The Role of Ventilation
15th AIVC Conference, Buxton, Great Britain
27-30 September 1994

The Testing and Rating of Terminals used on Ventilation Systems

P Welsh

Building Research Establishment, Garston Watford, Herts
WD2 7JR United Kingdom

TESTING THE PERFORMANCE OF FREE STANDING VENTILATION TERMINALS

By Paul Welsh BSc

Building Research Establishment, Garston, Watford, Hertfordshire, WD2 7JR, UK.

Summary
Terminals are used on all types of ventilation system exhausts, often to prevent rain water and animal entry, but also to prevent wind induced flow-reversal and enhance wind induced up-draught. There are many different terminal designs available displaying a wide range of characteristics.

This report discusses a terminal testing and rating method. The tests highlight terminal wind performance as well as terminal resistance to the exhaust flow. The terminals are ranked according to loss coefficients and wind performance which allows them to be matched more closely to system requirements.

Whilst the data gathered here can help with the choice of terminal for any ventilation system, it is probably most applicable to those systems affected by the wind. Such systems include passive stack ventilation, passive gas extraction, combustion flues and chimneys.

This paper is intended as a test guide for manufacturers and as source of information to help system designers with terminal selection.

1. Introduction
Terminals are used on all types of ventilation systems, ranging from mechanical air-conditioning units to chimneys and passive ventilation systems, and their presence inevitably alters system behaviour. Often a particular design is installed for a specific reason; for example to increase wind induced up-draught or prevent wind induced flow-reversal.

Numerous designs are available displaying a wide variety of properties. Wind tunnel testing can highlight both desired and undesired properties, and by rating terminal performance installers can choose the best design for a particular application. For example, a passive gas extraction system may require a terminal which causes up-draught due to wind action whilst the chimney of an open-fire may benefit more from one which prevents wind induced flow-reversal.

This paper discusses a procedure for testing free standing terminals (as opposed to roof ridge vents or tile vents) which can be used as a basis for manufacturers to test their own products. A rating method is suggested which rates terminal performance relative to other designs.

2. Nomenclature
The following notation is used in this report.

C_p	-	a pressure coefficient defined as $C_p = 2\Delta P_{ab}/(\rho U^2)$
$C_{p\|v=0}$	-	value of C_p when v=0
d	-	duct diameter (m)
g	-	acceleration due to gravity (m/s^2)

K	-	loss coefficient of a terminal
P_{dw}	-	dynamic pressure in the wind (Pa)
P_a, P_b	-	static pressure in the duct and wind respectively (Pa)
Re_{in}	-	Reynolds number relating to the flow inside the duct
Re_{ex}	-	Reynolds number relating to the wind and geometry of the terminal
S	-	suction coefficient
U	-	average wind speed (m/s)
v	-	average duct flow speed (m/s)
Z_a, Z_b	-	height of point 'a' and 'b' above reference level respectively (m)
ρ, ρ_d, ρ_w	-	density of air, of air in duct and of air in wind respectively (kg/m^3)
ν_d, ν_w	-	kinematic viscosity of air in duct and wind respectively (m^2/s)
ΔP	-	a static pressure difference (Pa)
ΔP_{ab}	-	static pressure difference between points 'a' and 'b' ie. $P_a - P_b$ (Pa)
ΔP_{loss}	-	pressure loss due to flow resistance of terminal between points 'a' and 'b'. $\Delta P_{loss} = ½K\rho v^2$ (Pa)
$\Delta P_{suction}$	-	pressure change between points 'a' and 'b' caused by wind. $\Delta P_{suction}=½S\rho U^2$ (Pa)
ΔP_i	-	wind and duct flow interaction factor (Pa)

3. Theory

3.1 Flow resistance

Ventilation ducts, terminals, bends, and inlets all restrict flow to some extent and cause pressure drops. Loss coefficients give a measure of this resistance, the larger the factor, the greater the resistance.

The loss coefficient, K, for a terminal is defined by:

$$K = 2\Delta P/(\rho v^2) + 1 \quad (1)$$

where ΔP is the static pressure drop across the component and v is the average air velocity through that component. It is calculated under zero wind conditions.

For turbulent duct flow (Reynolds number, Re_{in}, >5000) terminal loss coefficients are approximately constant. It is this value that is calculated. For laminar flow (Re_{in}<2000) the loss coefficient varies inversely with Reynolds number[1].

3.2 Wind effects

Wind can have significant effects on the performance of a ventilation system, especially when the system operates passively. It can assist the flow by causing up-draught or it can restrict the flow and may sometimes cause flow-reversal. Such effects depend on the ventilation system, terminal design, wind angle and wind direction.

To analyse wind performance two separate flows need to be considered, ie the wind and duct flow. Dimensional analysis and Bernoulli's equation, discussed below, give an insight to how terminals perform in the wind.

3.2.1 Dimensional Analysis

Assume that the static pressure difference, ΔP_{ab}, between the inside of the duct and the wind is (for a particular wind direction, wind angle and terminal geometry) a function of v, U, ρ_d, ρ_w, ν_d, ν_w, d. That is:

$$\Delta P_{ab} = h(v, U, \rho_d, \rho_w, \nu_d, \nu_w, d) \qquad (2)$$

which in dimensionless terms gives,

$$C_p = \Delta P_{ab}/P_{dw} = j(v/U, \rho_d/\rho_w, Re_{in}, Re_{ex}) \qquad (3)$$

Experimental data[2] shows that the pressure coefficient C_p is independent of both Re_{in} and Re_{ex}. Hence if the two air densities are equal ($\rho_d=\rho_w$), C_p is a function of v/U alone, ie:

$$C_p = j(v/U). \qquad (4)$$

3.2.2 Bernoulli's equation

Applying Bernoulli's equation between points 'a' and 'b' in Figure 1 we find,

$$P_a + \rho_d g Z_a + \rho_d v^2/2 = P_b + \rho_w g Z_b + \rho_w U^2/2 + L \qquad (5)$$

where $L = \Delta P_{loss} + \Delta P_{suction} + \Delta P_i$.

After substituting the relevant expressions for ΔP_{loss} and $\Delta P_{suction}$ (see Nomenclature), and if $\rho_w=\rho_d=\rho$ and $Z_a = Z_b$, it follows that:

$$C_p = 2\Delta P_{ab}/(\rho U^2) = C_{p|v=0} + (K-1)(v/U)^2 + (\Delta P_i/P_{dw}) \qquad (6)$$

where the coefficient $C_{p|v=0}$ is a constant. ΔP_i is an unknown representing a pressure difference due to the interaction between the wind and duct flows. This will depend on terminal geometry, wind direction and wind angle.

4. Experimental details

It has been shown in the theory that the pressure coefficient C_p is a function of v/U. Thus the performance of a terminal can be found by measuring the variation of C_p as v and U vary.

The experimental rig, devised after the revision of the existing British Standard[3] and previous work in this area, is shown in Figure 1. A fan provides a constant flow through a duct. The flow rate, controlled by a butterfly valve, is monitored using a volumetric flow meter. Swirl, caused by the fan, is reduced prior to air entering the flow meter by using a flow straightener. Simulated duct flow velocities, v, are 0, 1, 2, 4m/s for the 110mm diameter duct and 0, 1, 2, 3m/s for the 150mm diameter duct. These represent typical flows found in most types of ventilation systems.

From the flow meter the air passes through a length of flexible pipe to the base of the duct and then through another flow straightener. The duct (either 110mm or 150mm in diameter depending on the terminal size) measures a minimum of 13 diameters from the flow straightener to the pressure tappings. This length, together with the flow straightener, provides for an approximately uniform velocity profile within the pipe at the pressure tapping location.

To avoid interference from air exiting the system through the terminal, the wall pressure in the pipe is monitored 0.5m from the terminal. The tapping points are made, located, and connected to the micromanometers according to BS848[4]. The static pressure difference, ΔP_{ab}, between the pipe wall and the wind is monitored by two identical micromanometers to ensure the results are both accurate and reliable.

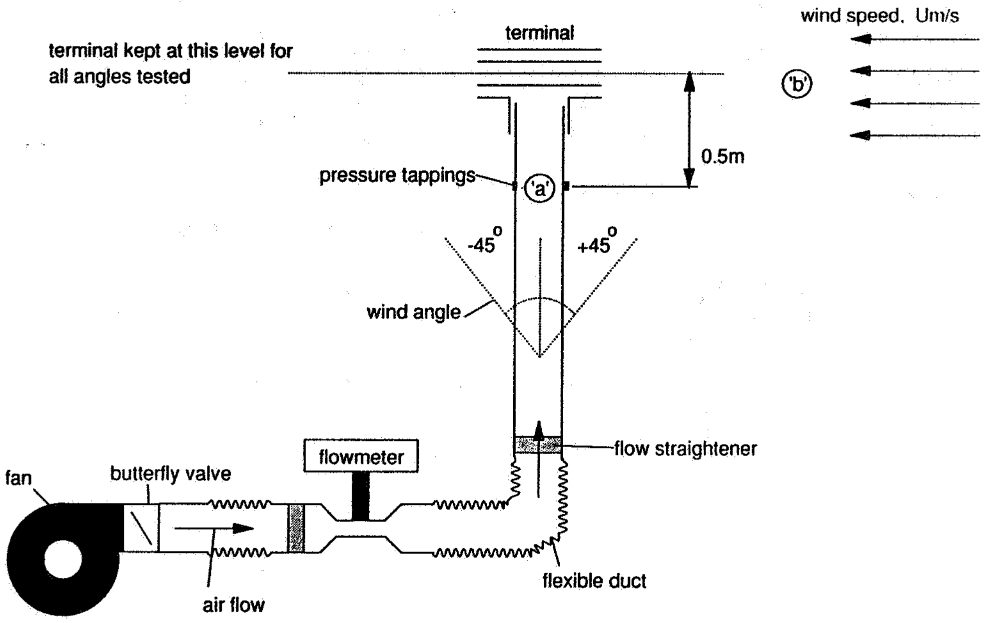


Figure 1: The experimental apparatus

A open-jet wind tunnel blows air directly at the terminal at speeds, U, between 0m/s and 10m/s, monitored using a pitot-static tube connected to a micromanometer. There are no blockage effects since the entire rig sits outside of the tunnel and the terminals are small relative to the tunnel cross-section.

The ventilation pipe can be tilted to monitor the terminals performance for various wind angles from the vertical. Angles range from -45° (away from the wind) to +45° (into the wind), in 15° steps. The terminal is kept at the same height (in line with the centre of the wind tunnel) for each angle by moving the ventilation pipe (see Figure 1). This ensures, as far as possible, that the wind speed conditions are the same for each angle.

Performance variation with wind direction is also investigated when necessary, depending on terminal geometry. For terminals that are symmetrical about the ventilation pipe centre line, only one wind direction is needed. For others, tests are carried out with the wind blowing onto the side with the minimum cross-sectional area and with it blowing onto the side with the maximum cross-sectional area. This is in accordance with BS715[3].

The pressure differences are monitored for a specific wind angle and wind direction as the duct flow and wind speed is varied. The tests are repeated for all combinations of wind angles and wind directions for each terminal. The terminals tested are shown in Figures 2 and 3.

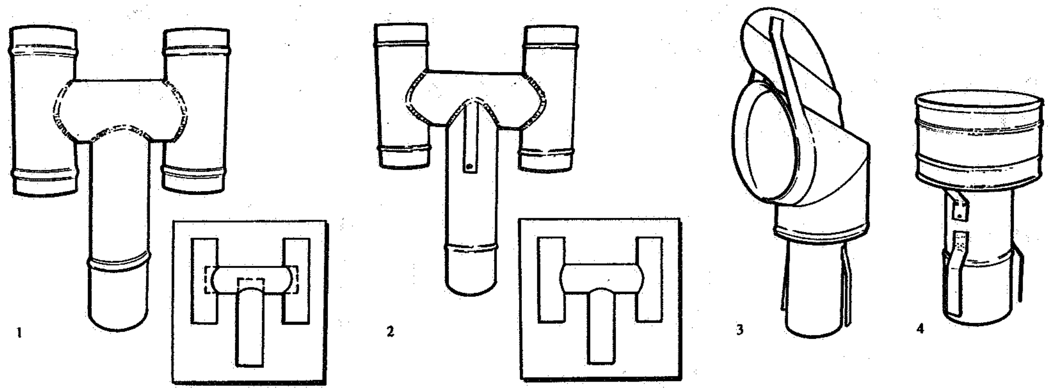


Figure 2: The 110mm terminal designs

1- H pot 1	2- H pot 2
3- Grey vane	4- Gas flue
5- Mushroom cap	6- Balloon

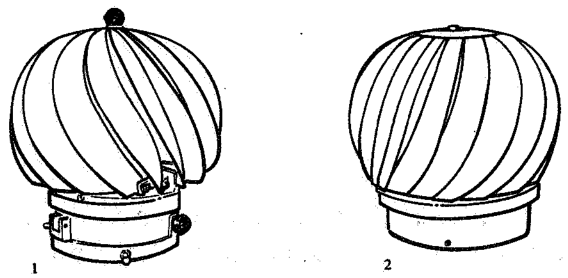
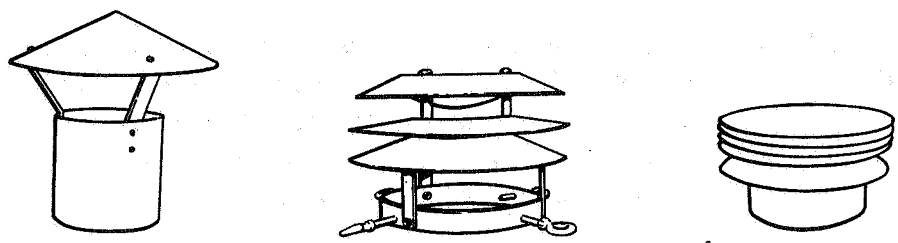


Figure 3: The 150mm terminal designs

1- Rotating cowl 1	2- Rotating cowl 2
3- Chinese hat	4- Aero-dynamic cowl
5- Gas flue	



5. Data analysis and results

5.1 Flow resistance

From Equation 1, a plot of ΔP_{ab} against $\frac{1}{2}\rho v^2$ will produce a straight line with gradient equal to K-1. Table 1 shows the loss coefficients for the designs shown in Figures 2 and 3. The figures are ranked in descending order of performance with the least restrictive first.

Terminal 110mm	Loss factor, K	Terminal 150mm	Loss factor, K
Open pipe	1.0	Open-pipe	1.0
Mushroom cap	2.1	Chinese hat	1.1
Balloon	2.2	Rotating cowl 1	1.1
H pot 1	2.7	Rotating cowl 2	1.3
Gas flue	3.2	Gas flue	2.0
H pot 2	4.7	Aero-dynamic cowl	2.3
Grey vane	6.7		

Table 1: Ranking terminals using loss coefficients only

5.2 Wind effects

5.2.1 Suction

The pressure coefficient C_p indicates how a terminal is performing for a specific duct flow and wind condition. Plotting C_p against v/U gives an approximate quadratic (Equation 6, assuming ΔP_i is small compared to the other components). When the data lie in the negative C_p region the extractive properties of the terminal exceed the resistive. When data are in the positive C_p region resistive forces exceed the extractive.

The two values discussed below can be used to describe a terminal's extractive performance (see Figure 4):

a) the value of C_p when v=0, [$C_{p|v=0}$]. This factor gives an indication of the greatest suction that can be produced by a specific terminal. The more negative this value the greater the suction. A range of $C_{p|v=0}$ values are collected from the experiment since this value varies with wind direction an wind angle. From this range an average value and an error value (two standard deviations) are calculated.

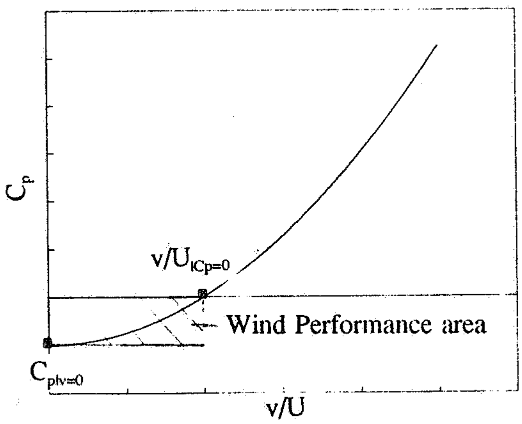


Figure 4: The suction performance indicators

b) the value of v/U when C_p=0, [$(v/U)_{|Cp=0}$]. This indicates the v/U range for which the extractive property dominates the resistive. As with $C_{p|v=0}$, this value varies with wind direction and angle, and an average value and error value (two standard deviations) are calculated.

Under specific conditions a terminal may not cause suction when v=0 (an example of this is when open pipe points into the wind causing flow-reversal). When this is the case the minimum of the $(v/U)_{|Cp=0}$ range is undefined, and in such cases flow-reversal is possibility.

These two figures are best combined by multiplying together the average of each range to produce a single *wind performance indicator*. This figure indicates the average performance over the conditions examined. Table 2 shows these values in descending order of performance, the first being the terminal that induces up-draught the most.

Terminal 110mm	Wind performance indicator	Terminal 150mm	Wind performance indicator
H pot 1	-0.23 ± 0.22	Rotating cowl 1	-0.53 ± 0.50
Balloon	-0.16 ± 0.09	Rotating cowl 2	-0.12 ± 0.07
H pot 2	-0.16 ± 0.13	Gas flue	-0.07 ± 0.04
Gas flue	-0.11 ± 0.11	Aero-dynamic cowl	-0.03 ± 0.04
Grey vane	-0.09 ± 0.04		

Table 2: Wind performance indicator ranking

5.2.2 Flow-reversal

The easiest way of identifying flow-reversal potential is to inspect the $C_{plv=0}$ range. If the maximum value is positive then there is flow-reversal potential. Alternatively flow-reversal is possible whenever the pressure drop across the terminal increases with wind speed ie. $d(\Delta P_{ab})/dU > 0$.

It is shown in Figure 5 how the wind angle alters the performance of a "Mushroom cap" terminal. Flow-reversal will not occur between the angle range 45° to -15°, but it can for angles -30° and -45°. Figure 6 shows the results for the "H pot 1". This terminal protects against flow-reversal for all wind angles investigated.

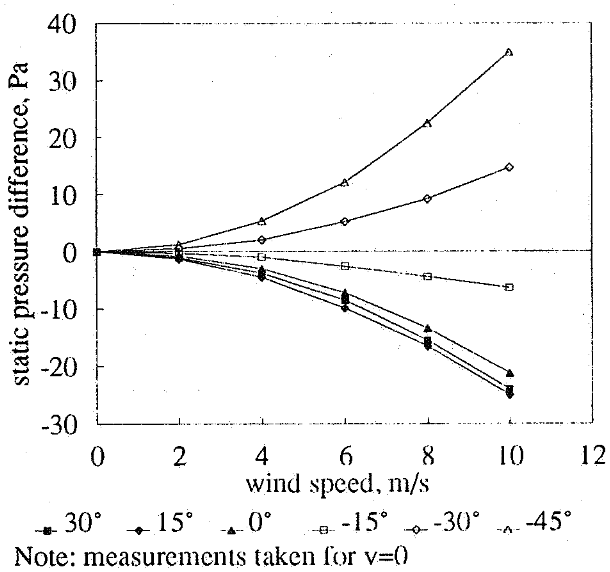


Figure 5: Flow-reversal for the "Mushroom cap" at -30° and -45°

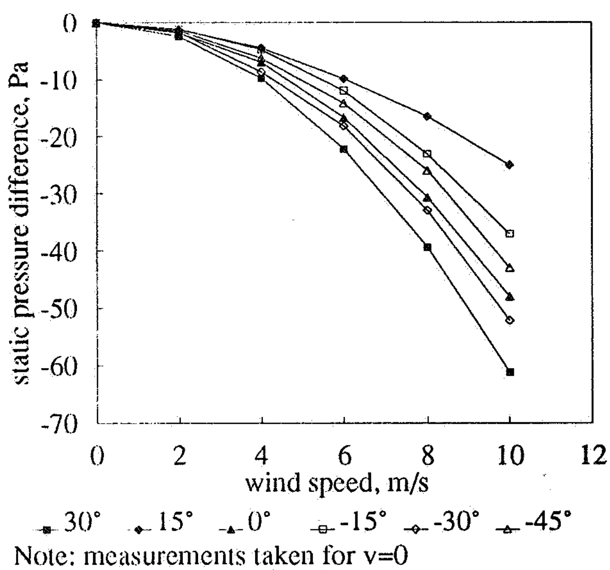


Figure 6: No flow-reversal for "H pot 1"

6. Discussion of results

Loss factors are seen to vary widely, some designs being considerably more restrictive than others. For mechanical ventilation systems the loss coefficient ranking (Table 1) may be used as a basis for terminal selection. Note the large difference between the loss factors for the two H type terminals which are visually similar.

For systems affected by the wind the wind performance indicator (Table 2) should be used to select terminals. A large 'error' is associated with this type of indicator because of the wide range of wind conditions examined. The error shows how consistent a terminal performs over the range of conditions. It is interesting that there is a large difference between the two rotating cowls.

Terminals capable of causing flow-reversal are the open pipe, "Mushroom cap" and "Chinese hat". This will only occur for specific wind directions and angles and it is most likely to occur in passive ventilation systems. Terminals which display such properties are undesirable especially when used on open-flued combustion appliances.

7. Conclusions

The test procedure discussed in this paper can be used to rank terminal performance. Such data allows terminals to be selected on the merit of their performance.

Terminals can be rated using three factors that are easy to establish ie loss coefficient, wind performance indicator and flow-reversal potential. Loss coefficients are most significant for mechanical ventilation systems whilst wind performance is more relevant for passive venting systems. Protection against flow-reversal is important for ventilation of open-flued combustion appliances.

The terminals examined in this paper may be grouped as follows:
(a) those with large loss factors (the most restrictive): "Gas flue" (110mm), "H pot 2", and "Grey Vane".
(b) those good at inducing up-draught: "Rotating cowl 1", "H pot 1".
(c) and those which may cause flow-reversal: open pipe, "Mushroom cap", "Chinese hat".

8. References

1. Miller D S
"Internal flow systems"
Volume 5 in the BHRA fluid engineering series (1979)

2. Gonzalez M A
"On the aerodynamics of natural ventilators"
Building and Environment Volume 19 N°3 179-189 (1984)

3. BS 715 : 1989 British Standard Specification for "Metal flue pipes, fittings, terminals and accessories for gas-fired appliances with a rated input not exceeding 60kW"

4. BS 848 : PART 1 : 1980 British Standard, "Fans for general purposes: Part 1. Methods of testing performance"