of pollutants from internal sources, such as fine particulate matter, moisture, carbon monoxide, and radon. However, if permeability assumption A(2) is true and party walls are already impermeable then a sensible energy efficiency measure is the tightening of exposed façades. Although the dwelling types and weather data applied here from the UK, the findings can be applied by the policy makers of any country with a large number of conjoined dwellings and for those building codes that apply Equation (1) in some form.

CONCLUSIONS

This paper presents an analysis of infiltration rates in conjoined dwellings based on two limiting assumptions of party wall permeability at high pressure. The first assumption assumes that party walls are permeable, and in this instance the leakage-infiltration ratio is predicted to be significantly greater than that used by building codes to evaluate the energy and environmental performance of dwellings. The second assumption assumes that party walls are impermeable and here the leakage-infiltration ratio is predicted to be close to that used in practice. With this knowledge, it is now possible to amend the leakage-infiltration ratio for a given application, and to use it to make informed decisions on the implementation of energy efficiency measures. These findings have significant energy and health implications and should be of great interest to the policy makers of any country with a large number of conjoined dwellings. Finally, the paper also provides evidence for AIVC guidance on the modelling of infiltration using envelope flow models where none existed previously.

ACKNOWLEDGEMENTS

The authors are grateful to the European Commission for its funding of the PURGE project by its 7th Framework Programme under grant agreement number 265325. They are also grateful to Elina Manelius of Tampere University of Technology, Finland, for her guidance on Finnish building regulations.

REFERENCES

[1] HM Government, 2010. The Building Regulations 2000 (2010 edition): Approved Document L1A: Conservation of fuel and power in new dwellings. Crown Copyright 2010.

[2] Etheridge, D.W. 2012. *Natural Ventilation of Buildings: Theory, Measurement and Design*, John Wiley & Sons.

[3] Younes, C., Shdid, C.A., and Bitsuamlak, G. 2012 Air infiltration through building envelopes: A review. *Journal of Building Physics* **35**(3), 267-302.

[4] Sherman, M.H., 1987. Estimation of infiltration from leakage and climate indicators. *Energy and Buildings* **10**(1), 81-86.

[5] Ministry of the Environment of Finland. 2012. National Building Code of Finland, Part D5: Calculation of power and energy needs for heating of buildings, Department of the Built Environment, Ministry of the Environment, Finland.

[6] Stephen, R. 1998. Airtightness in UK dwellings: BRE's test results and their significance, Building Research Establishment.

[7] DCLG. 2011. English Housing Survey: Headline report 2009-10. London, Department for Communities and Local Government.

[8] Orme, M., and Leksmono, N. 2002. Ventilation Modelling Data Guide - GU05. Air Infiltration and Ventilation Centre, Brussels, Belgium.

[9] Lowe, R.J. (2000) Ventilation strategy, energy use and CO_2 emissions in dwellings - a theoretical approach. *BSERT* **21**(3), 179-185.

[10] Walton, G.N., and Dols, W.S. 2005. CONTAMW 2.4 User Guide and Program Documentation, NISTIR 7251. Gaithersburg, MD.

[11] Shrubsole, C., Ridley, I., Biddulph, P., Milner, J., Vardoulakis, S., Ucci, M., Wilkinson, P., Chalabi, Z., and Davies, M. 2012. Indoor $PM_{2.5}$ exposure in London's domestic stock: modeling current and future exposures following energy efficient refurbishment. *Atmospheric Environment.* **62**, 336-343.

[12] HM Government, 2010. The Building Regulations 2000 (2010 edition): Approved Document F1: Means of Ventilation. Crown Copyright 2010.

[13] Swami, M and Chandra, S. 1987. Procedures for Calculating Natural Ventilation Airflow Rates in Buildings, ASHRAE.

[14] Oikonomou, E., Davies, M., Mavrogianni, A., Biddulph, P., Wilkinson, P. and Kolokotroni, M. The relative importance of the urban heat island and the thermal quality of buildings for overheating in London. *Building and Environment* **57**(0), 223-238.

[15] CIBSE. 2006. *Guide A - Environmental Design*. London, CIBSE Publications.

[16] CIBSE. 2002. Guide J - Weather, Solar and Illuminance data. London, CIBSE Publications.

[17] Hamilton, I, *et al.* 2011. The impact of housing energy efficiency improvements on reduced exposure to cold — the 'temperature take back factor'. *BSERT* **32**(1), 85-98.

[18] BSI, 1991. BS5925 - Code of Practice for Ventilation Principles and Designing for Natural Ventilation. London.

[19] Dimitroulopoulou, C. 2012. Ventilation in European dwellings: A review. *Building and Environment* **47**(0), 109-125.