

## **Airflow measurement methods to optimise minimum fresh air UK65.L2**

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### **1. Introduction and background**

This paper presents interim results of a research project part funded by the DETR under the Partners In Innovation scheme to investigate measurement methods appropriate for setting minimum fresh air rates in mechanical ventilation systems. A range of potential measurement techniques are outlined together with preliminary advice of which may be most appropriate. This advice will be enhanced in the next phase of the project which is to test the techniques in approximately 15 buildings with different mechanical ventilation system types, sizes and installation configurations.

Fresh air is necessary to provide building occupants with a comfortable environment and air conditioning systems often vary the fresh air rate between a set minimum and full outside air to reduce the need for additional heating and cooling. For long periods in winter, and also during peak summer, systems typically operate on minimum fresh air and this should be optimised to the requirements of the building and occupants. However, measuring minimum fresh air accurately is often difficult because air flow rates are typically low, space may be restricted and installations may not have been designed adequately for commissioning.

- if the period between checks (typically greater than 5 years) has been exceeded
- if recommended minimum fresh air rates change.

## **2. Fresh air requirements**

Minimum fresh air rates should, where possible, be based on design requirements but if this information is not known the rate can be based on guidance. CIBSE Guide A (1) recommends 8 l/s per person for most space types with non-smoking environments and sedentary occupants. The rate can be based on peak or average conditions depending on how variable occupancy is and assumes perfect mixing in the space (it should be adjusted if the ventilation effectiveness is not 1.0).

## **3. Fresh air measurement**

Fourteen potential measurement methods were investigated. These can be broadly divided into three groups of direct fresh air measurement, direct fresh air measurement with an attachment on the air intake and indirect fresh air measurement.

### **3.1 Direct fresh air measurement methods**

#### Method 1

Pitot static tube or anemometer traverse in the intake duct. The number and location of test points is specified in BS 1042 (2).

#### Method 2

Vane anemometer traverse across the face of the intake louvre using techniques developed for measuring airflow from outlet grilles. The flow rate is calculated from face velocity and louvre free area or a factor which relates face velocity to volume flow eg area factor or equivalent area. A vane anemometer with a large head is recommended to integrate a larger area including both louvre structure and open areas.

### **3.2 Direct fresh air measurement methods using an attachment on the intake**

#### Method 3

Duct attachment fitted to the intake louvre with an anemometer traverse at the end of the duct.

#### Method 4

Airflow hood (typically used for grille airflow measurement) fitted to the intake louvre. This technique could be applied to the air intakes of small AHUs and the hood must be calibrated for exhaust air flow measurements.

#### Method 5

Duct attachment with integral venturi or orifice plate, fitted to the intake louvre.

#### Method 6

Airflow compensation. This method is similar to an airflow hood but the instrument resistance is compensated for by an integral fan thus improving this overall accuracy.

### **3.3 Indirect fresh air measurement methods**

#### Method 7

Spot temperature measurement (using a hand-held instrument or Building Management System sensor readings) combined with a pitot static tube traverse of the total supply duct. Fresh air rate can be calculated as follows:

$$\text{Fresh air rate (m}^3\text{/s)} = \frac{(T_m - T_r) * Q_s}{(T_f - T_r)}$$

$T_m$  = Mix air temperature (°C)  
 $T_r$  = Return air temperature (°C)  
 $T_f$  = Fresh air temperature (°C)  
 $Q_s$  = Air supply rate (m<sup>3</sup>/s)

#### Method 8

Traverse of the total supply and recirculation ducts by pitot static tube and determination of the fresh air rate from the difference.

#### Method 9

Traverse of the total supply, return and exhaust ducts by pitot static tube and calculation of the fresh air rate by subtraction (supply- [return-extract]).

#### Method 10

Measurement of CO<sub>2</sub> in the total supply, return and intake ducts and a traverse of the total supply duct by pitot static tube. The difference in CO<sub>2</sub> concentration at the measurement points is due to metabolic production. This can be enhanced by injection of CO<sub>2</sub> in the return air. Fresh air rate can be calculated as follows:

$$\text{Fresh air rate (m}^3\text{/s)} = \frac{(C_m - C_r) * Q_s}{(C_f - C_r)}$$

$C_m$  = Mix air CO<sub>2</sub> (ppm)  
 $C_r$  = Return air CO<sub>2</sub> (ppm)  
 $C_f$  = Fresh air CO<sub>2</sub> (ppm)  
 $Q_s$  = Air supply rate (m<sup>3</sup>/s)

#### Method 11

CO<sub>2</sub> (or tracer gas) constant rate injection into the air intake at a known concentration and measured flow rate combined with concentration measurement downstream from the injection point and also in the outdoor air. The fresh rate can be calculated from the mass balance as follows:

$$\text{Fresh air flow rate (Q}_0\text{)} = \frac{Q_1 (C_2 - C_1)}{(C_o - C_2)}$$

$Q_0$  = fresh air flow rate (m<sup>3</sup>/s)  
 $C_o$  = outdoor air CO<sub>2</sub> concentration (ppm)  
 $C_1$  = CO<sub>2</sub> concentration of the injection gas (ppm) (1,000,000 if pure CO<sub>2</sub> cylinder)  
 $C_2$  = CO<sub>2</sub> concentration downstream from the injection point (ppm)  
 $Q_1$  = flow rate of the injection gas (m<sup>3</sup>/s)

#### Method 12

Assessment of damper characteristics and a traverse of the total supply duct by pitot static tube. The fresh air rate is determined from the intake damper position and the damper characteristics which are provided by the damper manufacturer. Damper performance is defined by the characteristic ratio which is the ratio of series resistance (weather louvre, bird screen, duct between damper and louvre) to damper resistance. The damper characteristic ratio should be 2.5 for parallel blade and 10 for opposed blade to achieve a near linear performance.

#### Method 13

Perfluorocarbon tracer (PFT) emitter and sampler located in the air intake. This is a passive tracer technique and PFT emission rate is related to the temperature whilst the fresh air rate is related to the

test period and weight of tracer collected in the sampler. Sampler concentration is analysed by an external laboratory and therefore it requires several tests to be performed at different intake damper settings eg 5%, 10%, 15%, 20%. A graph of damper position against flow rate can then be produced and the required damper setting determined (an example is shown in Figure 1).

$$Q = \frac{S * \phi_T * (T/T_{\text{expt}})}{(M/t) * 60,000}$$

- Q= fresh air rate (m<sup>3</sup>/s)  
 $\phi_T$ = effective sampling rate (1/h)  
 S= emission rate (mg/hour)  
 T= reference temperature (K)  
 T<sub>expt</sub>= average temperature during sampling period (K)  
 M= tracer collected (mg)  
 t= time (hours)

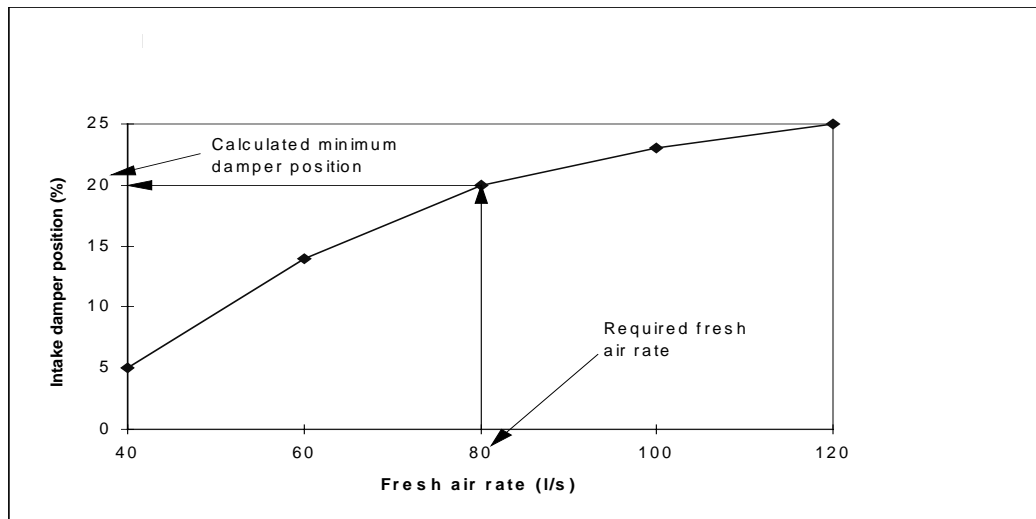


Figure 1 Example of using PFT to determine minimum intake damper position

#### Method 14

A bag of known volume is fixed to the intake louvre and sealed to prevent ingress. The fresh air rate is calculated by measuring the period for the bag to become completely deflated. The bag must be of sufficient volume to allow measurement over a period greater than 10 seconds.

### 3.4 Continuous monitoring

VAV systems may be set up with fixed air flow rate measurement systems which continuously monitor and adjust the damper to maintain minimum fresh air regardless of changing conditions in the rest of the system. The range of measurement devices which can be applied is very limited (typically pitot static tubes or hot wire anemometers) and their application is often difficult because they are subject to the same problems as setting minimum fresh air by spot check:

- low air flow rates
- limited space
- turbulent flows.

Fixed air flow rate measurement systems are typically applied in grids across the duct to provide an average and minimise the affect of turbulence. However, other problems can occur such as blockages or sensor drift through dirt build-up in the unfiltered airstream. Hot wire systems may overcome these problems by having both heated and unheated sensing elements exposed to unfiltered air.

#### 4. Selection of fresh air rate measurement procedure

The two most important considerations when selecting an airflow measurement method are:

- ventilation system characteristics
- accuracy of measurement.

##### 4.1 Ventilation system characteristics

There are several system characteristics which can influence the test method selection including:

- intake configuration
- system size
- damper type/mixing arrangements.

The following outlines important variations in systems and Table 1 shows test methods which cannot be applied due to different system characteristics.

##### Intake configuration

Air intake paths may have long or short/non-existent ducts and may have good, restricted or no access to the intake louver. Short ducts and poor access will restrict the application of some air flow measurement methods.

##### System size

The physical size of an intake louver or the fresh air flow rate can affect selection of measurement technique. The physical size may limit the opportunity to test using methods which apply attachments to the air intake whilst if the air flow rate is too low it will prevent certain techniques from being used.

##### Damper types/mixing arrangements

Some techniques require good mixing of fresh and recirculated airstreams. If they enter the mixing plenum at right angles to each other then parallel blades on both dampers, set up such that the two airflows deflect towards each other will enhance mixing. If they enter the mixing plenum in opposition then opposed blade dampers will enhance mixing through direct impingement.

Table 1 Test methods excluded for selected important parameters

Important parameters	Methods excluded
No access to intake louver	2, 3, 11, 12, 13, 14
Intake duct too short/non-existent	1, 11, 13
Intake louver large	3, 4, 5, 6
No access to intake damper	12
Recirculation duct short/non-existent	8
Exhaust duct short/non-existent	9
No suitable return air measurement point	7, 9
Poor mixing of intake and recirculation	7, 10
Heating/cooling/humidification on	7
Air velocity too low	1, 3, 9
Inside and outside temperatures similar	7
Building occupied	10, 11

##### 4.2 Accuracy of measurement

The previous section detailed potential test procedures which can not be applied depending on ventilation system set-up whilst this section allows the accuracy of those methods remaining to be compared. There are a number of important considerations to the accuracy of different techniques including:

- instrument/measurement accuracy
- measurement test point location
- test operatives
- external affects.

### Instrument/measurement accuracy

Table 2 shows instruments and other factors which can influence the overall measurement accuracy of each of the sixteen methods investigated whilst Table 3 and Table 4 show the typical accuracy of the instruments used.

Table 2 Factors influencing accuracy of test methods

Test method	Instrument 1	Instrument 2	Instrument 3	Duct size calculation	Poor air flow test location	Additional resistance	Mixing of two airstreams	Mixing of tracer in airstream	Other affects (see notes)
1	pitot tube	manometer		X	X				(a)
2	anemometer								(b)
3	pitot tube	manometer				X			
4	airflow hood								
5	venturi	manometer				X			
6	venturi	manometer							
7	pitot tube	manometer	temp sensors	X	X		X		(c), (d), (e), (f), (g)
8	pitot tube	manometer		X	X				
9	pitot tube	manometer		X	X				
10	pitot tube	manometer	CO <sub>2</sub> sensor	X	X		X		(a), (e), (h), (i)
11	CO <sub>2</sub> inj conc	CO <sub>2</sub> flowrate	CO <sub>2</sub> sensor					X	(e)
12	pitot tube	manometer		X	X				(j)
13	emitter acc	sampler acc	temp sensor					X	(e), (k), (l), (m)
14	bag volume								(n)

Notes:

- (a) Low flow results in measurement at bottom end of instrument.
- (b) Requires accurate assessment of louvre free area.
- (c) Temperature difference between measurement points must be significant.
- (d) Erroneous heat input (heater batteries, cooling coils, humidifiers, fan pick-up) will produce errors.
- (e) Airstreams must be well mixed (airstreams can remain unmixed through filters, coils and fans).
- (f) Three sensors used in BMS may have different errors.
- (g) The temperature recorded by BMS outdoor air sensor may differ from that in the AHU intake.
- (h) CO<sub>2</sub> difference between measurement points must be significant.
- (i) Extended test period may be required to ensure a stable CO<sub>2</sub> concentration is measured.
- (j) Measurement method depends on accuracy of manufacturers damper characteristics data.
- (k) Requires a constant permeation rate from the emitter (this is affected by temperature).
- (l) Requires high adsorption and desorption efficiencies from the sampler.
- (m) Sampler accuracy also depends on its orientation to air stream.
- (n) Accuracy depends on ability to judge that bag is completely deflated.

Table 3 Typical accuracy of instruments used in direct airflow measurement techniques (3)

Type	Min vel(a) m/s or (m <sup>3</sup> /h)	Max vel(a) m/s or (m <sup>3</sup> /h)	Min temp °C	Max temp °C	Select largest (unless stated)			
					Accuracy % reading	Accuracy (±m/s)	Accuracy % full scale	Accuracy (± digit)
Vane- 75-125mm	0.12	25	0	80	5	0.1		
Hot wire	0	2	0	80	3	0.1		
Airflow hood	(0)	(2400)	0	50			5	
Compensated hood	(0)	(225)	-20	80	5			
Ultrasonic	0	50	0	80	1			1
Pitot static tube	4	82			2(b')			

Manometer	0	76			1			1
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Notes: (a) Max/ min flows may be with different instruments/ranges, (b) With suitable manometer Air flow measurement accuracy will vary with air flow rate and an example of a pitot static tube and manometer is shown in Figure 2. This figure is based on a manometer inaccuracy of  $\pm 1$  Pa and shows excellent performance at high flow rates but a rapid deterioration at low rates due to the increasing relative importance of the manometer inaccuracy in the measurement. This demonstrates the potential problems associated with measuring minimum fresh air rates.

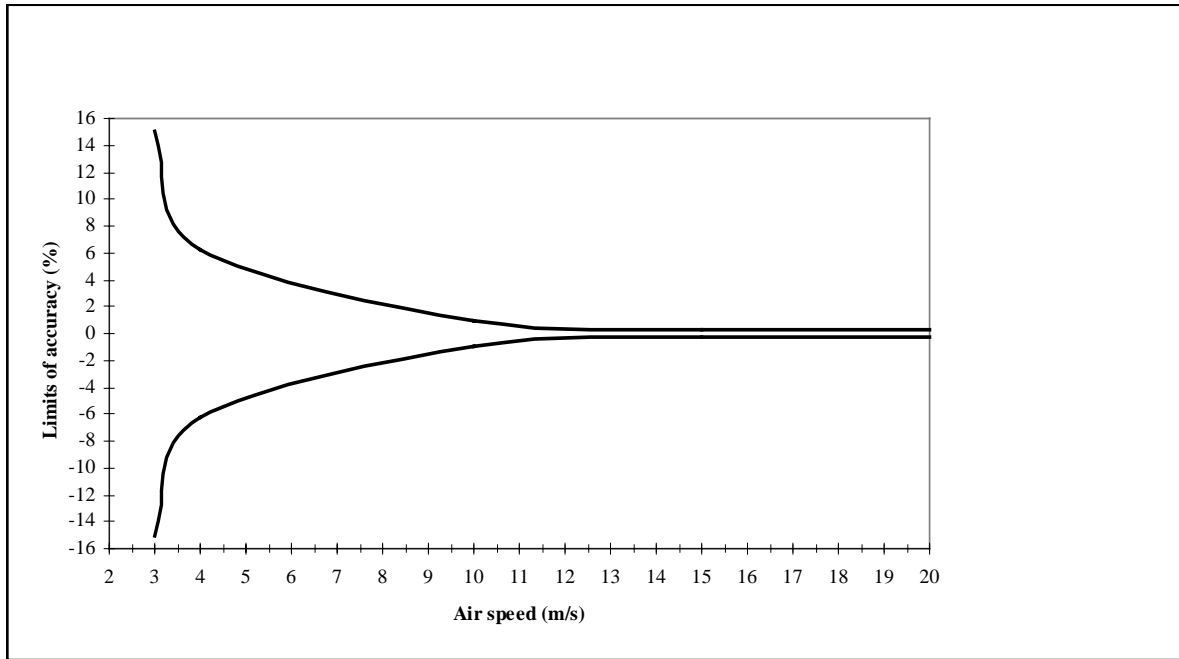


Figure 2 Variation in pitot static tube accuracy with air speed

Table 4 Typical accuracy of instruments used in indirect airflow measurement assessments

Technique	Sensor accuracy ( $\pm$ unit)	Typical overall accuracy (%)
Spot temperature	0.5-1K	-

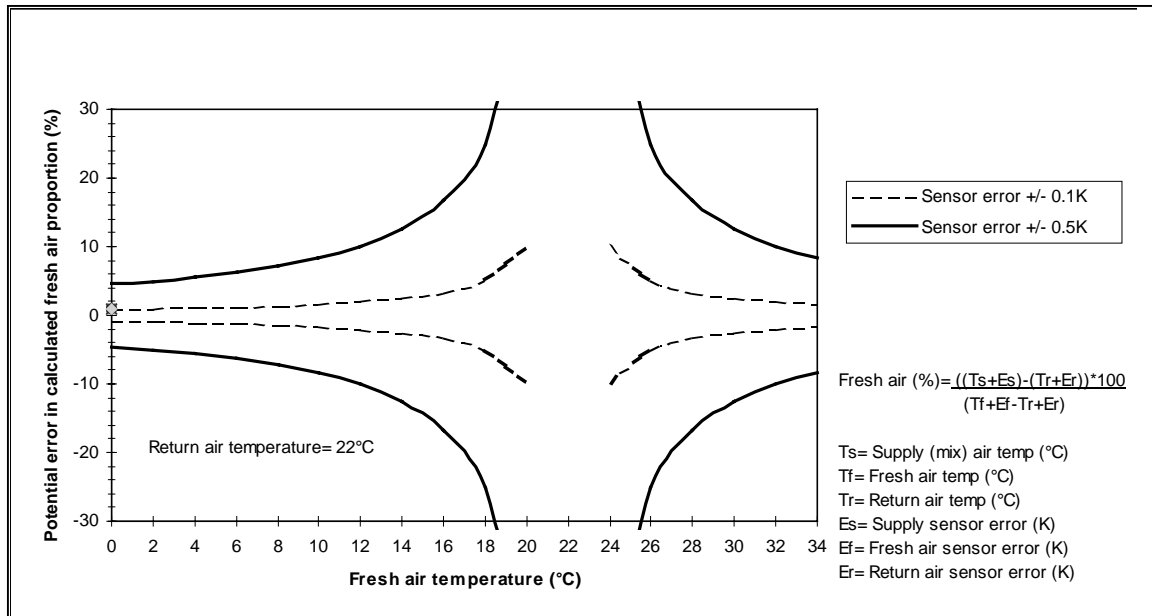


Figure 3 Potential error in calculated fresh air proportion through temperature sensor inaccuracy

Figure 4 is similar to Figure 3 but shows the potential error in calculating fresh air proportion from CO<sub>2</sub> measurement. Similarly to Figure 3, Figure 4 only applies if the sensor error changes over the measurement range eg 350ppm to 1500ppm.

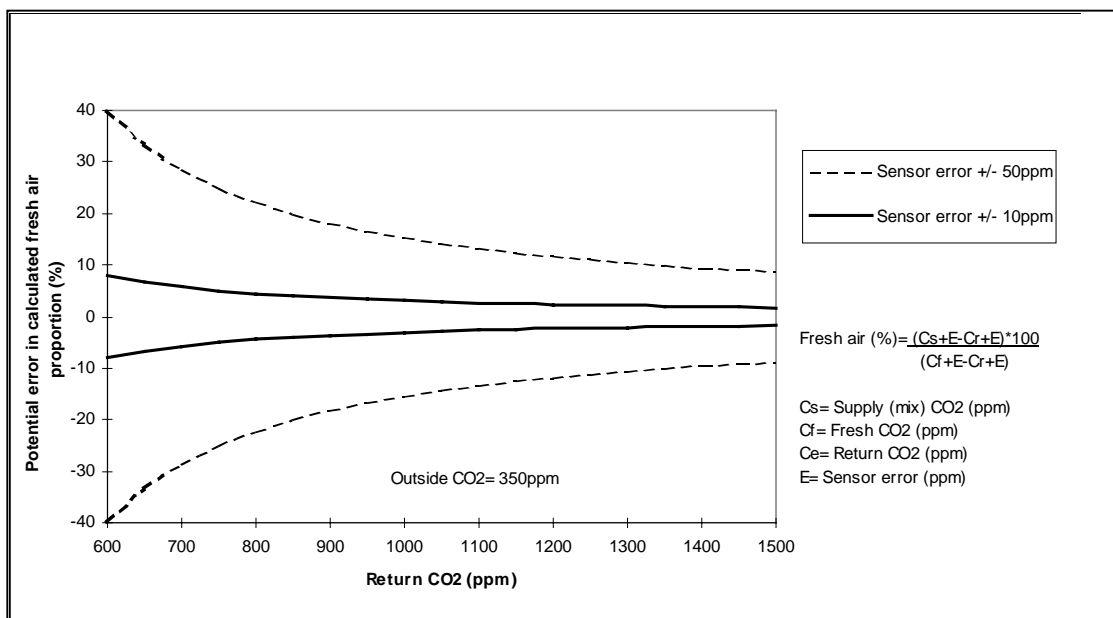


Figure 4 Potential error in calculated fresh air proportion through CO<sub>2</sub> sensor inaccuracy

### Test personnel

The impact of the test personnel will vary according to their familiarity with the test equipment, method and calculations. If all test methods are considered, in some cases the test techniques and equipment will be familiar but their use in other applications may be less well known eg methods 2 and 4. In these cases the operator impact should be minimal. However, if methods 10 to 14 are

applied it is likely that the procedure will be unfamiliar to a typical commissioning engineer and therefore operator impact could be significant.

### External effects

Wind speed/direction and stack effect are the two main external effects which can be important if there is significant difference between the test conditions and those under normal operation.

### Wind speed and direction

All test methods can be affected by wind speed and direction although method 2 may be more susceptible to gusting conditions because the measuring equipment is directly exposed to external conditions. Figure 5 shows the change in wind pressure with wind speed.

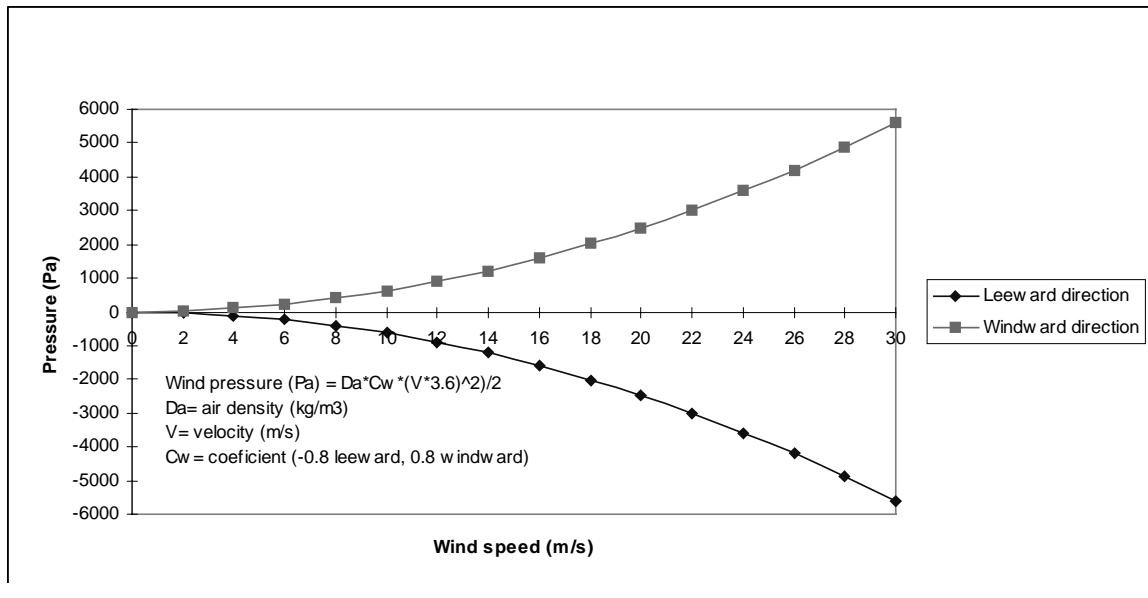


Figure 5 Change in wind pressure with wind speed

### Stack effect (4)

All of the test methods will be affected by stack effect. This is a natural airflow which occurs when there are openings in the building eg AHU intakes, and a temperature difference between outside and inside (see Figure 6). The effect can be significant for AHUs located in a basement or a low floor of a multi-storey building where there are airflow paths between low and high levels eg stairwells and lift shafts. Precautions should be taken to restrict potential airflow paths between low and high levels, particularly when there is a significant driving force (temperature difference) to increase airflow. The greatest impact of stack effect may be with measurement method 7 which actually requires a significant temperature difference between internal (return air) temperature and external temperature to ensure accurate measurement.

Arrows indicate magnitude and direction of pressure differences.  
Assumes internal temperature is higher than external temperature. If this is not the case flows are reversed.

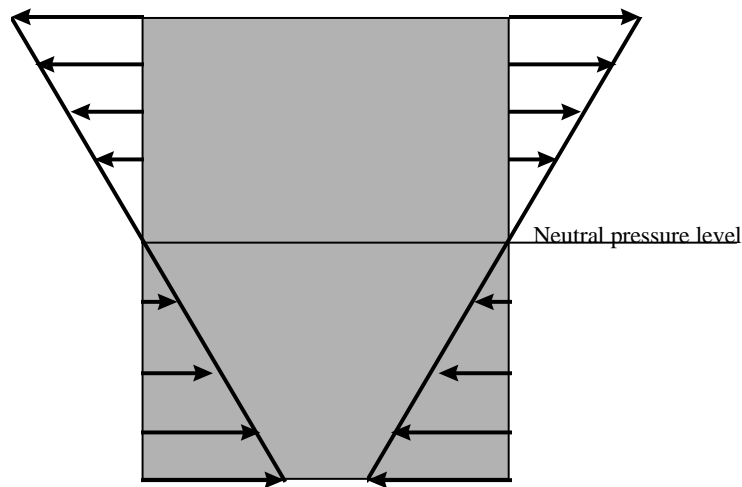


Figure 6 Stack effect in a building

Pressure difference due to stack effect is defined as:

$$dP_s = \rho_i g (H - H_{npl}) (T_i - T_o) / T_o$$

$dP_s$  = stack effect pressure difference (Pa)

$\rho_i$  = air density ( $\text{kg/m}^3$ ) (typically 1.2 for indoors)

$g$  = gravitational constant ( $9.81 \text{m/s}^2$ )

$H$  = height (m)

$H_{npl}$  = height of neutral pressure level (m) (between 30% and 70% of the total building height)

$T_i$  = internal temperature (K)

$T_o$  = external temperature (K)

The above calculation is the maximum as it assumes no internal resistance to airflow. In practice there is the added complications of stairwells, lift shafts, partitions, chimneys, vents and mechanical ventilation systems. If there are airtight separations at each floor they act independently.

### Combined wind and stack effect

The static pressure difference between inside and outside ( $dP$ ) can be expressed as a combination of wind and stack effects as follows:

$$dP = dP_s + P_o + P_w - P_{i,r}$$

$dP_s$  = stack effect pressure difference (Pa)

$P_o$  = static pressure at reference height (Pa)

$P_w$  = wind pressure (Pa)

$P_{i,r}$  = internal pressure at height (Pa)

The wind speed and direction and should be measured before and after testing as should the internal and external temperatures and an assessment made of the air flow paths between floors. The effect of

wind and stack under the test conditions should ideally be compared to those likely to occur under prevailing conditions.

## **5. Conclusions**

There are several potential techniques for measuring minimum fresh air rates in mechanical ventilation systems. This paper provides guidance on the range of techniques available, factors which affect measurement accuracy and ventilation system characteristics which may influence test method selection to allow test engineers to make the right choice.

## **6. Future work**

The test method selection guidance will be enhanced from the results of testing in 15 HVAC systems. The systems have been selected and supply a range of building types including a library, lecture theatre, function suite, swimming pool, department store and several offices. All test systems use recirculation with dampers which modulate between full fresh air and a set minimum but also have a number of different features including:

- constant and variable volume systems
- small, medium and large AHUs
- various ducting arrangements ranging from intake and exhaust on opposite sides of AHU ie no ducts to fully ducted intake, exhaust and recirculation paths
- systems with heating only, heating & cooling or full air conditioning
- modulating only dampers (both parallel blade & opposed blade) or fixed & modulating damper systems
- system intakes supplying single AHUs, intake ducts shared by separate AHUs, common intake plenums serving several AHUs.

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