UNSTEADY WIND EFFECTS IN NATURAL VENTILATION DESIGN

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Unsteady wind effects can be important in natural ventilation, but their treatment requires knowledge of instantaneous surface pressure distributions which are extremely difficult to obtain. The paper describes a theoretical investigation aimed at determining the effects of unsteadiness and, perhaps more important, the conditions for which it may be worth accounting for them in the design process. For generality the study uses nondimensional parameters.

The effects of unsteadiness on both mean and instantaneous flow rates are covered. The latter effect is particularly important for natural ventilation stacks, where flow reversal is undesirable.

It is concluded that unsteady effects can be important, but they are restricted to a relatively narrow range of conditions. A simple procedure for calculating the mean flow rates when the unsteady effects are large has been derived. In its simplest form the procedure does not require knowledge of the instantaneous wind pressures.

For instantaneous flow rates it is shown that substantial reductions in the occurrence of flow reversal can be achieved by the use of long ducts, but the siting of openings is also important.

Current Natural Ventilation Design Procedures

The determination of the size and position of openings in the envelope is perhaps the most important aspect of a natural ventilation design. Although design procedures are available [1,7], they invariably assume steady flow conditions. In fact the basic design condition is usually taken to be the case with stack effect alone (zero wind speed). It is however relatively easy to extend the calculations to include wind effects, provided the envelope flows are treated as completely steady [2]. The main difficulty is in specifying the relevant wind parameters, namely wind speed and surface pressure distributions but fortunately the latter information is often available in data sheets [8].

The treatment of envelope flows as completely steady is of course an approximation in the presence of wind. Unsteady wind effects are however very difficult to deal with. There are several reasons for this, but the most straightforward one is that a proper treatment requires knowledge of instantaneous surface pressures. Not only does one need to know the time variation of the pressures, but such records need to be simultaneous. Such data is very scarce, because of the difficulty and expense of obtaining it. This raises the question of how important it is to include unsteady effects. The aim of the present study was to investigate these effects and to determine under what conditions account should be taken of them. For generality the investigation was carried out in nondimensional form.

Basic Theory for Unsteady Envelope Flows

The unsteadiness in the wind manifests itself as fluctuations in the external surface pressures and these lead to fluctuations in the flow rates through the envelope openings and in the internal pressure. The internal pressure fluctuations are accompanied by changes in density. These changes are small, but they affect a large volume and the associated rates of change of mass can be of similar magnitude to the total flow rates through the openings. Thus the unsteady flow theory needs to account for two effects, namely the unsteady behaviour of the openings and the compressibility of the internal air. The theory used here is described in detail in [3] and [4]. The compressibility effect is relatively straightforward, because the behaviour of the internal air should follow the isentropic relation between pressure and density. It can therefore be accounted for by a modification to the continuity equation. For the conditions which are considered here, the effects of compressibility are usually less important than the effects of inertia, particularly when dealing with instantaneous flows in ducts. However at high frequencies of fluctuation they are important and since they are easier to model they should generally be included.

The unsteady flow behaviour through the openings is much more difficult to treat. The approach adopted is known as the "quasi-steady temporal inertia" theory (see page 76 of [5]). Basically the pressure difference across an opening is divided into three components associated with momentum change between inlet and outlet, wall friction (with long openings such as stacks) and unsteady inertia. To account for the first two components it is assumed that they are given by the steady flow relationships applied at each instant of time - hence the term "quasi-steady". The third component, the inertia term, is accounted for by evaluating the force (per unit area) required to accelerate an "effective volume" of air which has a velocity equal to the mean velocity through the opening. The effective volume is obtained empirically.

Two types of opening are considered. The first is a square-law opening such as an open window or air vent, with a steady discharge coefficient, C_z, equal to about 0.6. The second type is a long duct, where the discharge coefficient depends on the length/diameter ratio, L/d, and on Reynolds number, Re. For the high Reynolds numbers encountered with large ventilation stacks, the flow can be expected to be turbulent with only a weak dependence of C_z on Re. For the present calculations C_z is therefore assumed to be constant for this type of opening and it too can be treated as a square-law opening.

With the above assumptions, the equations which describe the flow through two openings are, in nondimensional form,

$$\frac{1}{D}\frac{dC_{PI}}{dt'} = q_1'\{t\} + \frac{C_{z2}A_2}{C_{z1}A_1}q_2'\{t\} \qquad (1)$$

$$q_1'^2.S_{q1} + \frac{2}{F_1}\frac{dq_1'}{dt'} = -C_{PI} - 2Ar.\frac{z_1}{H} + C_{p1} \qquad (2)$$

$$q_2'^2.S_{q2} + \frac{2}{F_2}\frac{dq_2'}{dt'} = -C_{PI} - 2Ar.\frac{z_2}{H} + C_{p2} \qquad (3)$$

Equation (1) is the mass conservation equation for the air contained within the envelope. For a sharp-edged opening, the flow equations (2) and (3) are derived from the unsteady Bernoulli equation (see [3]). For a duct, the equations are derived from the momentum principle applied to the air within the duct (see [4]). In both cases, the inertia term (the second term on the left hand side) is described by an effective length, l_e, which is empirically related to the geometry of the opening. For a duct l_e is taken as the sum of L

and the effective lengths of the inlet and outlet. The derivation of the equations and the notation are summarised in the Appendix. The three simultaneous differential equations for the internal pressure and the two flow rates have been solved using Matlab [6] software.

Scope of Calculations

The calculations include buoyancy as well as wind effects and the use of nondimensional graphs makes the results of wide application. However there are some limitations to the calculations which need to be appreciated. The main one is that the number of openings is restricted to two. There are however many buildings which have two dominant openings. Figure 1 shows the basic cases which are covered.

Case 1. Single large space with two sharp-edged openings.
This case is perhaps the most hypothetical of the five. It can however represent a simple atrium.
Cases 2 and 3. Isolated rooms with respectively single-sided and crossflow ventilation.
Single-sided ventilation of office rooms is a common strategy with natural ventilation. The instantaneous wind pressures are likely to be almost identical with single-sided openings. With cross-flow openings the instantaneous differences may be very large.
Case 4. Single large space with one sharp-edged opening and one long opening.
Good examples of this case are the lecture theatres in the Queen's building at De Montfort University in the UK [1]. Also covered by this case are certain configurations of "windcatchers". The large distance between the inlet and outlet implies that the correlation between the pressures will be relatively low.
Case 5. Single space with two long openings in close proximity. This case corresponds to a certain type of "windcatcher" whereby the inlet and outlet ducts form a single unit. The proximity of the inlet and outlet implies that differences between the phase and frequencies of the pressure fluctuations at the two points will be relatively small i.e. high correlation.
Case 6. Single space with two long openings, one vertical and one horizontal. An example of this approach is the Canning Crescent Centre [1]. The basic aim is that fresh air entry is taken from a less polluted area via the horizontal duct.

Some of the calculations presented in [3] and [4] were carried out with simple sinusoidal fluctuations of the wind pressures and some were carried out using real simultaneous records of pressure (of duration 27 minutes).

The parameter $W/\sigma_{\Delta Cp}$.

It will be seen below that a parameter which is of overriding importance is $W/\sigma_{\Delta Cp}$. This parameter is a measure of the relative sizes of the steady pressure difference (due to wind and stack effect) and the fluctuating component of the pressure difference (due to wind). W is defined by

$$W = Ar\left(\frac{z_2}{H}-\frac{z_1}{H}\right)+\left(\frac{\overline{C_{p1}}-\overline{C_{p2}}}{2}\right) \qquad (4)$$

where the first term is due to buoyancy and the second term is the difference between the mean wind pressure coefficients. W appears explicitly in the conventional steady state solution (i.e. $q_1 = q_2 = \sqrt{W}$). $\sigma_{\Delta Cp}$ is the standard deviation of the instantaneous difference between the surface wind pressure coefficients, where $\Delta C_p = C_{p1} - C_{p2}$. Clearly as $W/\sigma_{\Delta Cp}$ becomes large, unsteadiness will have a smaller effect and vice versa. Table 1 gives some idea of the values of W which may be encountered in practice for a large building in summer (ΔT = 3 K) and winter (ΔT = 20 K) at two wind speeds. With $\sigma_{\Delta Cp} = 0.3$, $W/\sigma_{\Delta Cp}$ ranges from 0.9 to 37.5.

Table 1

Wind speed U [m/s]	$H = z_2 - z_1$ [m]	$C_{p1}-C_{p2}$ [-]	Summer Ar [-]	Summer W [-]	Winter Ar [-]	Winter W [-]
1	16	0.5	1.6	1.85	11.0	11.25
10	16	0.5	0.016	0.27	0.11	0.36

For the above Table, the reference height, *H*, has been taken as the height between the two openings. *Ar* is the Archimedes number defined by (A5) in the Appendix.

Effects on Mean Flow Rates

The main effects of unsteadiness on mean flow rates are summarised by the solid line in Figure 2. The line is a fit to calculated results, but the variation about the line is not great (typically less than 10 %). The nondimensional total fresh air flow rate, $q'_F / \sqrt{\sigma_{\Delta Cp}}$, is plotted against the pressure parameter $W/\sigma_{\Delta Cp}$. q'_F is the actual flow rate divided by $C_z A U$ (see equation A4).

The hatched line shows the results of the normal steady calculation procedure. The steady results can be plotted on the unsteady graph, because the steady solution is simply given by $q'_F = \sqrt{W}$ i.e. $q'_F / \sqrt{\sigma_{\Delta Cp}} = \sqrt{W / \sigma_{\Delta Cp}}$. For $W/\sigma_{\Delta Cp} > 0.4$ the effect of unsteadiness is small and the steady calculation method should suffice. When $W/\sigma_{\Delta Cp} < 0.4$ it may be preferable to employ the unsteady calculation method, but the requirement for simultaneous records of pressure fluctuations is very demanding. If such records are not available, the nondimensional graph of Figure 2 can be used to give reasonable estimates much more easily. The main problem is to specify $\sigma_{\Delta Cp}$. If the standard deviations of the pressure coefficients are known, σ_1 and σ_2, they can be used to estimate $\sigma_{\Delta Cp}$. Tabulated data for σ_1 and σ_2 is available, although not to the same extent as mean pressure coefficients. Values of $\sigma_{\Delta Cp}$ for the pressure records used here range from 0.22 to 0.40 and the values of σ_1 and σ_2 from 0.08 to 0.32.

For $W/\sigma_{\Delta Cp} > 0.4$, the steady and unsteady solutions converge. The steady solutions are larger than the unsteady values, because the square-root of the time-averaged pressure difference is greater than the time-average of the square-root.

It is worth noting (see Table 1) that high temperature differences (large *Ar*), high (C_{p1}-C_{p2}) and/or low wind speeds leads to values of $W/\sigma_{\Delta Cp}$ which are much greater than 0.4. For most cases therefore an unsteady calculation is not needed for *mean* flow rates. For Case 2 however (and possibly Case 5) the values of (C_{p1}-C_{p2}) will tend to be small and with low temperature differences an unsteady calculation may be desirable. As a very simple example of this, one can take Case 2 with two openings of area A = 0.01 m^2, U = 4 m/s,

H = 1.5 m, ΔT = 10 K, $(C_{p1}-C_{p2})$ = 0 and $\sigma_{\Delta Cp}$ = 0.3. It follows that Ar = 0.03 and $W/\sigma_{\Delta Cp}$ = 0.1. From Figure 2, $q'_F / \sqrt{\sigma_{\Delta Cp}}$ = 0.54 and hence q'_F = 0.30 and the total fresh air flow rate, q_F, is 26 m^3/h. The steady flow result is 15 m^3/h. For the same case but with ΔT = 0 K, the unsteady and steady results are respectively 25 and 0 m^3/h.

Effects on Instantaneous Stack Flow

Not surprisingly the parameter $W/\sigma_{\Delta Cp}$ is also of overriding importance to the instantaneous flow rates in stacks. However, because we are dealing with instantaneous flow rates it is not possible to summarise the results in a general way, partly because the detailed nature of the instantaneous pressures is important.

An important feature is to what extent the use of ducts with their increased inertia reduces the occurrence of flow reversal. This has been investigated using simple hypothetical gusts and recorded time-histories.

Figure 3 shows the volume of flow reversal for a given gust strength at typical winter design conditions. Three curves are shown corresponding to the three different opening configurations, namely Cases 1, 4 and 6 in Figure 1. The precise definitions of the plotted quantities are not of interest here. The point of interest is the effect of the ducts and it can be seen that they lead to a clear increase in the resistance to flow reversal. For example, the gust strength required to cause flow reversal increases from about 0.8 to 3.0 with one duct and to 6.0 with two ducts. This is purely due to the increased inertia; the duct resistance is taken account of by the discharge coefficient included in the nondimensional volume.

In reality the effect of ducts is rather more complex and depends on the detail of the pressure fluctuations. Figure 4 shows results obtained for one of the pressure records in the form of a plot of reversal volume against $W/\sigma_{\Delta Cp}$ again using the three opening configurations. Flow reversal occurs for all configurations and this is a reflection of the chosen pressure record, which has long periods of adverse pressure differences. The avoidance of flow reversal can only be guaranteed by siting the openings such that $W/\sigma_{\Delta Cp}$ exceeds a value of about 1.0 for all wind directions. This emphasises the need to achieve sites with a large value for $(C_{p1}-C_{p2})$. However even in this case the addition of ducts gives clear benefits.

Conclusions

Accounting for unsteady wind effects in natural ventilation design is very difficult and will often not be justifiable, simply because of the amount of input data required to solve the equations. Unsteady effects can be important, but they are restricted to a relatively narrow range of conditions which can be approximately described by the parameter $W/\sigma_{\Delta Cp}$. If this parameter exceeds 0.4, unsteady effects on *mean* flow rates can probably be ignored. When the unsteady effects are thought to be large, estimates of mean flow rates can be obtained by means of a simple graphical procedure which does not require knowledge of the instantaneous wind pressures.

For *instantaneous* flow rates the main concern is with the potential for reducing the occurrence of flow reversal by the use of long ducts instead of sharp-edged openings. Substantial reductions can be achieved in this way. The results also indicate that the best way to avoid reversal is to site the openings such that the parameter $W/\sigma_{\Delta Cp}$ is never less than about 1.

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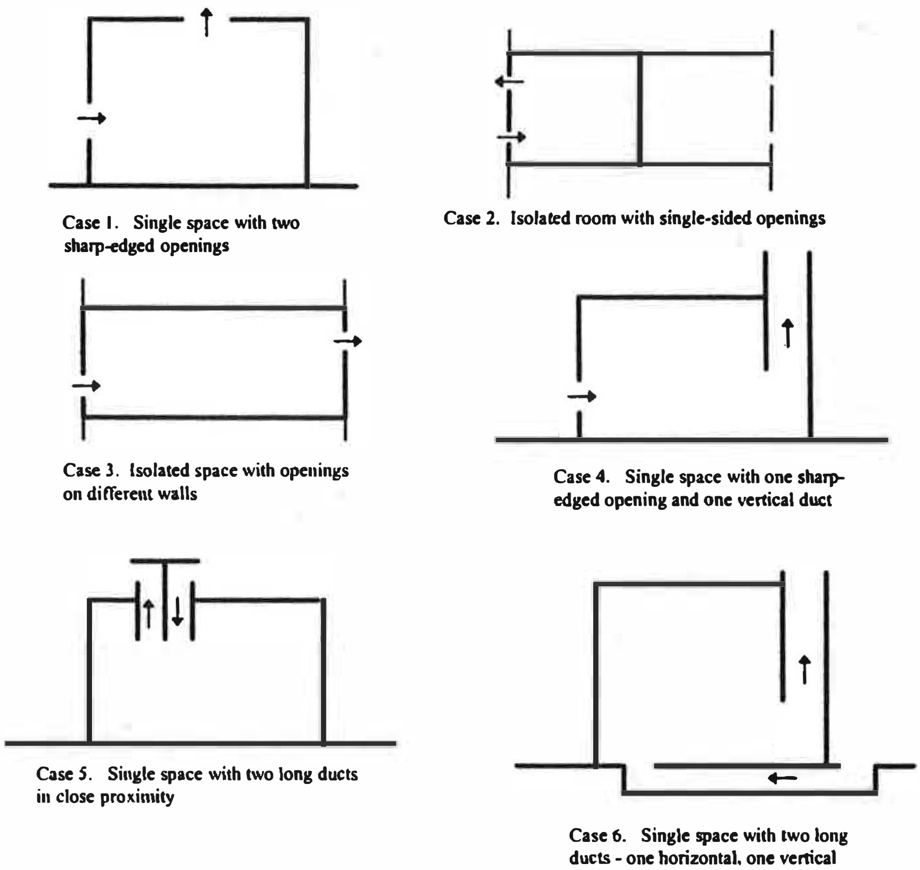

Figure 1 Opening configurations covered by the calculations

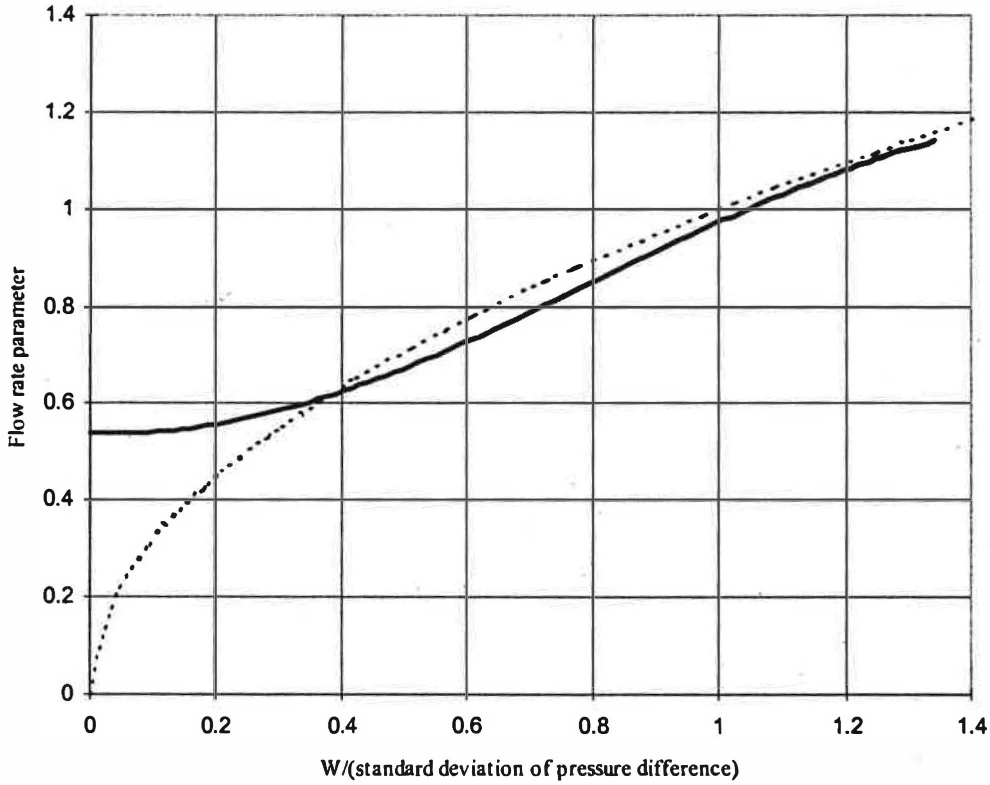

Figure 2 Summary graph of unsteady wind effects on total mean flow rate. Solid and hatched lines are respectively from unsteady and steady theories.

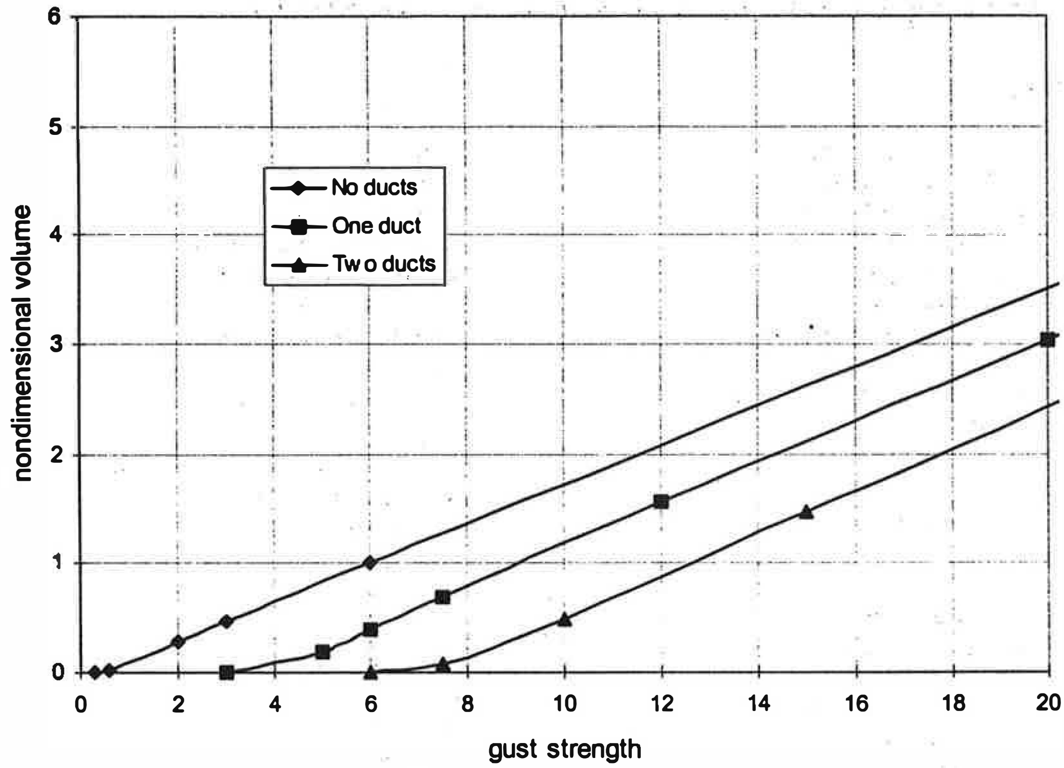

Figure 3 Effect of duct inertia on flow reversal volume in vertical stack exposed to hypothetical gust of varying strength.

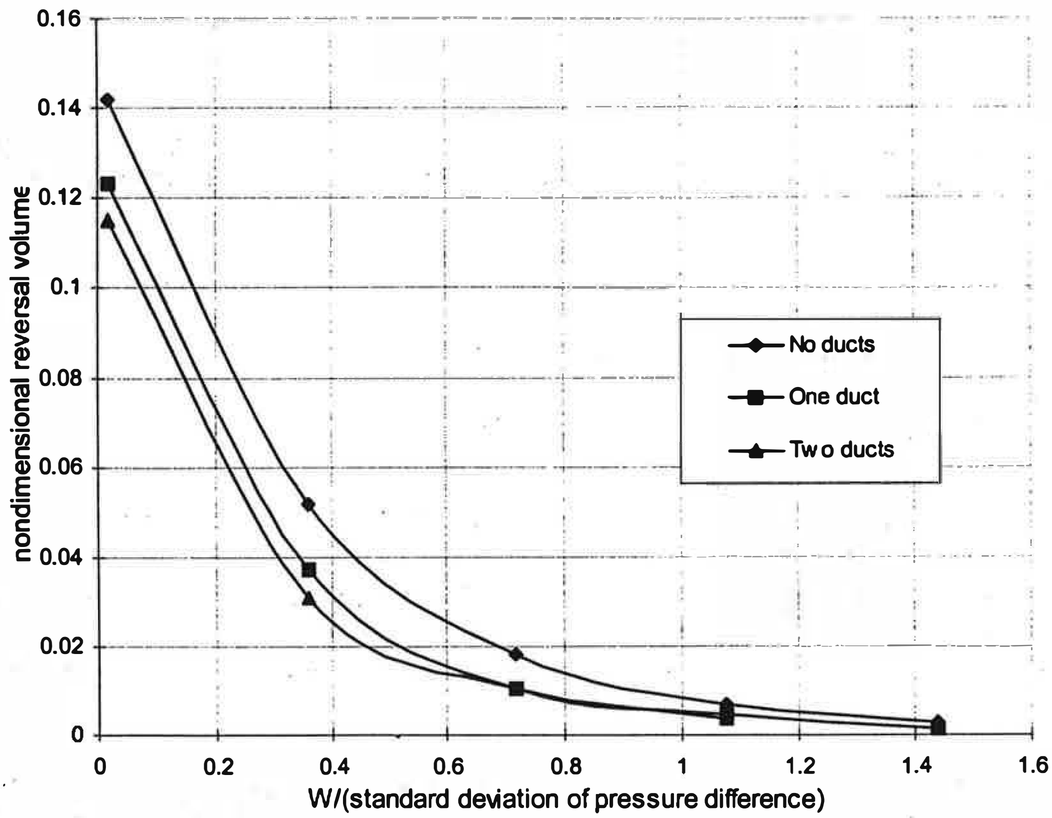

Figure 4 Summary graph of unsteady wind effects on total mean flow rate for a real wind pressure record.

APPENDIX Equations for quasi-steady temporal inertia theory

Notation

A	area of opening	[m^2]
Ar	Archimedes number, defined by (A5)	[-]
c	speed of sound	[m/s]
C_{pI}	internal pressure coefficient defined by (A11)	[-]
C_{p1}, C_{p2}	wind pressure coefficients defined by (A10)	[-]
C_z	discharge coefficient	[-]
D	coefficient defined by (A8)	[-]
F	coefficient defined by (A9)	[-]
g	gravitational force per unit mass	[m^3/s]
H	reference height	[m]
l_e	effective length of opening	[m]
L	depth of opening	[m]
p	pressure due to wind	[Pa]
P	absolute pressure	[Pa]
q	volume flow rate through opening	[m^3/s]
q'	nondimensional flow rate defined by (A4)	[-]
S_p, S_q	sign of Δp and q	[-]
t	time	[s]
t'	nondimensional time defined by (A6)	[-]
U	reference wind speed	[m/s]
V	volume of space	[m^3]
W	defined by (4)	[-]
z	height of opening from ground	[m]
γ	ratio of specific heats	
ρ	density	[kg/m^3]
$\Delta\rho$	density difference	[kg/m^3]
Δp	pressure difference	[Pa]
σ	standard deviation	
$\sigma_{\Delta Cp}$	standard deviation of ΔC_p	[-]
τ	time scale, H/U	[s]

Subscripts

1,2	opening number
E	external
F	fresh air
I	internal
w	wind surface pressure
0	z = 0

overbar denotes time mean

The dimensional equations used to describe the flow through two openings (with square-law characteristics) are the continuity (mass conservation) equation for the air within the envelope

$$\frac{V}{\gamma}\frac{1}{P_{I0}}\frac{dp_{I0}}{dt} = q_1\{t\} + q_2\{t\} \qquad \text{(A1)}$$

and the flow equations for the two openings

$$\left(\frac{\rho q_1\{t\}^2}{2C_{z1}^{\ 2}A_1^{\ 2}}\right).S_{q1} + \rho\frac{l_{e1}}{C_{z1}A_1}\frac{dq_1}{dt} = p_{w1}\{t\} - p_{I0}\{t\} - \Delta\rho.gz_1 \qquad \text{(A2)}$$

$$\left(\frac{\rho q_2\{t\}^2}{2C_{z2}^{\ 2}A_2^{\ 2}}\right).S_{q2} + \rho\frac{l_{e2}}{C_{z2}A_2}\frac{dq_2}{dt} = p_{w2}\{t\} - p_{I0}\{t\} - \Delta\rho.gz_2 \qquad \text{(A3)}$$

In the latter two equations, the first term on the left-hand side is the steady flow pressure difference arising from momentum change and the second term is the unsteady inertia term. On the right-hand side the pressure difference is generated by the surface wind pressures, p_{w1} and p_{w2}, and buoyancy.

It is convenient to express the equations in a nondimensional form, because solutions then become more general. The nondimensional flow rates $q_i'\{t\}$ are defined by dividing $q_i\{t\}$ by $C_{z1}UA_1$ and $C_{z2}UA_2$ respectively to give

$$q_1'\{t\} \equiv \frac{q_1\{t\}}{C_{z1}A_1U} \qquad q_2'\{t\} \equiv \frac{q_2\{t\}}{C_{z2}A_2U} \qquad \text{A4}$$

The relative strength of the buoyancy and wind forces is measured by the Archimedes number, defined as

$$Ar = \frac{\Delta\rho gH}{\rho U^2} \qquad \text{A5}$$

Time is nondimensionalised as follows

$$t' \equiv t/\tau \qquad \text{A6}$$

where

$$\tau \equiv H/U \qquad \text{A7}$$

The nondimensional coefficients which appear in the differential equations are the compressibility parameter

$$D \equiv \frac{2C_{z1}A_1H}{V}\frac{c^2}{U^2} \qquad \text{A8}$$

and the inertia parameters

$$F_1 \equiv \frac{H}{l_{e1}}, F_2 \equiv \frac{H}{l_{e2}} \qquad \text{A9}$$

Pressure coefficients arising from the wind (i.e. the unsteady pressure components) are defined by

$$C_{p1}\{t\} = \frac{p_{w1}\{t\} - p_{w0}}{0.5\rho U^2} \quad \text{and } C_{p2}\{t\} = \frac{p_{w2}\{t\} - p_{w0}}{0.5\rho U^2} \qquad \text{A10}$$

and $$C_{PI}\{t\} = \frac{p_{I0}\{t\} - p_{w0}}{0.5\rho U^2} \qquad \text{A11}$$

where p_{w0} is a steady reference pressure.

In the above definitions H and U are reference quantities which can be arbitrarily specified, although it is more useful for comparative purposes if they are chosen in an appropriate way.

The nondimensional form of the equations is then

$$\frac{1}{D}\frac{dC_{PI}}{dt'} = q_1'\{t\} + \frac{C_{z2}A_2}{C_{z1}A_1}q_2'\{t\} \qquad \text{A12}$$

$$q_1'^2.S_{q1} + \frac{2}{F_1}\frac{dq_1'}{dt'} = -C_{PI} - 2Ar.\frac{z_1}{H} + C_{p1} \qquad \text{A13}$$

$$q_2'^2.S_{q2} + \frac{2}{F_2}\frac{dq_2'}{dt'} = -C_{PI} - 2Ar.\frac{z_2}{H} + C_{p2} \qquad \text{A14}$$

where use in (A12) has been made of the expression for the speed of sound, c,

$$c^2 = \gamma\frac{\overline{P}_{I0}}{\rho} \qquad \text{A15}$$

and γ is the ratio of specific heats.