

Modelling Ventilation and Infiltration within the Home Energy Model

A technical explanation of the methodology

Acknowledgements

This methodology has been developed for the Department for Energy Security & Net Zero by a consortium led by the Building Research Establishment (BRE), including AECOM, Sustenic, University of Strathclyde's Energy Systems Research Unit, Kiwa Ltd., Loughborough University Enterprises Limited, Chris Martin and John Tebbit.

Quality assurance has been undertaken by a consortium led by Etude, including Levitt Bernstein, Julie Godefroy Sustainability, and UCL.

Document reference: HEM-TP-06

Document version: v1.0

Issue date: 13/12/23

Home Energy Model version: HEM v0.24



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Contents

Background to the Home Energy Model	4
What is the Home Energy Model?	4
Where can I find more information?	4
Related content	5
Methodology	6
1. Overview	6
2. Ventilation – Uncontrolled / Infiltration	6
3. Ventilation – Purpose-built openings	7
4. Ventilation – Controlled	8
4.1 Intermittent mechanical extract ventilation with background ventilators	10
4.2 Continuous mechanical extract ventilation with background ventilators	11
4.3 Mechanical ventilation with heat recovery	11
4.4 Summary of controllable ventilation air change rates	13
5. Calculation of ventilation and infiltration heat loss	14
6. Mechanical ventilation electricity consumption	16
7. Overventilation requirements	16
Future development	17
Annex A – Derivation of conversion from N4 to N50	18
Annex B – Flow rates for purpose-built openings and intermittent extract fans	21
Summary of evidence	21
Summary of air flow rates	25
References	27
Annex C - Extract from George Henderson/Gastec at CRE report	28
Calculations of flow rates in chimneys	28
Incorporation of test results into SAP	33

Background to the Home Energy Model

What is the Home Energy Model?

The [Home Energy Model \(HEM\)](#) is a calculation methodology designed to assess the energy performance of homes, which will replace the government's [Standard Assessment Procedure \(SAP\)](#).

The Home Energy Model is still under development and its first version will be implemented alongside the [Future Homes Standard \(FHS\)](#) in 2025. We are publishing information about the model while it is still at a formative stage to enable industry to participate in the ongoing development process.

Where can I find more information?

This document is part of a wider package of material relating to the Home Energy Model:

Home Energy Model technical documentation (e.g. this document)

What: This document is one of a suite of [technical documents](#), which go into further detail on the methodology and the validation exercises that have been carried out. We intend to update and produce further technical documentation throughout the model development process.

Audience: The technical documentation will be of interest to those who want to understand the detail of how the Home Energy Model works and how different technologies are treated.

The Home Energy Model consultation

What: The [Home Energy Model consultation](#), which explains the overhaul to the SAP methodology and seeks views on the approach taken by the new Home Energy Model.

Audience: The Home Energy Model consultation will be of interest to those who want to understand the proposed changes to the SAP methodology and wider SAP landscape.

The Home Energy Model reference code

What: The full Python source code for the Home Energy Model and the Home Energy Model: FHS assessment has been published as [a Git repository](#). This code is identical to that sitting behind the consultation tool. We are currently considering whether the open-source code could serve as the approved methodology for regulatory uses of the Home Energy Model.

Audience: The reference code will be of interest to those who want to understand how the model has been implemented in code, and those wishing to fully clarify their understanding of the new methodology. It will also be of interest to any potential contributors to the Home Energy Model.

Related content

Ventilation of dwellings is required to provide fresh air, but this leads to heat loss as warm air leaves the dwelling and is replaced with colder air from outside. The rate of this heat loss depends on the rate of air flow and the temperature difference between incoming and outgoing air. Air flow may be intentional, to provide adequate ventilation via passive or mechanical means, or unintentional, due to air leakage through the fabric of the building.

For more information on how the ventilation and infiltration heat loss is accounted for in the space heating and cooling demand calculations, see HEM-TP-04 Space heating and cooling demand.

To understand how this methodology has been implemented in computer code, please see:

src/core/space_heating_demand/ventilation_element.py

src/core/space_heating_demand/zone.py

Methodology

1. Overview

The Home Energy Model (HEM) firstly calculates the dwelling's background/uncontrolled infiltration rate allowing for local sheltering based on an airtightness measurement using the methods described in CIBSE Guide A and BS5925. The controlled ventilation rate (as provided either through background ventilators with intermittent extract fans or a mechanical ventilation system) as required in Part F to the Building Regulations is entered into HEM. The two rates are then combined to derive an overall air change rate which is used to calculate the dwelling's ventilation heat loss.

2. Ventilation – Uncontrolled / Infiltration

The Home Energy Model (HEM) expects an air tightness measurement¹ at either 50 Pa or 4 Pa to be provided in air changes per hour (ach). Where the air tightness measurement has been obtained through a test at 4 Pa, HEM converts the associated air change rate N_4 (in air changes per hour, or ach) into the equivalent N_{50} (in ach) using equation 1 below, allowing for the geometry of the dwelling (see [Annex A](#) for the origin of this equation).

$$N_{50} = 5.2540 \times (N_4)^{0.9241} \times \left(\frac{\text{dwelling envelope area}}{\text{dwelling volume}} \right)^{1-0.9241} \quad (1)$$

This N_{50} air tightness (measured directly or calculated from N_4) is then divided by an appropriate divisor to give the infiltration rate for a dwelling under the typical driving pressures produced by the wind and stack effect. The divisor is intended to give an average infiltration rate over the course of, for example, one year for a dwelling in 'typical' circumstances. These infiltration rates vary significantly as wind and temperature conditions change and in different locations where levels of sheltering are greater or lesser.

Divisors for different dwelling types (i.e., houses and flats of different storeys) are given in CIBSE Guide A, Table 4.24. To extend the divisors in Table 4.24 to account for different levels of shelter the guidance in section 4.6.1.2 of CIBSE Guide A was used. Specifically, this states that on severely exposed sites, a 50% increase above the tabulated values should be allowed

¹ This measurement is assumed to have been conducted under the current approved airtightness methodology (BS EN ISO 9972:2015, Method 3, as described in CIBSE TM23, 2020. This means that all openings, vents etc. that have been provided for the purpose of ventilation should be closed (but not sealed), except if no closing mechanism exists in which case temporary sealing may be used. This differs from other methodologies (e.g. Passivhaus) where openings, vents etc. should be tested in the state they would be in during normal operation (e.g. trickle vents would be open). Both AP50 (m3/m2/hr) and N_{50} (ach) values should be reported on an air tightness test certificate. The AP50 and N_{50} values can be quite similar numerically depending on a dwelling's geometry, but HEM bases its infiltration calculations on N_{50} (ach) to improve accuracy and to be consistent with the supporting standards.

and on sheltered sites, the infiltration rate may be reduced by 33%. Extending this logic, it was assumed that for very sheltered sites a 50% decrease was reasonable. Divisors for flats on the 11th storey or higher were derived by extrapolating wind speeds for each shelter category using the methods in BS 5925.

Based on this data, a set of divisors to use with the N50 (ach) measurement was derived; these are shown in Table 1.

	Very sheltered [City]	Sheltered [Urban]	Normal [Country with scattered windbreaks]	Exposed [Open flat country]
House: 1-storey	41.2	30.7	20.6	13.7
House: 2-storey	34.0	25.4	17.0	11.3
Flat (Storeys 1-5)	34.6	25.8	17.3	11.5
Flat (Storeys 6-10)	30.2	22.5	15.1	10.1
Flat (Storeys 11+)	29.3	19.9	13.7	9.3

Table 1 – Divisors used to convert the N50 pressure test figure into an infiltration rate

Applying the appropriate divisor gives an infiltration rate, Qv (ach). The infiltration rate for the dwelling for each hour can then be calculated depending on the wind speed from the weather data file. This is normalised to the annual UK average wind speed of 4 m/s (at a height of 10m above the ground)². As an example, if the average wind speed in an hour is 3.8 m/s then the infiltration rate in that hour is calculated to be $Qv * (3.8/4)$.

This method still only provides an approximate assessment and does not reflect local conditions like prevailing wind direction. It also does not fully consider stack effect which might be the dominant driving force at certain times of the day or year. Further work is needed to address this and would require development of a more detailed infiltration model (see [Future development section](#)).

3. Ventilation – Purpose-built openings

The ventilation rate from chimneys, flues and other purpose-built openings is calculated based on user input of the number of each type of opening and the flow rates from Table 2. These flow rates are based on research summarised in [Annex B](#)³.

² This wind speed and height was also assumed in CIBSE Guide A, Table 4.24.

³ These flow rates are unchanged from SAP 10.2

Opening Type	Average air flow rate (m^3/h)
Open chimney	80
Open flue	20
Chimney/flue attached to closed fire	10
Flue attached to solid fuel boiler	20
Flue attached to other heater	35
Blocked chimney	20
Passive stack vent	10
Flueless gas fire	40

Table 2 – Flow rates assumed through chimneys and flues

The flow rates due to these openings are then summed and multiplied by a shelter factor based on the number of dwelling sides that are sheltered. The shelter correction factor reflects how wind pressures on housing models vary under different sheltered conditions as presented in documents such as CIBSE Guide A and AIVC Guide 5 Ventilation Modelling Guide. The shelter factor is calculated from the number of sheltered sides (which is a user-input integer between 0 and 4 inclusive) as shown in equation 2:

$$\text{shelter factor} = 1.0 - (0.075 \times \text{no. of sheltered sides}) \quad (2)$$

The resulting flow rate after applying the shelter factor is then adjusted for wind speed in the same way as the flow rate due to infiltration (see previous section). Note that in the next section, on controlled ventilation, references to “infiltration rate” include the contribution from purpose-built openings.

4. Ventilation – Controlled

HEM also models the provision of controlled ventilation of the following types⁴:

- Intermittent mechanical extract ventilation with background ventilators (Intermittent MEV)⁵

⁴ Note that positive input ventilation (PIV), either from outside or from loft, has not been implemented at the time of writing. PIV can be used to provide ventilation in a dwelling provided it can be demonstrated that it meets the requirements of Part F which is likely to entail delivering ventilation rates comparable to continuous MEV, MVHR etc.

⁵ Note that in Part F this is referred to as natural ventilation with background ventilators and intermittent extract fans. Note also that the naming of this type of ventilation in this document is not intended to imply that intermittent extract fans are the dominant cause of air flow – it is likely that wind or stack driven air flow will be the most significant component.

- Continuous mechanical extract ventilation with background ventilators (Continuous MEV)
- Balanced mechanical ventilation with heat recovery (MVHR)⁶

Note that an MVHR system would not have background ventilators.

In all the above cases, HEM requires the user to input the number of air changes per hour required, which should be the as-designed or as-commissioned air change rate for the dwelling:

- For MVHR and Continuous MEV systems, [draft Approved Document F, Volume 1: Dwellings](#), Table 1.3 specifies a minimum volume flow rate based on the number of bedrooms and/or total floor area, which is typically in the range 0.45 to 0.55 ach. Note, however, that HEM does not currently check whether the value entered is in fact compliant with Part F, so users should ensure that it is.
- For Intermittent MEV a whole house ventilation rate is not easily defined from the Part F background ventilator area requirements. However, it is intended to deliver an equivalent performance to an MVHR or Continuous MEV solution so users should enter a required air change rate calculated in the same way as Approved Document F specifies for MVHR and Continuous MEV.
- For Continuous MEV systems and for Intermittent MEV, Part F specifies the required area for background ventilators (e.g. trickle vents) which is not directly used in the current HEM calculation, although their contribution is recognised in an approximate way (see relevant sections below).

To derive an overall air change rate HEM adjusts the controlled ventilation rate depending on the infiltration rate⁷ and type of ventilation system using a series of semi-empirical equations given below and summarised in figures 1 and 2. The original basis of these equations is unclear, but they are intended to reflect the fact that occupants can control the amount of ventilation (for example, closing them to avoid draughts under windy conditions, and subsequently opening them to boost ventilation). Part F also specifies a minimum opening area for windows to provide additional (purge) ventilation during, for example, calm conditions.

Although Part F states that background (trickle) ventilators should be left open, evidence^{8,9,10} indicates that although householders say they are aware of trickle ventilators, their use of them is limited and, in most cases, the vents are left in the closed position. The evidence shows that householders prefer to open windows to provide the ventilation they require which they do periodically (e.g. once a day or a few times a week) to manage moisture, heat and improve indoor air quality. Evidence⁹ on the use decentralised MEV systems in homes shows that the majority failed to have the extract fan flow rate and/or trickle vent area required by Part F, and

⁶ Note that balanced mechanical ventilation without heat recovery can be modelled as MVHR with heat recovery efficiency of zero.

⁷ Note that this includes air flow through purpose-built openings, as stated in the previous section.

⁸ Ventilation and Indoor Air Quality in Part F 2006 Homes. Report BD502 for CLG (March 2010)

⁹ [Ventilation and Indoor Air Quality in New Homes. Report for MHCLG \(September 2019\)](#)

¹⁰ https://www.researchgate.net/publication/280712247_Occupant_Interactions_and_Effectiveness_of_Natural_Ventilation_Strategies_in_Contemporary_New_Housing_in_Scotland_UK

in over half of cases the fans were not in continuous operation as they were only used intermittently by householders or even turned off altogether.

Whilst the equations referred to above do allow occupants to exercise control over ventilation, HEM still uses a minimum controlled ventilation rate that meets the requirements of Part F. In other words, the ventilation rate never falls below this level. As shown in Figure 3 below, HEM predicts a ventilation rate for new dwellings of about 0.5 to 0.6 ach for much of time. The overall aim of the equations therefore is to ensure a ventilation rate in accordance with Part F requirements which occupants can also control to prevent ventilation being excessive. It is acknowledged that this is an area which is poorly understood and would benefit from further development. Feedback from consultees is welcome.

Performance characteristics (e.g. specific fan power, heat recovery efficiency etc.) for individual mechanical ventilation systems are expected to be available eventually on the Product Characteristics Database (PCDB) (or future equivalent) when it has been developed (although a default product may be provided for use where the actual system is not in the database). At present, these performance characteristics are user inputs.

4.1 Intermittent mechanical extract ventilation with background ventilators

Additional air flow provided by operation of intermittent extract fans is included in the infiltration rate in the same way as for purpose-built openings (see previous section). An average flow (including periods when the fan is not running) of $10\text{m}^3/\text{hr}$ per fan is assigned, the derivation of which is described in [Annex B](#).

In this case the total air change rate is calculated from the final infiltration rate as follows¹¹:

If infiltration_rate < 2 × air_change_rate_req:

$$Ach_{total} = air_change_rate_req + (infiltration_rate^2 \times (0.25 / air_change_rate_req))$$

Otherwise:

$$Ach_{total} = infiltration_rate$$

No specific allowance is included for controlled ventilation through background ventilators. However, the equation above effectively includes a generic allowance for background ventilators in more airtight dwellings where the ventilation rate through background ventilators is assumed to vary between the rate required by Part F and zero, depending on the infiltration rate (as shown in Figure 3). HEM does not assume perfect control between these two points (i.e., the total air change rate in this case is not just the minimum of the Part F requirement and the infiltration rate).

¹¹ This approach is unchanged from SAP 10.2. The required air change rate figure of 0.5 in SAP 10.2 was taken from BRE Digest 398: Continuous mechanical ventilation in dwellings: design, installation and operation.

4.2 Continuous mechanical extract ventilation with background ventilators

Note that if the dwelling has Continuous MEV then the number of intermittent extract fans should always be set to zero.

In this case the total air change rate is calculated as follows¹²:

If infiltration_rate < air_change_rate_req:

$$Ach_{total} = air_change_rate_req + (infiltration_rate^2 \times 0.5 / air_change_rate_req)$$

Otherwise:

$$Ach_{total} = infiltration_rate + (0.5 \times air_change_rate_req)$$

No specific allowance is included for controlled ventilation through background ventilators. However, the equation above effectively includes a generic allowance for background ventilators in more airtight dwellings where the ventilation rate due to extract fans and background ventilators is assumed to vary between the rate required by Part F and half the rate required by Part F, depending on the infiltration rate (as shown in Figure 3). HEM does not assume perfect control between these two points (i.e. the total air change rate between these two points could be lower and still meet the Part F requirement).

4.3 Mechanical ventilation with heat recovery

Note that if the dwelling has MVHR, then the number of intermittent extract fans should always be set to zero.

In this case the total effective air change rate is calculated as follows¹³:

$$Ach_{total} = infiltration_rate + (1 - efficiency) \times air_change_rate_req$$

This assumes that the MVHR system is set up to provide the full air change requirement in addition to the infiltration rate and there are no background ventilators. It is expected that the heat recovery efficiency will eventually come from a PCDB (or future equivalent) record for the specific product (or failing that a default product); however, it is currently a user input.

Technically, the MVHR system supplies air at a higher temperature than the outside air, i.e.:

$$temp_supply = temp_external_air + efficiency * (temp_internal_air - temp_external_air)$$

¹² This approach is unchanged from SAP 10.2 except that there was previously a sharp transition from a fixed overall air change rate of 0.5 to an overall air change rate increasing linearly with infiltration rate, which essentially assumed perfect control. For HEM, this sharp transition has now been replaced with a smooth curve. The required air change rate figure of 0.5 in SAP 10.2 was taken from BRE Digest 398: Continuous mechanical ventilation in dwellings: design, installation and operation.

¹³ This approach is unchanged from SAP 10.2. The required air change rate figure of 0.5 in SAP 10.2 was taken from BRE Digest 398: Continuous mechanical ventilation in dwellings: design, installation and operation.

However, calculating this requires the internal air temperature, which depends on the air change rate and supply temperature, thus introducing a circularity in the calculation. Therefore, it is simpler to adjust the air change rate to account for the heat recovery effect using an equivalent flow rate of external air. For example, if the MVHR system recovers 85% of the energy from outgoing air, then this means that it has reduced the temperature difference between internal air and incoming air by 85%. Given that the ventilation heat loss is directly proportional to both the air flow rate and the temperature difference, this is the equivalent of reducing the air flow rate by 85% while keeping the original temperature difference, i.e.:

$$\begin{aligned} & constants \times (temperature\ difference \times (1 - efficiency)) \times air\ flow\ rate \\ & = constants \times temperature\ difference \times (air\ flow\ rate \times (1 - efficiency)) \end{aligned}$$

Note that adjusting the air flow rate instead of the temperature difference is only valid when calculating heat loss, and the adjusted air flow rate should not be used in any other context.

Losses from MVHR ductwork are also calculated based on the length and diameter of ducts subject to heat transfer and the duct insulation properties as illustrated in Figure 1. The calculation of total resistance of duct insulation is based on the same principles as the equivalent calculation for hot water pipework described in HEM-TP-10 Ductwork and pipework losses. Note that at the time of writing, HEM assumes that ductwork is cylindrical. The heat loss for each duct is therefore:

$$duct_heat_loss = (temp_inside_duct - temp_outside_duct) / total_resistance * length$$

The ductwork losses are then accounted for in the main space heating calculation in the same way as internal gains. Note that in the case of an MVHR unit outside the thermal envelope of the building, it is the supply and extract ducts that are subject to heat transfer. In the case of an MVHR unit inside the thermal envelope, it is the intake and exhaust ducts that are subject to heat transfer (see Figure 1).

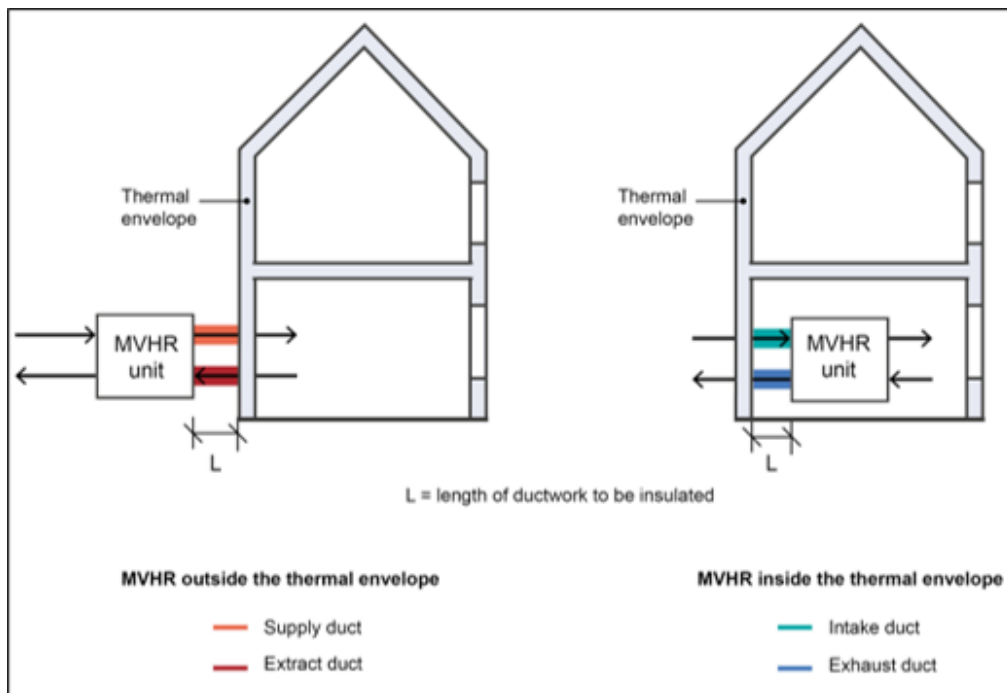


Figure 1 – The section of duct that needs to be insulated depends on the location of the MVHR unit. Length of insulated ducts subject to internal to external temperature difference should be entered in the HEM.

Energy consumption by fans is also calculated (see later in this document) and for MVHR it is assumed that half of this energy adds to internal gains in the dwelling. This is based on the assumption that the energy consumed by fans supplying air to the dwelling heats the incoming air, while the energy consumed by fans extracting air from the building is exhausted along with the extracted air, and that the energy consumption by fans is divided equally between them.

4.4 Summary of controllable ventilation air change rates

Figure 2 shows the air change rate due to controllable ventilation only (and not including intermittent extract fans) which is calculated by subtracting the infiltration rate from the total air change rate. An important point to note is that the infiltration rate range shown here is broad and is unlikely to represent the typical figures that would be seen in a new-build dwelling. Therefore, Figure 2 also highlights the likely range of average infiltration rate that would be seen assuming a measured airtightness of 4 ach @ 50 Pa under normal to sheltered conditions.

Note also that this does not include any adjustment of the air change rate to account for MVHR heat recovery efficiency.

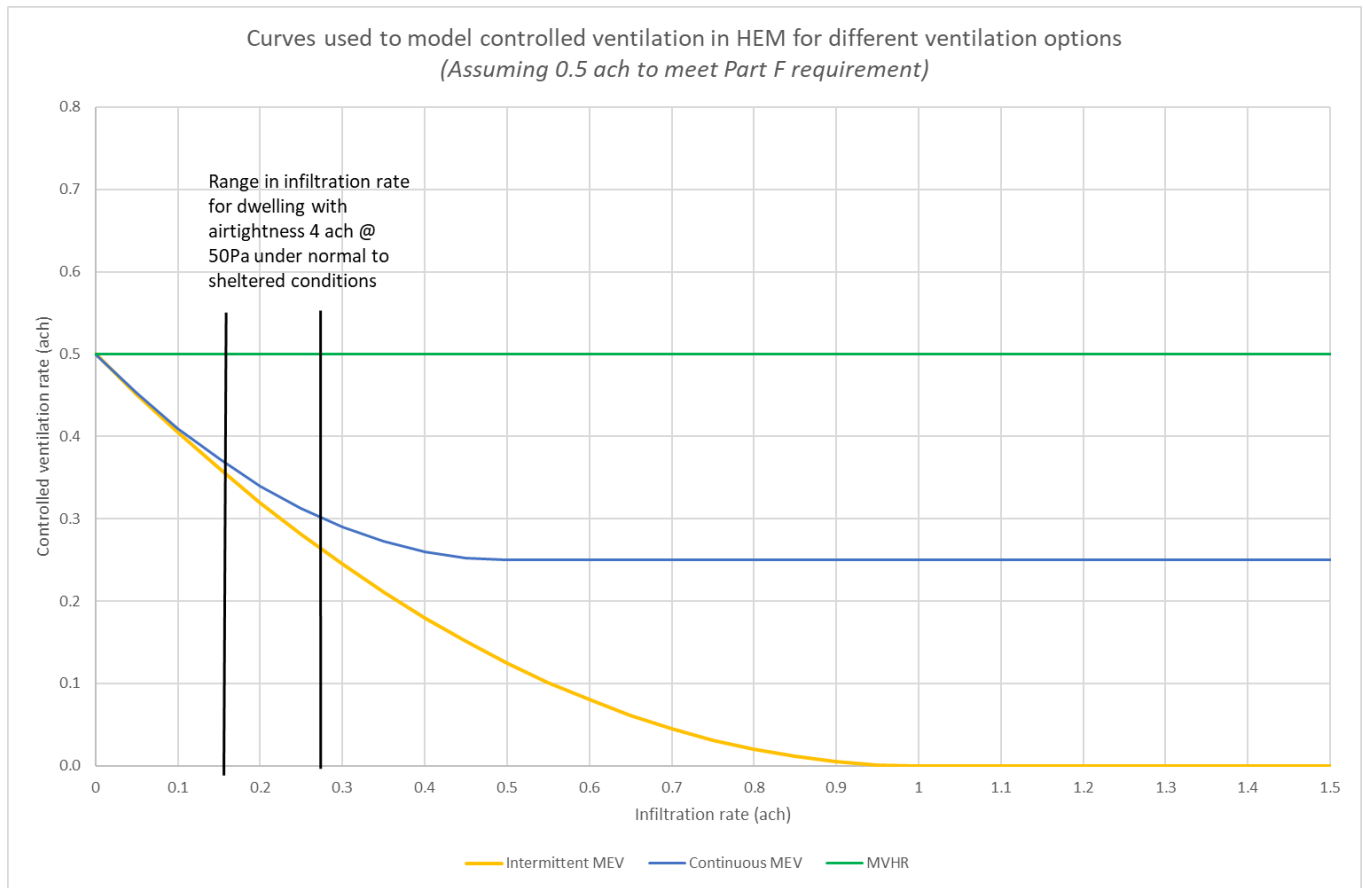


Figure 2 – Variation in controlled ventilation rate for different ventilation options

5. Calculation of ventilation and infiltration heat loss

Figure 3 shows how the total effective air change rate used in the heat loss calculation is assumed to vary with the infiltration rate (which includes the contribution of purpose-built openings and intermittent extract fans). Note that the effective air change rate for MVHR is adjusted according to the heat recovery efficiency (see section above).

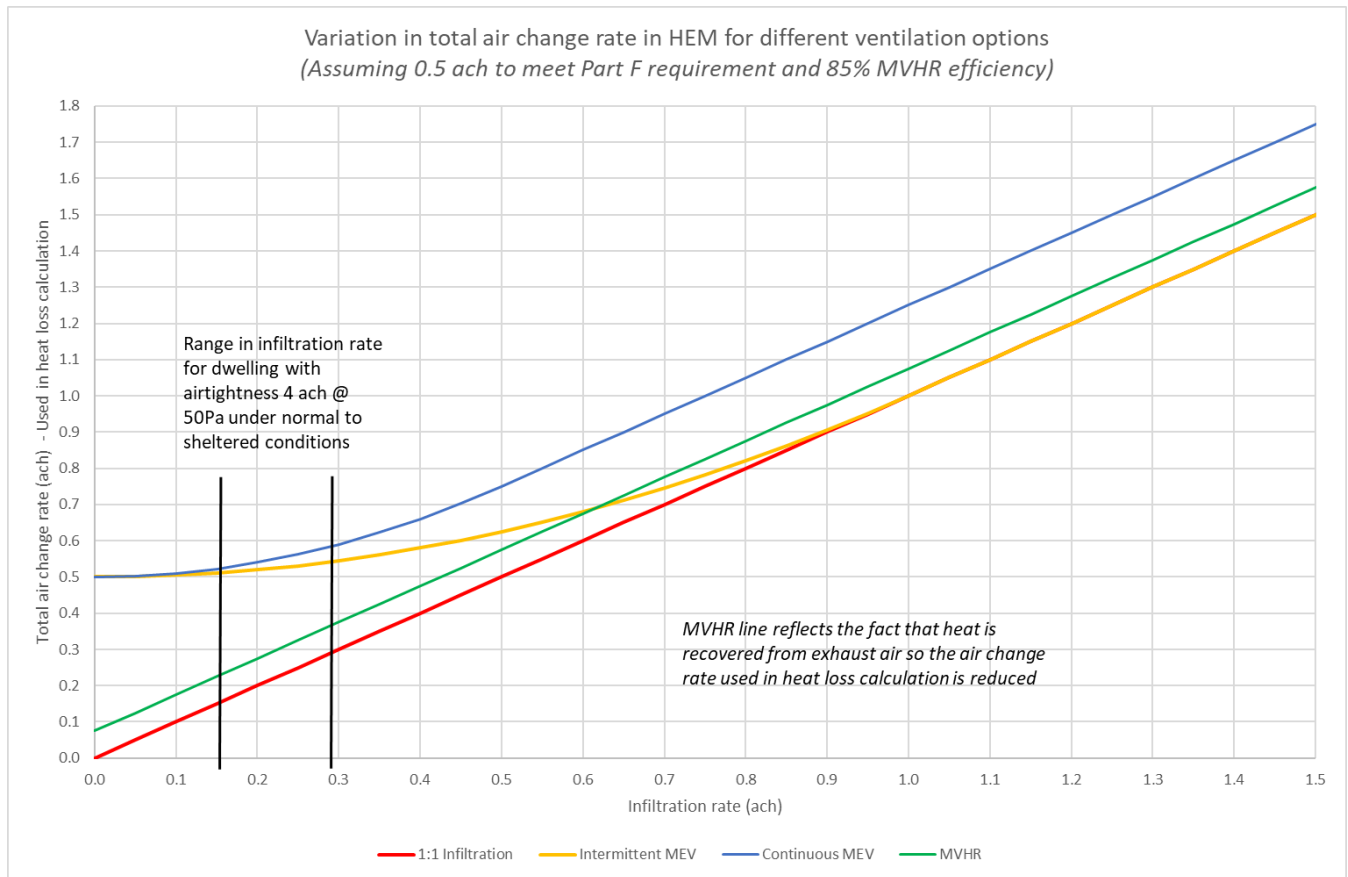


Figure 3 – Variation in total effective air change rate for different ventilation options

As noted above with Figure 2, the infiltration rate range shown here is broad so Figure 3 also highlights the likely range of average infiltration rate that would be seen assuming a measured airtightness of 4 ach @ 50 Pa under normal to sheltered conditions.

The total air change rate is then used¹⁴ in the calculation of the ventilation heat loss coefficient which is a variable in the zone balance equations (see HEM-TP-04 Space heating and cooling demand):

$$q_v = \frac{\text{air changes per hour} \times \text{zone volume}}{3600}$$

$$h_{ve} = \rho_{air} \times c_{air} \times q_v$$

Where:

- q_v is the air flow rate in m³/s.
- 3600 is the number of seconds in an hour.
- h_{ve} is the ventilation heat loss coefficient (a variable in the zone heat balance equations) in W/K.

¹⁴ In the [consultation tool](#), the ventilation heat transfer coefficient is calculated separately for infiltration (including purpose-built openings) and controlled ventilation, and then summed later. This reordering is mainly to facilitate separate reporting of the heat loss due to infiltration and controlled ventilation and has no effect on the final results.

- ρ_{air} is the density of air in kg/m³.
- c_{air} is the heat capacity of air in J/(kg.K).

Note that the ventilation heat loss coefficient is calculated for each timestep, as it depends on the air change rate which is adjusted for wind speed at each timestep.

6. Mechanical ventilation electricity consumption

In the case of mechanical ventilation systems, fans are assumed to run all the time at a single energy consumption rate determined by their specific fan power (this is currently a user input but we expect it will come from the PCDB (or future equivalent) when it has been developed). We note that this may not reflect mechanical ventilation systems with more sophisticated control arrangements.

At present, the HEM calculation software does not apply any adjustments to account for in-situ differences in specific fan power, but these may be applied to the figures stored in the PCDB (or future equivalent) later. We will consider the possibility of introducing in-situ testing in the next phase of model development.

7. Overventilation requirements

In some cases (e.g., exhaust air heat pumps), overventilation may be required under some conditions to give sufficient heat output, so the additional energy associated with this is determined using an overventilation requirement multiplier. See HEM-TP-12 Heat pump methodology for details of this calculation.

Future development

As noted above, there are a range of simplifying assumptions in the derivation of both the infiltration and overall ventilation rates in HEM. A rigorous treatment would require a nodal model where the air flow through each path (e.g., infiltration through the building envelope, air flow through fans and openings etc.) is considered and the mass balance principle applied in order to derive an internal pressure from which the air flow rates can be determined. This is the approach described in BS EN ISO 16798-7:2017 and will be assessed as an alternative to the current method. The extent of data input required to run such a ventilation model would need to be considered and simplifications proposed if deemed necessary.

It was noted above that the assumption that ventilation fans run continuously at a constant rate may not reflect systems with more sophisticated control arrangements. Modelling of variable fan rates and their effect on electricity consumption and overall air change rate could be added in future.

The assumptions on how occupants operate background ventilators will also be revised in future if better evidence is available and could be integrated into any implementation of BS EN ISO 16798-7:2017.

Annex A – Derivation of conversion from N4 to N50

(The work described in this annex was done as part of the development of SAP 10.2)

One method of establishing the air change rate associated with infiltration is to pressurise or depressurise the building and measure the rate at which air leaks into or out of it, via a 'blower door' style air permeability test. This is then converted to an air change rate at typical ambient pressures by dividing it by a suitable divisor.

An alternative method of establishing the air permeability of buildings, by releasing a low-pressure 'pulse' (LPP) of air from a pressurised container within the building, has recently been trialled and shown to give results of comparable reliability to blower door tests in around 100 homes with a good range of air tightness¹⁵. This annex therefore considers how the results of an LPP permeability test result can be used to estimate air change rates.

Rather than the measured air permeability at 50 Pa, as provided by a blower door test, an LPP test provides the air permeability at 4 Pa. For this reason, the divisors used to convert the 50 Pa test result to an air change rate at ambient pressures are not applicable, so a different conversion is needed. Build Test Solutions (who manufacture the LPP system that has been tested) proposed a conversion formula based on analysing data from field trials and comparison with blower door tests, which BRE reviewed alongside the other evidence provided. The derivation is outlined below.

The proposed conversion formula is derived by calculating the ratio of the measured air permeability at 4 Pa (AP4) from an LPP test to the measured air permeability at 50 Pa (AP50) from a blower door test result over a range of leakage rates. The ratio was found to deviate slightly from a constant value of around 5, increasing at lower leakage rates. A power law fit was made to allow for this variation (see Figure A1).

¹⁵ See series of papers here: <https://buildtestsolutions.com/wp-content/uploads/2020/07/Pulse-Test-Reports-as-submitted-to-UK-Government-June-2020.zip>

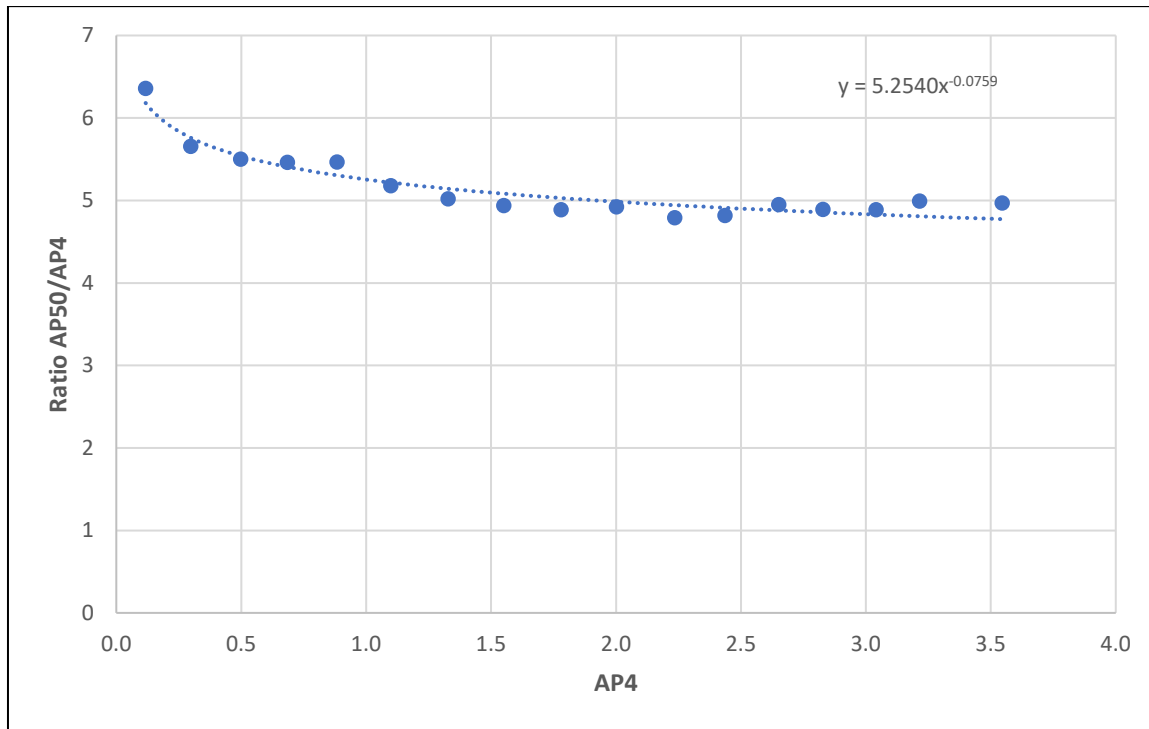


Figure A1 – Ratio of the measured air permeability at 4 Pa (AP4) from an LPP test to the measured air permeability at 50 Pa (AP50) from a blower door test result over a range of leakage rates.

The formula of this fit therefore provides a means to convert an AP4 value to an equivalent AP50 value, which can then be converted to the infiltration rate at ambient pressure conditions on a consistent¹⁶ basis compared to a blower door test.

$$\frac{AP50}{AP4} = 5.254 \times AP4^{-0.0759}$$

Therefore, to get directly from an AP4 to an AP50 we can apply the following formula to an AP4 result:

$$AP50 = 5.254 \times AP4^{0.9241}$$

Using this formula on the original test data (of around 100 homes) gives the comparison of the LPP results (when converted using this formula) and the blower door results for the same dwellings shown in Figure A2, when using the formula above and a divisor of 20 (as per SAP 10.2) to convert to an air change rate at ambient pressure.

¹⁶ That is, consistent including any shortcomings in the existing 50 Pa conversion.

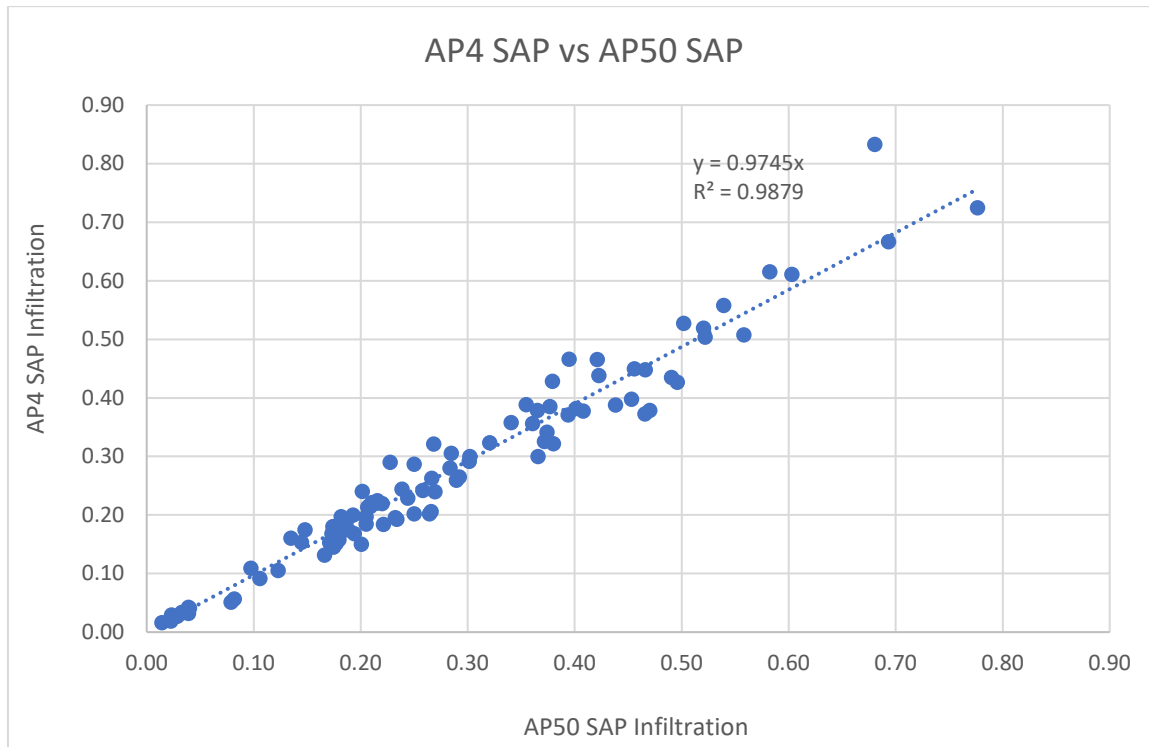


Figure A2 – Comparison of the LPP results (when converted using this formula) and the blower door results for the same dwellings, using a divisor of 20 to convert to an air change rate at ambient pressure.

This shows that the test and conversion methods are to a good approximation equivalent and should give similar outcomes. The relationship described above is in terms of air permeability (AP). To convert the air permeability (AP) value to the air change rate (N) value requires the total dwelling volume (V) and dwelling envelope area (A) which is used by HEM:

$$N_{50} = 5.254 \times N_4^{0.9241} \times \left(\frac{A}{V}\right)^{1-0.9241}$$

Annex B – Flow rates for purpose-built openings and intermittent extract fans

(The work described in this annex was done as part of the development of SAP 10.2 and was previously published as SAP 10 technical paper S10TP-02 “Amendments to SAP’s treatment of the heat loss from chimneys and flues”)

Summary of evidence

A BRE project undertaken in 2015 aimed to measure chimney airflow rates, with fire unlit, in typical occupied dwellings heated by other means. Direct monitoring of volume airflow is difficult so measurement of the driving pressure, the difference between the top and bottom of the chimney, was developed. Following this, a two-step methodology was used.

For dwellings with a chimney and open fireplace:

- The pressure difference between the top and bottom of the chimney was monitored over a period of seven days. No fires were lit and the dwelling was occupied as normal.
- Two airtightness tests were carried out, firstly with, and then without the chimney fireplace opening sealed, over a range of pressure differences. The measured airflow rates at the pressure differences applied were then used to derive an equation relating these two variables.

The dwellings were selected from an invitation to BRE employees or their family/friends. The project involved physical measurements so this should not have resulted in any bias. The chimneys were swept before monitoring due to the risk of disturbed debris and soot causing damage in the room, although it would have been preferable to monitor them ‘as found’. To take account of this, the amount of debris swept out in each dwelling was assessed.

The following factors which may significantly affect the airflow were recorded:

- Dwelling-specific factors, constant over the period of monitoring:
 - ‘airtightness’ of the dwelling as measured by a standard air pressurisation test
 - length of flue and number of storeys
 - chimney throat, damper, flue area, device on chimney pot
- Common factors, not constant over the period of monitoring in each dwelling:
 - temperature internally and externally (the temperature difference)
 - wind speed (from local weather data)

Other factors, such as opening of windows, doors and vents would also cause some variation. Since the results are over a number of days and dwellings, this will have contributed to the experimental variation, and since these factors will be representative of dwellings in normal use, it is not thought that this will bias the average result.

Twenty dwellings were monitored from late February to early April 2015, a period with external temperatures below 10 to 15°C much of the time. During later analysis, problems were encountered with some of the data from three properties, so it was only possible to successfully calculate full results for 17 properties, as shown in Figure B1.

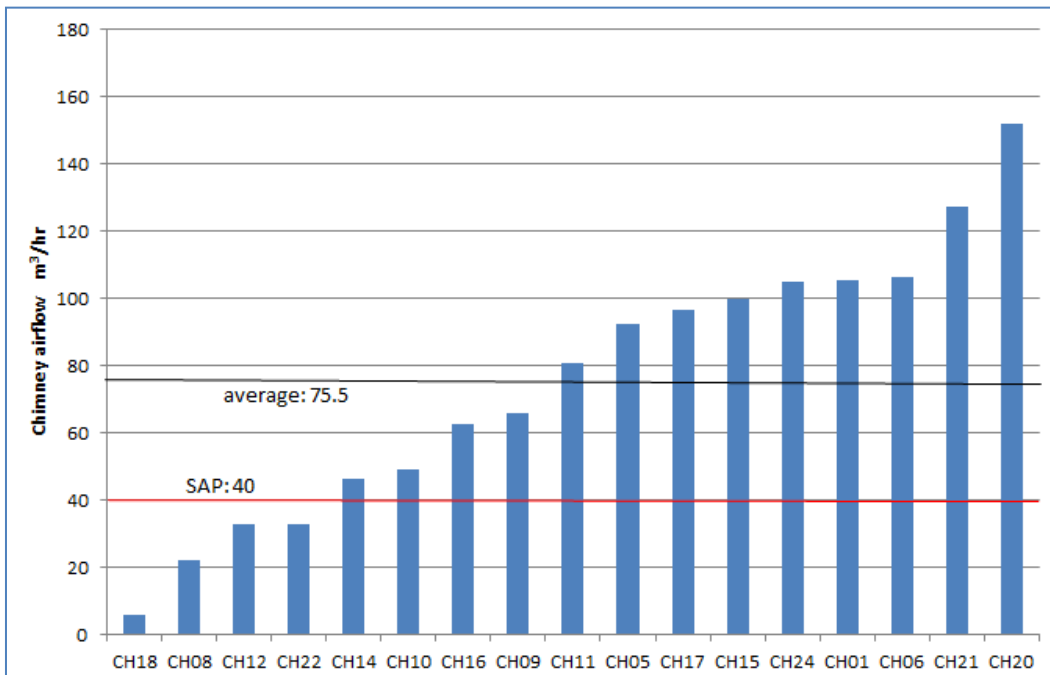


Figure B1 – Calculated seven-day average chimney airflows for 17 dwellings. The line labelled “SAP” shows the air flow rate assumed for chimneys in SAP 2012.

The results indicate seven-day average chimney airflows of between 5 and 150 m3/hr.

- The average of the values is 75.5 m3/hr.
- The standard error is 10 m3/hr, so based on the variability of these results this indicates a 95% probability of the true mean being between 75.5 ± 20 m3/hr.

Analysis for CH08 and CH10 suggests that these may be less reliable results. With these two cases removed, this still gives chimney airflows of between 5 and 150 m3/hr.

- The average of the values is 80.8 m3/hr.
- The standard error is 10.5 m3/hr, so based on the variability of these results this indicates a 95% probability of the true mean being between 80.8 ± 21m3/hr.

Items such as cowls, dampers, and solid floors were recorded, but no features correlated strongly to the airflow measured. A weak correlation was noted for the dwellings with solid floors, which had generally lower airflows; this may restrict the air available for the chimney.

The average temperature and windspeed data from local weather stations during the monitoring were 6.8 to 8.0°C and 4.3 to 5.0 m/s. When compared with 20-year averages of 7.6°C and 5 m/s, this indicates conditions that were representative of the UK average. Compared to the air permeability of 384 dwellings (average 11.5 m³/hr/m²) reported by Stephens¹⁷, the 17 dwellings monitored (average 7.5 m³/hr/m²) are mostly in the lower half of the distribution. However, no correlation was found between the overall airtightness and chimney airflows of the 17 dwellings, suggesting this is not a major factor.

Assessment of the debris swept from each chimney was recorded as blocking the flue airflow 'minimally', 'significantly' or 'substantially'. All except two chimneys were assessed as 'minimally' blocking the airflow.

It is clear from Figure B1 that there is a large variation in the results. A wide variety of factors will be causing this, including the following:

- The airtightness of the room allowing air into and up the chimney; both the leakiness of the dwelling envelope and the opening of the internal door(s) to the rest of the house and the opening of windows to the outside,
- The wind speed and direction and the effect of the roof configuration affecting the airflow around and over the top of the chimney, creating changes in pressure,
- The shape of the chimney at the fireplace opening and approaching the roof.

Examining graphs of the pressure difference showed variation from hour to hour over the seven days, presumably as the wind changed direction and speed and as doors and windows were opened. (One of the participants could identify a brief but clear change in pressure at the time his wife normally left the house in the morning, for example.)

The data was also analysed to investigate correlation with different variables, in the hope this might be used to reduce the variability of the results. A clear relationship between windspeed and chimney airflow was noted, although the correlation coefficient was only 0.47 and other factors are clearly having an effect. The temperature difference creating a 'stack effect' was analysed, and no correlation was found overall; however, if small time periods of an hour or two during low wind speed were isolated, a correlation could be detected. It was thought that these represented periods when the dwelling was in a stable state so that the relatively small effect could be detected. The pressure difference could be seen to quickly drop or rise at particular times, maybe due to a door or window being opened or closed. It may be possible with further analysis of the data and some theoretical analysis to relate airflow to the temperature difference.

As part of work undertaken by George Henderson in 2006, an Excel based model of air flow through chimneys was developed by Gastec at CRE Ltd (see [Annex C](#)). This calculates the pressure difference up the chimney from the difference in density between the air/gases in the chimney and the density of the external air. The pressure drop along the length of the chimney due to flow resistance is also calculated, using an estimate of the area of openings through

¹⁷ Stephen R, K. Airtightness in UK dwellings: BREs test results and their significance. BRE report BR359

which air enters the room with the chimney, together with other factors characterised in standard fluid dynamics such as a friction factor and discharge coefficients. The calculated flow rate is then adjusted until the pressure difference matches the pressure drop arising from the flow resistance. This model gives the average annual flow rates in Table B1.

Some reasonable estimates have been made in this model, and the results the model gives for chimneys are consistent with the values of 75 to 80 m³/hr from the BRE measurements. This gives support to the soundness of the model and suggests that the other results in the table may be used as a valuable source to inform revisions to other ventilation rates.

The specified heating in rows 1 to 10 of Table B1 were assumed to be secondary heating systems with 500 hours 'periodic' firing per year. The wood chip boiler in row 11 was assumed to be a primary heating source and the firing hours were raised to 1500hrs.

		No fire	Periodic firing	Full firing
1	Open chimney (12"x4") - 10 kW	102	111	245
2	Open chimney (12"x4") - 5 kW	102	109	207
3	Open chimney DGF 10 kW	94	101	211
4	Open chimney DGF 6.9 kW	66	70	132
5	ILFE 10 kW (9000mm ²)	40	43	106
6	ILFE 6.9 kW (9000mm ²)	38	42	93
7	Radiant gas fire 125mm flue 10 kW	28	32	83
8	ILFE 125mm flue 6.9 kW	28	31	82
9	Wood stove into unlined chimney (10kW)	10	12	58
10	Wood stove into unlined chimney (5kW)	10	11	29
11	Wood chip boiler 15 kW, 80% efficiency, into 125 mm flue (1500 hrs firing)	10	22	82

Table B1 – Average annual flow rate from Excel based model in m³/hour. DGF = decorative gas fire

In addition, George Henderson's work points out that Building Regulations ADF Table 5.2b gives Passive Stack Ventilation internal duct diameters required to give specified extract rates: 125 mm diameter is given for a kitchen to achieve 47 m³/hour and for a bathroom or utility room to achieve 29 m³/hour. A Passive Stack Ventilator is a vertical pipe and is essentially

similar to a chimney flue. The flow rate for a typical chimney flue (which has a cross section area perhaps 4 to 8 times larger) would be expected to be higher than these extract rates.

Summary of air flow rates

Work by George Henderson identified inconsistencies between SAP and Approved Document F, suggesting a flow rate around 118 m³/hr. This was supported by an Excel based model giving a value of 70 to 110 m³/hr.

The monitoring undertaken in 17 typical existing dwellings during typical heating period weather conditions gave an average of 75 to 80 m³/hr. Chimneys were swept first which might cause this average to be a slight overestimate, however few were significantly blocked. The airtightness values of the dwellings were mostly in the lower half of the distribution of a larger dataset of 384 dwellings and this may mean the average is a slight underestimate, although airtightness was not found to be a significant factor. Overall, it is thought that neither of these factors significantly affects the average results.

A flow rate of 80 m³/hr for chimneys is therefore adopted.

The issue of temporarily blocking the chimney with a commercial product or newspaper should be kept in mind. This cannot be considered for purposes such as an energy rating which must only take account of fixed measures. It may be noted that of the 20 open fireplaces in the BRE project, 15 were not temporarily blocked when not in use; moreover, of these, 8 were never used for a fire.

Rows 5 to 8 of Table B1 give values between 28 and 43 m³/hr. These sorts of flue have a heating appliance at the bottom which introduces resistance to air flow.

A flow rate of 35 m³/hr is therefore adopted for an appliance flue.

Rows 9, 10 of Table B1 give values between 10 and 12 m³/hr for a wood burning stove. A similar value might be expected for a solid fuel closed stove.

A flow rate of 10 m³/hr is therefore adopted for wood or solid fuel stove flues.

Row 11 of Table B1 gives a value of 22 m³/hr for a wood chip boiler, assuming this is used as a primary heating source. A similar value might be expected for a solid fuel boiler.

A flow rate of 20 m³/hr is therefore adopted in SAP 10.2 for wood or solid fuel boiler flues.

From the information on householders temporarily blocking a chimney above, the presence of a damper may not mean that it is pulled across to reduce the airflow.

It is therefore assumed that ‘Chimney fitted with a damper’ is included as a full chimney flue with a flow of 80 m³/hr.

At present a permanently blocked chimney with ventilation not exceeding 30,000mm² in area is given a value of 20 m³/hr.

A flow rate of 20 m³/hr is therefore retained for a blocked chimney.

The value of 10 m³/hr for an intermittent extract fan may be considered in terms of the extraction rate for a typical fan airflow of 80 m³/hr and an average running time of 7.5 minutes per hour. Increasing this would give an excessive running time.

A flow rate of 10 m³/hr is therefore used for an intermittent extract fan.

For Passive Stack Vents (PSVs), Approved Document F gives a duct diameter of 125mm (cross sectional area 12,000 mm²) for rooms to achieve between 22 and 47 m³/hr. However, PSVs are humidity-controlled and therefore a lower average flow is appropriate.

A flow rate of 10 m³/hr is therefore used for a Passive Stack Vent.

For flueless gas fires, the value relates to the air change rate needed to remove combustion products.

A flow rate of 40 m³/hr is therefore used for a flueless gas fire.

The air flow rates above are summarised in Table B2.

Chimney Vertical duct for combustion gases diameter 200mm or more including decorative gas fires and chimneys with a damper	80 m ³ /hr
Flue (1) Open flue gas fire with flue products outlet sealed to the chimney including radiant gas fires and ILFE	35 m ³ /hr
Flue (2) Flue for wood or solid fuel boiler	20 m ³ /hr
Flue (3) Flue for wood or solid fuel stove/appliance with controlled air supply	10 m ³ /hr
Blocked chimney Blocked chimney with ventilator area less than 30,000 mm ²	20 m ³ /hr
Intermittent extract fan Kitchen, bathroom, cooker hoods and other independent extract fans	10 m ³ /hr
Passive stack vent Extract grilles connected to ridge terminals by ducts, humidity control	10 m ³ /hr

Flueless gas fire	40 m ³ /hr
Balanced flue	zero

Table B2 – Proposed ventilation values

References

Iles P. Chimneys – monitoring airflows. DECC Client Report. July 2015.

Annex C - Extract from George Henderson/Gastec at CRE report

(The work described in this annex was done as part of the development of SAP and this extract was previously published as an appendix to SAP 10 technical paper S10TP-02 “Amendments to SAP’s treatment of the heat loss from chimneys and flues”)

Calculations of flow rates in chimneys

Gastec at CRE Ltd (GaC) have developed an Excel spreadsheet model of a chimney for this project. Pressure difference is calculated from the difference in density between the air and/or flue gases in the chimney and the ambient air, according to the expression

$$\Delta P = (\rho_a - \rho_f) \times g \times h \quad (2)$$

Where ρ_a is the density of the ambient outdoor air, ρ_f is density of air or air/gas mixture within the flue, g is the acceleration due to gravity and h is the height of the chimney. When firing is taking place, the energy imparted to the flue is used to calculate the flue temperature along with the temperature of the air inside the building.

Resistance to flow is calculated from consideration of the path taken by the combustion air into the room in which the chimney is located and through the appliance, and of the flue gases through the chimney itself.

The pressure drop due to the flow of air into the room from which the chimney takes its ventilation is calculated according to the expression

$$\Delta P = \frac{1}{2} \times \frac{\rho_a v^2}{C_d^2} \quad (3)$$

where v is the mean velocity through the ventilator and C_d its discharge coefficient, taken to be 0.61. Allowance needs to be made for infiltration and other background ventilation in the room. Appendix A of ADF assumes an infiltration rate of 0.15 ach (or 0.2 for single storey house), or around 30 m³/hour for a whole dwelling. Using equation (1) it may be observed that this equates to around 21,000 mm² of openings, taking account of the fact that the result must be doubled to allow for both inward and outward paths. If this area is distributed pro-rata with floor area, it may be assumed that around a quarter is in the living area, which contains the fireplace. It should also be noted that ADF specifies undercuts of at least 7,600 mm² on all doors to ensure good transfer of air throughout the dwelling. Taking that into consideration, it seems reasonable to assume an equivalent area of around 10,000 mm² in the room with the fireplace before any additional ventilator area, as required by Part J of the Building Regulations, is fitted. This is included in the spreadsheet as the “infiltration allowance”. It may be noted that an allowance for infiltration is also made when specifying the ventilator area for

some types of appliance in Approved Document J (ADJ). For example, Diagram 3.2 of ADJ shows a requirement for a gas appliance in a room only if the output exceeds 7kW.

Equation 3 is also used to calculate the pressure through the appliance and at the top of the chimney. If it can be assumed that restriction in the appliance is similar to that produced by an orifice, then a C_d of 0.61 should be applied in that case also. The chimney top, however, may be an open nozzle, in which case C_d should be close to 1.

The pressure drop through the length of the chimney is calculated using the Darcy equation

$$\Delta P = \lambda \times \frac{h}{d} \times \frac{1}{2} \times \rho_f v^2 \quad (4)$$

where λ is the friction factor, and h and d are the length and diameter of the chimney respectively. The friction factor, λ , depends upon the Reynolds number, R_e , and the relative roughness of the chimney wall. It is often obtained by reference to the Moody chart, as described in Section 4.3 of CIBSE Guide C. For laminar flow ($R_e < 3000$) it may be calculated using the simple expression

$$\lambda = 64/R_e \quad (5)$$

but for turbulent flow, accurate calculation requires iteration using the Colebrook-White equation. There are also a number of equations developed to give reasonable approximations without the use of iteration; the one used in this case was taken from Coulson and Richardson, Chemical Engineering, Volume 3 (1978).

The calculated flow rate is adjusted until the pressure difference matches that arising from the flow resistance, using the “solver” tool in Excel.

The spreadsheet described above was used to calculate airflows for a number of appliances under both cold and firing conditions, as shown in Table 3 below. The fifth column shows the average flow rate over a year based on the assumption that the appliance is firing at the equivalent of full rate for 500 hours, for cases 1 to 10, which are assumed to be secondary heating systems. For case 11, which is assumed to be the primary heating source, the firing hours are raised to 1500.

		No fire	Full firing	Average flow based on 500 hours firing	Room pressure drop when full firing
		m3/hour			Pa
1	Open chimney (12"x4") - 10 kW	102	245	111	11
2	Open chimney (12"x4") - 5 kW	102	207	109	8

3	Open chimney DGF 6.9 kW	66	132	70	11
4	Open chimney DGF 10 kW	94	211	101	8
5	ILFE 6.9 kW (9000mm ²)	38	93	42	13
6	ILFE 10 kW (9000mm ²)	40	106	43	10
7	Wood stove into unlined chimney (5kW)	10	29	11	0.8
8	Wood stove into unlined chimney (10kW)	10	58	12	0.6
9	Radiant gas fire 125mm flue 10 kW	28	83	32	6
10	ILFE 125mm flue 6.9 kW	28	82	31	8.1
11	Wood chip boiler 15 kW, 80% efficiency, into 125 mm flue	10	82	22	4

Table 3 – Air flow rates calculated for various appliances

Cases 1 and 2 are for open chimneys using solid fuels in a grate, or other form of open fire, for which ADJ specifies a ventilator area in the room of half the throat area. The throat itself is the only restriction at the appliance and is typically 12 by 4 inches in the UK, giving an area of 31,000 mm² and a ventilator area of 16,500 mm². The calculated flow rate when there is no fire is more than twice that assumed in SAP. An analogy can be made with a 125 mm passive stack ventilator, as used in a kitchen, to which ADF attributes a flow rate of 47 m³/hour. If this is adjusted pro-rata for the throat area of the chimney, it yields a result of 118 m³/hour, which is even larger than the result in Table 3 for the no fire condition. By contrast, the result for the full firing condition is relatively low compared to those given on the American websites referred to earlier. This may be due to the relatively low firing rates used and, especially in the 10 kW case, appears to be significantly constrained by the pressure drop due to the air path into the room.

Cases 3 and 4 are also for open chimneys but fitted with decorative gas fires (DGF), as shown in Figure 2, item (c). The main difference from cases 1 and 2 is the size of room ventilator required. The appliance assumed for case 3 is assumed to require no additional ventilation into the room, being under 7 kW and compliant with the conditions set out paragraph 3.12 of ADJ. This has the effect of reducing the air flow, especially under no fire conditions. Case 4 has a larger appliance which requires the addition of a 10,000 mm² ventilator, which makes it more comparable to that for cases 1 and 2. Taking cases 1 to 4 together, the most significant fact is that all have flow rates in the no firing condition that are much higher than is assumed in SAP, even when no additional ventilation into the room is required in case 3.

Cases 5 and 6 are for inset live fuel effect gas fires (ILFE), as described in Figure 2, item (b), operating into an unlined chimney. Unlike the DGF types in cases 3 and 4, ILFE fires significantly restrict the airflow into the chimney opening. The extent of this restriction probably varies considerably from model to model but for the purpose of this calculation was assumed

to be 9000 mm², which is the area of a 7 by 2 inch “letterbox” opening. As for case 3, case 5 does not require additional ventilation into the room because the consumption rate of the appliance is below 7 kW. Case 6 does require additional ventilation but only 1500 mm² (500 mm²/kW in excess of 7kW) compared to the 10,000 mm² in case 4. The effect of the restriction in the appliance is clearly evident in the reduced air flow, both when firing and when not. It is important to note, however, that the reduced rates achieved are comparable to those assumed by SAP for an open chimney, rather than for an appliance with restricted flow.

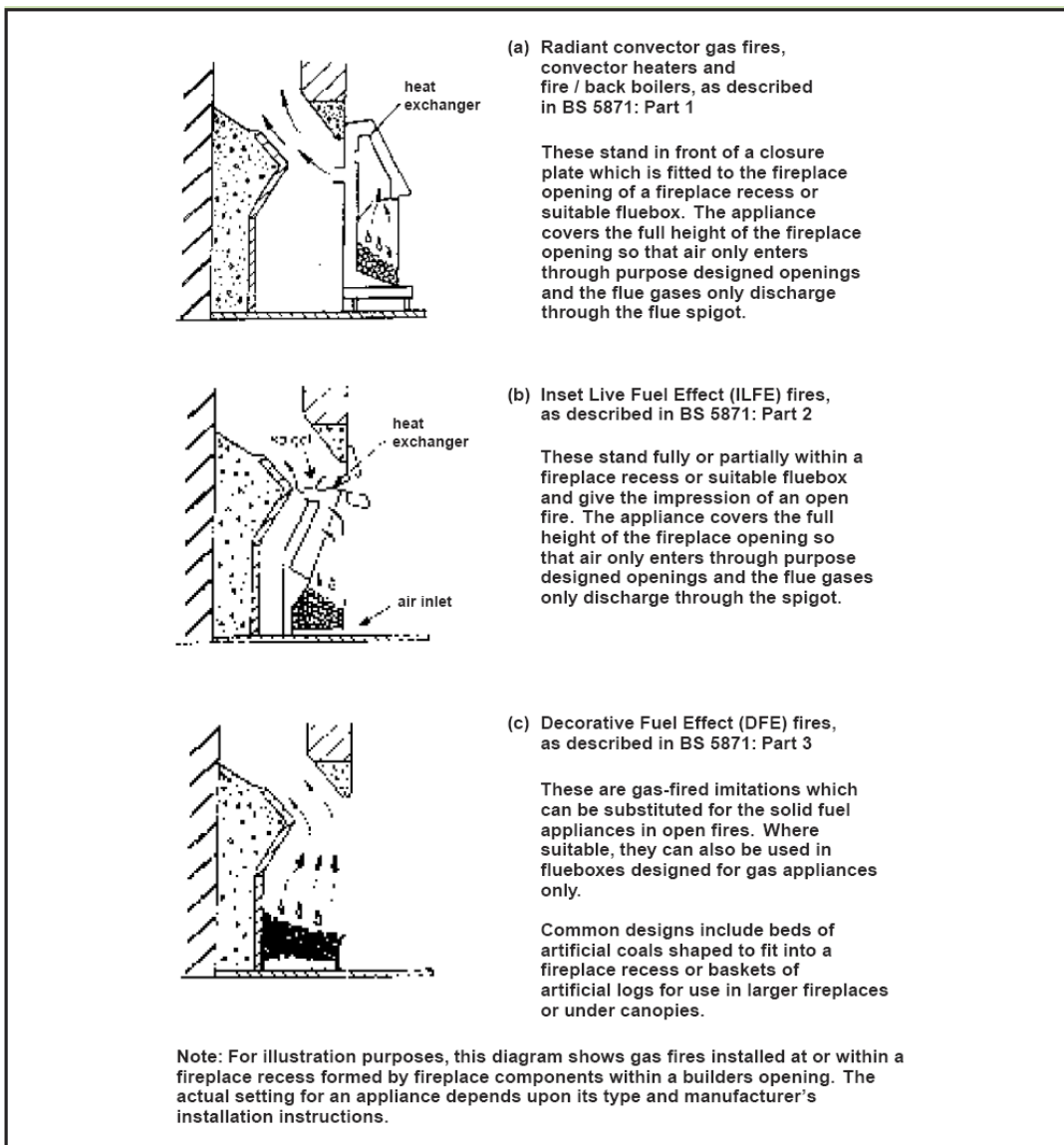


Figure 2 – Types of gas fire, copied from Diagram 3.1 of ADJ

Cases 7 and 8 are for a small modern wood burning stove, coupled to an unlined chimney through a short length of flue and a register plate, which ensures at the only air path into the chimney from below is through the appliance. Stoves of this type achieve high combustion efficiency by good control of airflow through the appliance. The same dampers used to control airflow during combustion can be used to reduce it to a very low level when the appliance is not firing. No data on the size of air inlets is normally given for wood burning stoves but, as

they claim to have high efficiency, it may be assumed that they operate with relatively low excess air ratios. For 50% excess air, it may be calculated that a 1 kW burn rate requires an air supply of around 1.4 m³/hour. The results shown assume effective areas through the appliance of 2000 mm and 4000 mm for 5 kW and 10 kW burn rates, respectively. Even those relatively small areas pass air at a much greater rate than is required for combustion but add only modestly to the ventilation rate. The effect of the high degree of restriction in the appliance may also be observed in the low pressure drop into the room.

Cases 9 and 10 are for gas fires connected to a 125 mm flue liner installed in a chimney. The area through the appliance is assumed to be 9000 mm², as for cases 5 and 6. Although the calculated flows are lower than obtained for cases 5 and 6, they are still above the 20 m³/hour assumed by SAP for flue. This may be because the appliance area is too large; data from manufacturers, or preferably measurements, are needed to establish whether or not this is so.

Case 11 is for a high efficiency wood pellet boiler. It is largely speculative in that it is hard to find any data on the air drawn by this type of appliance. The high efficiency requires, however, that excess air is limited and its contribution to ventilation will be low.

Taken together, the calculations show that the flow restriction at the appliance is a key factor determining the contribution to ventilation rate. Figure 3 shows the calculated air flow through a standard 8 inch chimney with no fire against the area of the restriction at the appliance with and without additional ventilation into the room. The range of areas covered extend from 2,000 mm², which might be appropriate for a well restricted appliance such as a wood burning stove, to 35,000 mm², which is around 13% larger than a standard chimney throat. The case with no additional ventilator assumes infiltration into the room directly and indirectly equivalent to that from 10,000 mm² of openings. The other case is for an open fire and is the ventilator area is set at half the throat area of 31,000 mm². For restricted appliances, the air flow through the chimney depends strongly on the area of restriction and relatively little of the presence of additional ventilator. This supports the case for adjusting the contribution to ventilation in SAP using accredited test result for individual appliance types. For unrestricted appliances, such as decorative gas fires, the presence of the additional ventilator becomes significant, even when the appliance is not firing.

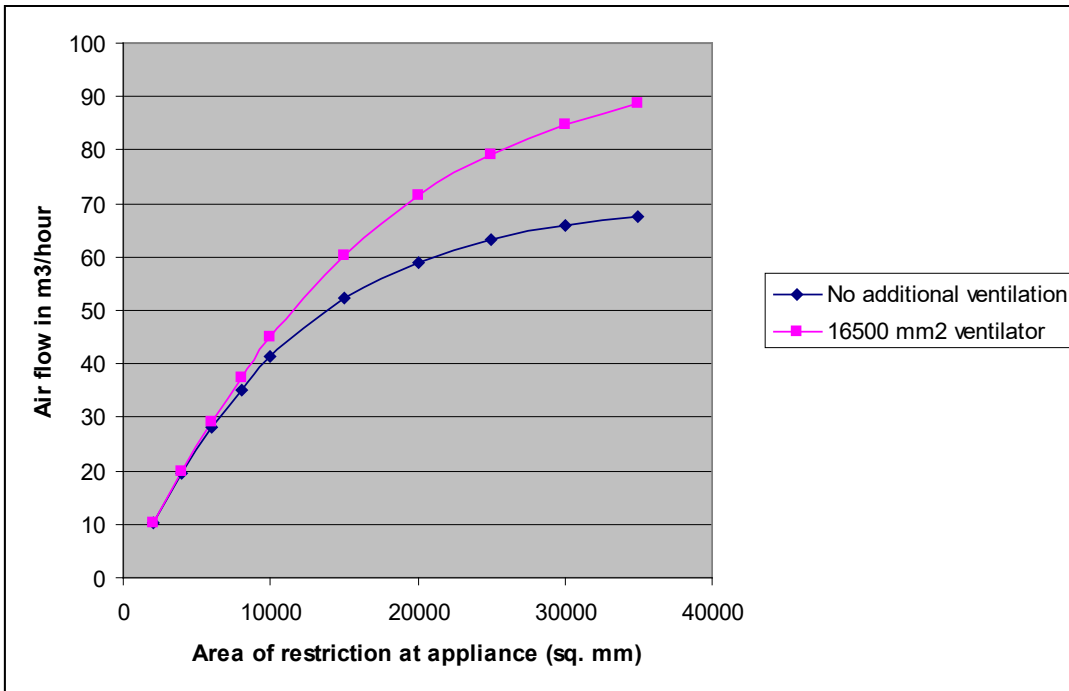


Figure 3 – Calculated air flow against area of restriction at the appliance

Incorporation of test results into SAP

For SAP, test results are of principal interest when the restriction through the appliance is the dominant factor in determining air flow. This is most clearly so when the area of the restriction is less than 15,000 mm², which is approximately 50% greater than a typical letterbox opening for a gas fire. In this region, the air flow in m³/hour through a standard 8 inch diameter chimney during no firing conditions may be obtained from

$$Q = (5.2A - 0.0001A^2)/1000 \quad (6)$$

where A is the effective area through the appliance in square millimetres measured at 4 Pa.

A similar relationship is found for an appliance is connected to a 125 mm diameter flue

$$Q = (4.4A - 0.00014A^2)/1000 \quad (7)$$

