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A New Integrated Design Tool for Naturally Ventilated Buildings Part 1: Ventilation Model

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In many cases natural ventilation may be sufficient to ensure acceptable comfort levels in occupied buildings. In these cases installation of energy-intensive active environmental control systems will not be necessary. This will result in considerable energy and cost savings and also indirectly in a reduced burden on the environment, since the use of energy is always associated with the production of waste materials.

This paper describes the development of a new model to predict natural ventilation flow rates in buildings. The model employs a flow network where openings are represented by non-linear flow resistances. It accounts for both wind-induced pressures and pressures due to thermal forces. The model draws on a healthy balance between purely theoretical equations and empirical data. Simplified equations are derived through a synthesis of measured data obtained in boundary layer wind tunnel tests as well as from the literature. Tracer gas measurements show a good comparison between measured and predicted ventilation rates.

The implementation of the new model into an integrated design tool for naturally ventilated buildings is discussed in Part 2 of this paper.

NOMENCLATURE

- Q flow rate (m^3/s)
- C_d non-dimensional discharge coefficient
- A area of opening (m^2)
- α non-dimensional velocity profile exponent
- p pressure (Pa)
- C_p non-dimensional pressure coefficient
- y height of opening above ground level (m)
- V velocity (m/s)
- h height above ground level (m)
- θ azimuth angle (degrees)
- ρ density (kg/m^3)
- D grouping density (%)
- T temperature (K).

INTRODUCTION

IN MANY cases natural ventilation may be sufficient to ensure acceptable comfort levels in occupied buildings. In these cases installation of energy-intensive active environmental control systems will not be necessary. This will result in considerable energy and cost savings. It will also indirectly result in a reduced burden on the environment, since the use of energy is always associated with the production of waste materials.

Typical buildings where natural ventilation may be applied are factories, workshops, farm buildings, schools, residential buildings and even some offices. A major problem encountered in the design of these buildings is that it is difficult to optimize the ventilation design. The main reason for this is that there is a complicated interaction between the flow rate and the indoor air temperature which is not accounted for in existing design tools [1].

Mechanism of natural ventilation

In the context of buildings the term ventilation usually refers to flow through purpose-provided openings such as open windows and ventilators caused by natural driving forces. Infiltration on the other hand refers to background leakage through unintentional openings such as cracks under doors and in ceilings. Both of these are directly influenced by the pressure distribution on the building envelope and the characteristics of the different openings. The pressure distribution is the driving force for ventilation while the characteristics of each opening, among other things, determine the flow resistance.

The pressures on the building envelope consist of wind-induced pressures and pressures arising from the difference in temperature between the indoor and outdoor air. Wind-induced pressures are dependent on the geometry of the building, the orientation of the building with respect to the wind direction, the wind speed and the nature of the terrain surrounding the building. A good design tool should therefore account for each of these effects.

The pressures due to thermal forces arise from the difference in density between the indoor and outdoor air. This is commonly referred to as the 'stack effect'. The stack effect will theoretically only result in flow if there

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are at least two openings at different heights connected by a flow path inside the building. In practice a very tall single opening will however also allow flow. The top and bottom parts will in effect act as two different openings. The 'stack' effect must be addressed properly during the design stage.

The flow resistance, or conversely the permeability, of each opening is determined by a combination of the area of the opening and the so-called discharge coefficient. The discharge coefficient is dependent on the geometry of the opening and can usually only be determined empirically. A design tool should provide for the specification of different sizes and types of openings to ensure acceptably accurate results.

Since the wind-induced pressures and pressures due to the stack effect are the result of different mechanisms, they are not simply additive [2]. The combined effect of these two may in one case be to reduce the total flow rate through the building and in another case to increase it. A good natural ventilation design tool should therefore cater for both of these and also combine their effect in the correct manner.

Another important requirement of a good tool is that it should allow for the interaction between the thermal characteristics and the flow characteristics of the building. Since the flow rate is dependent on the difference in temperature between the indoor and outdoor air, the tool must be able to predict the indoor air temperatures, taking into account all the important thermal characteristics. The indoor air temperature is in turn dependent on the flow rate. An integrated flow and thermal analysis must therefore be possible.

Literature review

Several models have been developed over the years to predict natural ventilation and infiltration flow rates in buildings. These models range from very simple single equation models to sophisticated models employing a multitude of accurately measured empirical data or even finite difference numerical techniques [1, 3].

Mathews [1] conducted a survey in 1985 of models existing at that time. He found that models were generally complex and did not cater for ventilation but only for infiltration. They also required as input many parameters that had to be measured on the building, making them unsuitable as design tools. He also could not find any model that integrated the thermal and flow characteristics of the building.

Feustal and Kandon [4] conducted a similar survey in 1986. They found that most of the models reviewed by them required extensive information about the flow characteristics and pressure distributions and were generally complex and not easy to use. They stressed the need for further work on the collation of existing data on wind pressure coefficients to simplify data requirements. A definite need for a simplified model for use by professional engineers and architects was identified.

A more recent survey was conducted by the present authors but it seems that very little has been published on the subject since 1986. A short review of this survey is presented below.

Münch and Ruden [5] studied the internal flow in a hospital stair shaft with the aid of a comprehensive numerical method based on the stream function vorticity finite difference method. Although it was concluded that the model was generally able to predict the detail of the flow field, no attempt was made to simplify the procedure to make it more accessible to industry. Furthermore, the indoor/outdoor temperature difference as well as envelope pressures were required as input, making it unsuitable for a design tool.

Davidson [6] used the SIMPLEC algorithm for solution of the turbulent full Navier–Stokes equations to obtain flow patterns within a room due to thermal forces. As in the previous case, temperatures also had to be specified since the model did not include the thermal characteristics of the building.

Etheridge [7] concluded that detailed models, similar to the ones described above, are not justified since the pressure differences associated with internal air motion are usually small compared to those due to wind and stack effect. Flow rates through openings can therefore be calculated without detailed knowledge of internal air movement. He also found that most models require input data obtained from measurements making them unsuitable for design purposes.

ASHRAE [8] proposes two very simple equations, one for the calculation of wind-driven ventilation and one for ventilation due to thermal forces. Each of these calculates the flow rate through a single opening in the building envelope. The total flow rate is obtained by simple quadratic addition of the wind-induced and stack-induced flows. Although this model is probably the most useful of all to practising engineers, it is subject to a number of limitations restricting its use as a design tool. The major drawbacks are that temperatures must again be specified and that no provision is made for the interaction of more than two different openings situated at different levels on the building envelope.

Zhang *et al.* [9] proposed a model for natural ventilation in livestock buildings induced by combined thermal buoyancy and wind. Wind-induced and stack-induced ventilation are treated separately and then added, similar to the ASHRAE model. The model also predicts the indoor air temperatures based on a simple heat balance. Unfortunately the thermal storage effect of the building mass is not accounted for, making this model only applicable to lightweight buildings.

Siurna, Bragg and Reusing [10, 11] proposed stochastic models of ventilation systems in buildings. The main aim of these models is however contaminant prediction and not the prediction of air flow rates. In these models air flow rates are described by Gaussian probability distributions and are not determined explicitly. Although models such as these may in future become more and more important in establishing guidelines for health risk management, they can at present not be applied with ease in the design of natural ventilation systems.

Saraiva [12] proposes a non-dimensional approach to modelling natural ventilation. All relevant parameters are grouped in dimensionless groups and it is suggested that correct relations between this reduced number of parameters can be found. Apart from the fact that these as yet unknown relations would probably be quite complicated, external pressures must still be specified.

Haghighat *et al.* [3] studied the influence of turbulent wind effects on air change rates. These effects are however usually small in comparison to the steady wind and stack effects and therefore of limited importance to designers.

Some information on the accuracy of ventilation and infiltration models was also found in the literature. Etheridge [7] concluded that at best the error between predicted and measured flow rates will be in the order of 25%. ASHRAE [8] states that such errors for existing models are typically in the order of 40% and can be as high as 100% for individual cases.

From the discussion above it is clear that none of these calculation procedures conform to all the requirements of a good design tool. A definite need for an easy-to-use yet comprehensive model for use by engineers and architects was therefore identified. The development of such a new integrated design tool for naturally ventilated buildings is the focus of this paper.

Summary

- Natural ventilation may be used in many buildings to reduce energy consumption and costs and to lessen the burden on the environment.
- Designing for natural ventilation is complicated by the interaction between the flow rates and the indoor air temperatures.
- A good design tool should account for all the important parameters that influence both the wind-induced and stack-induced pressures.
- It should allow for both infiltration and ventilation.
- A good ventilation model should allow for the specification of various openings of different sizes and flow resistance characteristics on the building envelope.
- It should account properly for the thermal performance of the building and must be able to predict indoor air temperatures.
- It should allow a fully integrated analysis of the flow characteristics and the thermal performance of the building.
- It should not require as input many measured parameters such as pressure distribution or temperatures.
- It need not account for detailed internal air movement or small-scale turbulent wind effects.
- A review of the literature has shown that at present no tool exists that conform to these requirements. A definite need for an easy-to-use yet comprehensive design tool to aid engineers and architects was identified.

VENTILATION MODEL

If one assumes that the static pressure throughout each zone is constant and that all air entering a zone mixes thoroughly with air already inside, any building may be represented by a flow network consisting of nodes coupled by non-linear flow resistances as shown in Fig. 1. These assumptions are usually valid in the case of natural ventilation since the pressure variation inside a zone is much smaller than that caused by wind and stack effects as shown earlier. One case where complete mixing may not occur is when air entering one window immediately exits through another close by. This so-called 'short-circuiting' effect will not be accounted for here. It does in any case not represent good design practice.

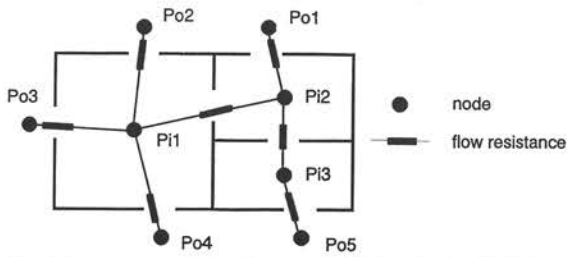

Fig. 1. Plan view showing flow network for a typical building.

The flow network

Each internal zone in the building is represented by a single internal node in the network. Each node has associated with it a specific static pressure. The outdoor air at each opening on the envelope is represented by a boundary value node which has a specific total external pressure associated with it. Each opening in an internal dividing wall or on the envelope is represented by a non-linear flow resistance between two given pressure nodes.

The air flow rate through an opening can be calculated from the pressure difference across the opening and its physical properties by employing the energy conservation equation in the following way:

$$Q = C_d A\left[\frac{2}{\rho}\Delta p\right]^{\frac{1}{n}} \quad (1)$$

with Q the flow rate in cubic metres per second, C_d the non-dimensional discharge coefficient, A the area of the opening, ρ the density of the air and Δp the pressure difference across the opening. The value of n varies between 1 and 2 [2,13,14]. In cases where the flow is fully turbulent, which is typically the case for purpose-provided natural ventilation through component openings, the value of n may be taken as 2 [15,16].

By enforcing mass conservation for each node, i.e. $\Sigma Q = 0$, the flow network may be solved numerically to find the internal pressure in each zone as well as the air flow rate through each opening. The numerical solution of the flow network may be based on any convenient non-linear solution technique. In this case the standard Newton–Raphson method gives good results. The specification of the boundary values for the solution, i.e. the total external pressure at each outdoor node, is discussed in the next section.

The total external pressure

The driving forces for natural ventilation are the external pressures due to wind as well as the indoor/outdoor pressure variation due to density differences resulting from the difference in temperature between the indoor and outdoor air. The total external pressure (p_o) at each boundary node in the flow network must therefore include both of these. Although the wind-induced and stack-induced flow rates are not additive, the external pressure due to wind (p_{wind}) and the 'effective' external pressure due to thermal forces (p_{therm}) are additive [1]. We may therefore say that:

$$p_o = p_{wind} + p_{therm}. \quad (2)$$

To find the value for the total external pressure we will first look at p_{wind} and then at p_{therm}.

External pressure due to wind. The wind-generated pressure at each opening on the envelope is dependent on the position of the opening on a particular facade, the exact geometry of the building, the wind speed, the shape of the atmospheric boundary layer, the orientation of the building with respect to the wind direction, and the shading effect of nearby buildings. The interaction of all these is extremely complex and it is therefore not an easy task to predict the pressure at any point on the building envelope.

Such a prediction is usually based on either exact scale model tests in a boundary layer wind tunnel or on results of detailed numerical analysis of the flow around the building. These methods are difficult and expensive and of course also have a degree of uncertainty associated with them. In keeping with the requirements of a good design tool, a number of simplifying assumptions have been made to develop simple equations for predicting the wind-generated external pressures.

The first simplifying assumption concerns the position of an opening on a specific facade of a building. Although the pressure may vary from point to point on the facade, the model will make use of a single averaged value for the pressure at all points on each facade. All openings on the same facade will therefore have the same wind-generated external pressure. This is not uncommon practice [8] and should be sufficient in most cases since the difference in pressure from one facade to another is usually much larger than the variation in pressure on a single facade. Cases where the variation is important are for instance when the whole building only has two windows on the same facade at the same height. This would however result in very little flow and cannot be regarded as good design practice for natural ventilation.

The next assumption concerns the geometry of the building. Although buildings may have very complex geometries we will assume that all buildings can roughly be approximated by rectangular shapes as shown in Fig. 2. The values of the average pressure on each facade will be dependent on the side ratio of the building (defined as the ration between the width of the short side to the width of the long side) as well as the aspect ratio (defined as the ratio between the building height and the width of the long side). This effect will be taken into account by averaging the results of measured pressures on model buildings with various shapes obtained in boundary layer wind tunnel tests.

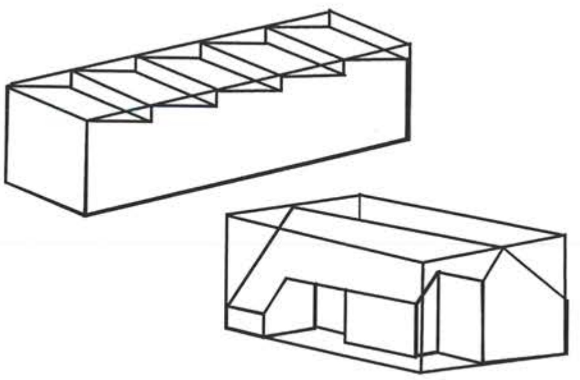

Fig. 2. Rectangular approximation of the building geometry.

The effect of the wind speed is taken into account by expressing the external pressures in terms of the non-dimensional pressure coefficient C_p defined as

$$C_p = \frac{p_{wind} - p_{ref}}{\frac{1}{2}\rho V_h^2} \quad (3)$$

with p_{ref} the reference pressure, which equals the static pressure of the undisturbed air flow and may be taken as equal to the barometric pressure, and V_h the free-stream velocity at roof height. The free-stream wind velocity is in general measured at a single specified reference height above ground level. The free-stream velocity at roof height for a specific building must therefore be deduced from this reference velocity.

The relation between the wind velocity at roof height and at reference height is determined by the shape of the atmospheric boundary layer. The shape of the atmospheric boundary layer is influenced by the relative 'roughness' of the terrain surrounding the building. The shape of the boundary layer is described by the power law equation

$$V_h = V_{ref}\left[\frac{h}{h_{ref}}\right]^{\alpha} \quad (4)$$

with h the roof height, h_{ref} the reference height and α the so-called velocity profile exponent. A value for α equal to 0.15 represents open fields such as an airport, and a value of 0.4 represents a densely built-up city environment [8]. The shape of the boundary layer will be taken into account by averaging measured pressure coefficients for a wide range of velocity profile exponents.

The orientation of the building with respect to the wind direction is taken into account by using measured values of pressure coefficients at different azimuth angles. The azimuth angle (θ) is defined as the angle between the wind direction and the vector perpendicular to the facade and pointing towards the inside of the building. An azimuth angle of zero would therefore mean that the facade is facing directly into the wind while an azimuth angle of 180° would mean that the facade is on the opposite side of the building facing away from the wind.

The values of pressure coefficients used in the model proposed here are based on measurements in boundary layer wind tunnels made by the present authors combined with extensive measured data published by Akins *et al.* [17]. The data represent a range of power law exponents varying between 0.12 and 0.38, building side ratios varying between 0.25 and 1 and aspect ratios varying between 1 and 8. Figure 3 shows the averaged pressure coefficient for a facade as a function of the azimuth angle. Values are shown for 15° intervals.

In order to simplify the calculation of C_p in the model, the data shown in Fig. 3 can also be represented as a function of the absolute value of sin θ as shown in Fig. 4. Values on the upper line are valid for $\theta \leqslant 90°$ and $\theta \geqslant 270°$. The bottom line represents $90° < \theta < 270°$. The solid lines in Fig. 4 represent polynomials fitted through the data. The top line is given by

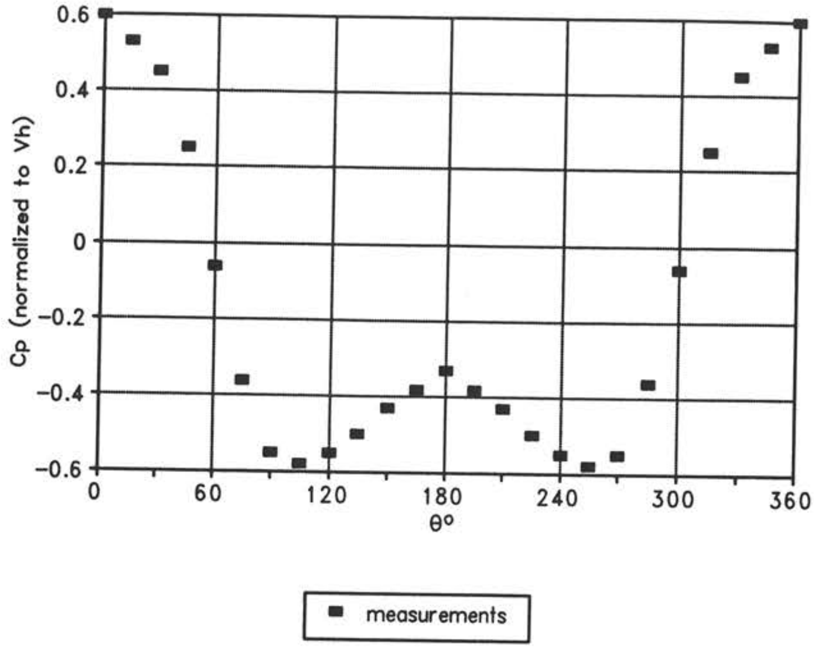

Fig. 3. Averaged facade pressure coefficient as a function of azimuth angle.

$$C_p = 0.5994 - 0.1426 abs(\sin\theta) - 0.8055 abs(\sin\theta)^2 + 2.0149 abs(\sin\theta)^3 - 2.1972 abs(\sin\theta)^4 \quad (5)$$

and the bottom line by

$$C_p = -0.33300 - 0.1544 abs(\sin\theta) - 0.1128 abs(\sin\theta)^2. \quad (6)$$

The pressure coefficient due to wind on the roof of a building is a function of the roof angle and varies across the surface of the roof. The averaged value of C_p for most roofs is however approximately equal to -1.0 [8]. The pressure coefficient at all openings, including ventilators, situated on any roof will therefore be taken as -1.0.

Soliman [18] investigated the shading effect of nearby buildings. Measurements of the pressure difference over any two faces of the building at different angles of attack were taken for different grouping densities and boundary layer profiles. The grouping density D is defined as the percentage of the total surface area in the immediate surroundings of the building covered by other buildings. It was found that buildings smaller than the one investigated had little influence while buildings of comparable

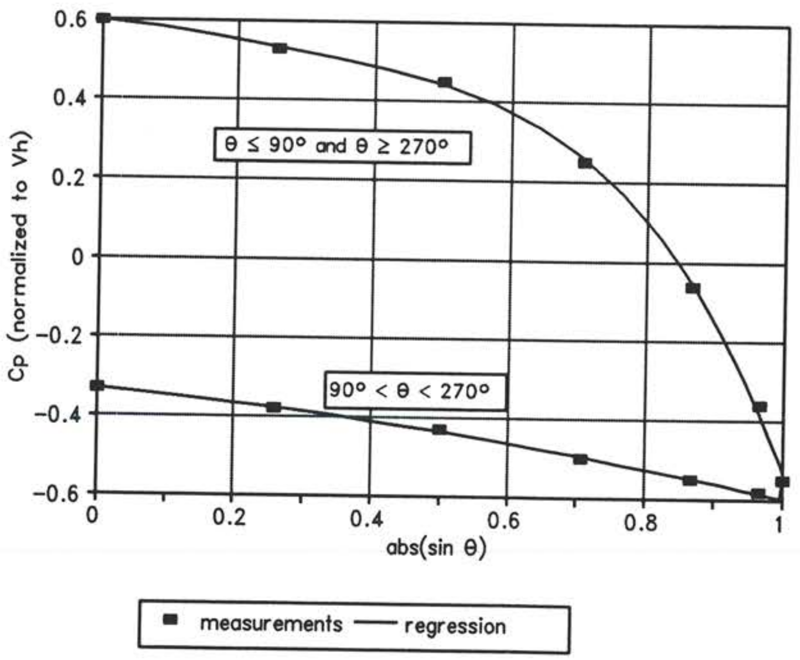

Fig. 4. Averaged facade pressure coefficient as a function of *abs*(sin *θ*).

height or taller had a notable influence. This influence will be taken into account in the model proposed here.

From the data supplied by Soliman the authors found a correlation between the reduction in the difference in pressure coefficient (ΔC_p) across any two facades of a building as a function of the grouping density (D). ΔC_p is multiplied by a factor β where

$$\beta = \frac{1}{e^{0.05D}}. \tag{7}$$

However, in the model ΔC_p is not specified but rather the value of C_p at each boundary node. The reduction in ΔC_p is therefore accounted for in the model by multiplying by β the value of C_p obtained from equations (5) and (6) at each boundary node. This is possible since for any two boundary nodes, say 1 and 2, we have that $\Delta C_p = C_{p1} - C_{p2}$ and therefore $\beta\Delta C_p = \beta C_{p1} - \beta C_{p2}$.

External pressure due to thermal forces. As stated earlier the flow rate due to thermal forces is caused by the difference in temperature between the indoor and outdoor air. This temperature difference results in different air densities inside and outside the building which in turn gives rise to different pressure gradients inside and outside. The difference in the pressure gradients causes pressure differences across openings in the building envelope. The ventilation flow rate is determined by the pressure differences.

Since the only boundary values supplied in the flow network are the external pressures, it is necessary to derive an equation for the 'effective' external pressure. The term 'effective' is used because this pressure will not really be measurable at the outside of each opening. It is however equal to the pressure needed to produce the same flow rate as that due to the actual pressure differences across the openings.

The appropriate equation can be derived by considering the case where no wind is present but where a difference in temperature exists between the indoor and outdoor air. By employing the ideal gas law to relate the pressure and density of air and by assuming that the difference between the indoor static pressure and the outdoor static pressure is small, the effective external pressure due to thermal forces can be calculated as [1,19]

$$p_{therm} = 0.0342 \frac{y p_{ref}}{T_i T_o}(T_o - T_i) \tag{8}$$

with y the height of the opening above ground level and T_i and T_o the indoor and outdoor air temperatures respectively. Equation (8) will hold true for cases where $T_o > T_i$ as well as where $T_o < T_i$.

In summary the ventilation model consists of the following steps.

- Specify the layout of the flow network by linking internal nodes for each zone and boundary nodes for the outside of each opening on the building envelope in the correct configuration to represent the building.
- Specify the value of the discharge coefficient (C_d) as well as the area (A) for each opening.
- Specify the height above ground level (y) as well as the facade on which each boundary node is situated.
- Specify the correct velocity profile exponent (α) and grouping density (D).
- Calculate the pressure coefficient (C_p) for each boundary node using equations (5) and (6).
- Reduce the value of C_p at each boundary node by a factor β with β calculated from equation (7).
- Calculate the free-stream wind velocity at roof height (V_h) from equation (4).
- Specify the indoor (T_i) and outdoor air temperatures (T_o).

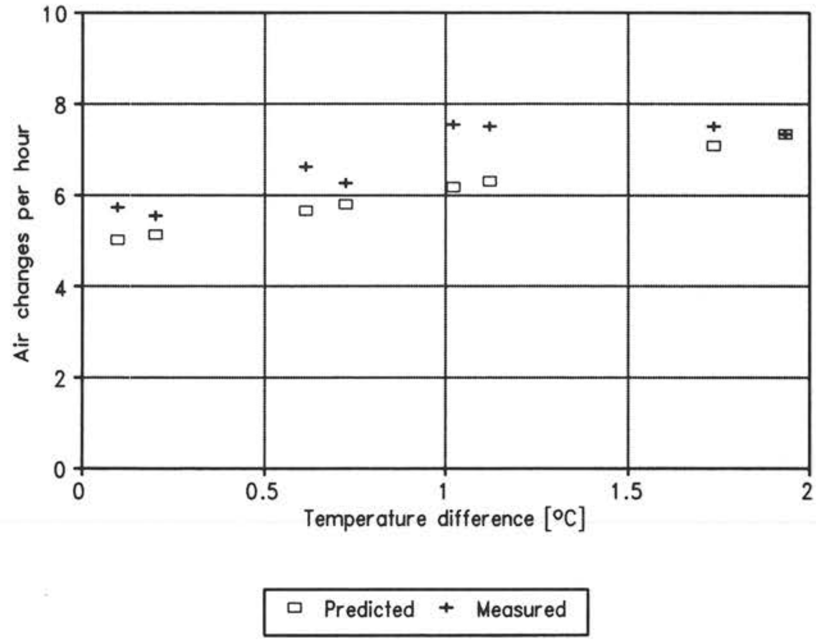

Fig. 5. Predicted and measured ventilation rates in the outbuilding versus the measured temperature difference between the indoor and outdoor air.

- Calculate the total external pressure at each boundary node from

$$p_o = p_{ref} + C_p \tfrac{1}{2}\rho V_h^2 + 0.0342\frac{y p_{ref}}{T_i T_o}(T_o - T_i). \quad (9)$$

- Solve the flow net numerically by enforcing energy conservation (equation (1) with $n = 2$) as well as mass conservation ($\Sigma Q = 0$ at each internal node).

Verification

In order to verify flow rates predicted with the new model, a number of decay rate tracer gas flow measurements were conducted in two different buildings. The results of these measurements are discussed below.

Outbuilding. The first set of measurements were carried out in an outbuilding with an internal volume of 26 m^3 situated in an open field. The building has one window at a height of 1.2 m above ground level with a free inlet area of 1.4 m^2 and another at a height of 1.5 m with an area of 0.2 m^2. It also has a rather large slit of 0.016 m^2 under the door. The value of the discharge coefficient for all openings was taken as 0.6. This value is based on data from various ventilator catalogues as well as results of measurements published by van Straaten *et al.* [20]. These measurements show that for a wide range of different window types the value of the discharge coefficient varies between 0.55 and 0.65.

While the measurements were conducted the wind speed at roof height was approximately 0.4 m/s with the larger window facing into the wind and the smaller window and slit underneath the door facing directly away from the wind. Figure 5 shows the predicted and measured air changes per hour for this case versus the measured temperature difference between the indoor and outdoor air. Comparison between the predicted and measured values shows a maximum error of 22% and an average error of 12%. This is acceptable if one keeps in mind the typical errors of between 25 and 100% quoted in the literature. However, it is clear that the predicted ventilation rate is slightly lower than the measured values throughout.

Laboratory. The second set of measurements were conducted in a laboratory with an internal volume of 250 m^3. It has two windows at a height of 1.9 m with a combined area of 2.988 m^2 and another with the same area at a height of 4.5 m. The building is closely surrounded on all sides by other taller buildings and the wind therefore had very little effect on the ventilation rate. Figure 6 shows that a good comparison was again obtained between measured and predicted values. The maximum error is in the order of 27% with an average of 10%.

If one compares the two sets of measurements shown above it seems that the effect of the wind may be underestimated slightly. In the first case a light wind was present and the predictions were slightly lower than the measurements throughout. In the second case no wind was present which resulted in greater accuracy.

Summary

- A simplified model was derived that accounts for both wind and thermally induced natural ventilation.
- It accounts for the layout of the building, the representative permeability and height above ground level of each opening, the wind speed and direction as well as the terrain and shading effect of other buildings in the vicinity.
- The model requires no measured input data or detailed description of the geometry of the building which makes it extremely suitable as a design tool.
- From the verification study it seems that the effect of wind is slightly underestimated while the effect of temperature is correctly taken into account.

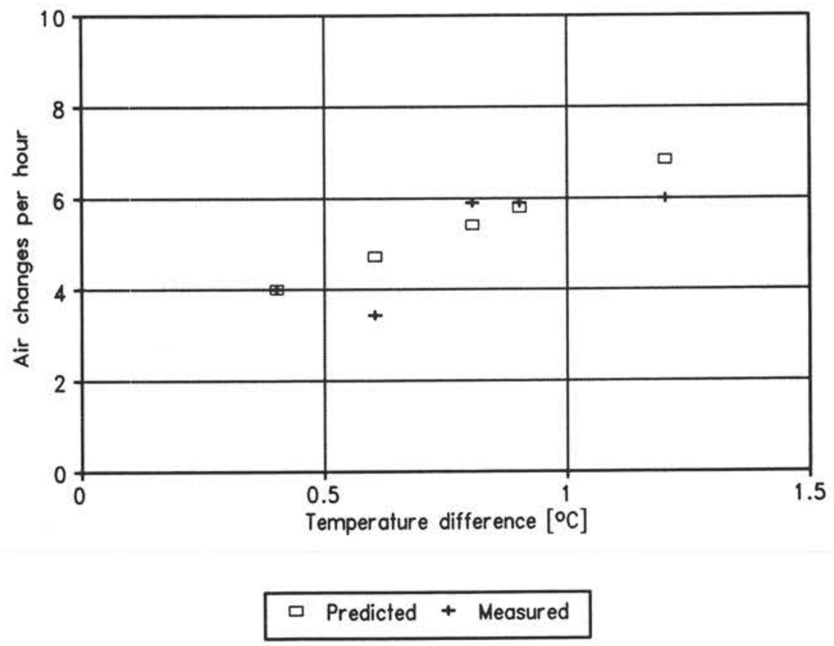

Fig. 6. Predicted and measured ventilation rates in the laboratory versus the measured temperature difference between the indoor and outdoor air.

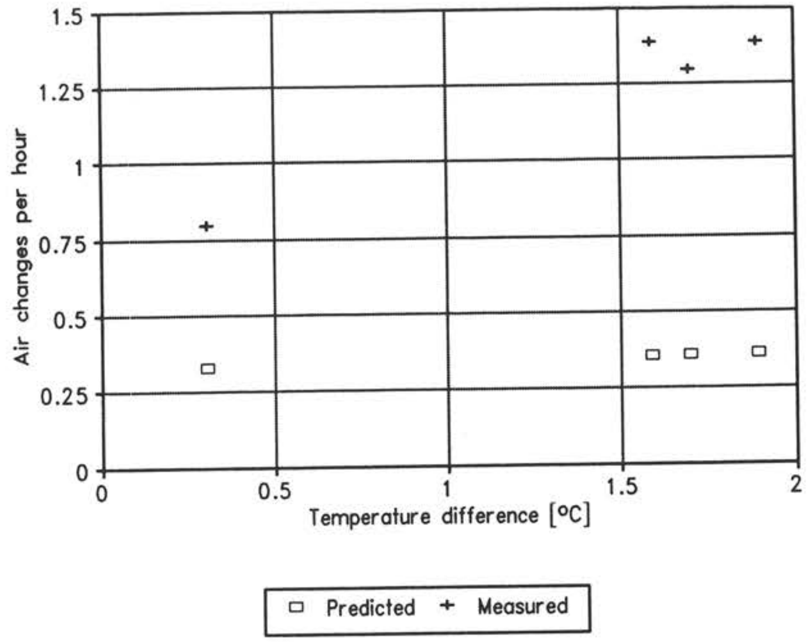

Fig. 9. Predicted and measured infiltration rates in the laboratory versus the measured temperature difference between the indoor and outdoor air.

wind and thermal effects on ventilation as well as the interaction between these two.

A new ventilation model is proposed that makes use of a healthy balance between empirical data and theoretical equations. In order to obtain a practical model a number of simplifying assumptions have been made, all of which are clearly motivated. The model accounts for the layout of the building, the permeability of openings, the height of different openings above ground level, the wind speed and direction, the difference in temperature between the indoor and outdoor air as well as the effect of the surrounding terrain in which the building is situated.

Measurements have shown that the 'stack' effect is accurately accounted for while the effect of the wind seems to be slightly underestimated. In the application of the model in a design capacity this is however not a major drawback since it will result in more conservative designs.

The use of the model derived by Kusuda and Saitch is proposed for cases where the windows are closed and only unintentional infiltration occurs. Some suggestions are made on the use of the model at the hand of measurements. A further classification namely that of a 'very leaky' building is proposed for use in typical South African buildings. The restriction of the model is also clearly illustrated.

The implementation of the new ventilation model as well as the infiltration model into a new integrated natural ventilation design tool is discussed in Part 2 of the paper [22].

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