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AN INTEGRATED COMPUTATIONAL PROCEDURE TO PREDICT NATURAL VENTILATION IN BUILDINGS

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A computational procedure to predict expected rates of natural ventilation for buildings at the design stage is investigated. This procedure integrates three computational methods, namely one to predict temperature-induced pressures, another to compute wind-generated pressure distributions around buildings, and the third to analyse the networks of resulting air flows in buildings. Experiments show that these methods are valid. The three methods can be used not only for the prediction of natural ventilation, but also for many other environmental engineering applications, such as the prediction of heat loads in buildings and of wind environments around buildings, as well as for the design of mechanical ventilation systems.

INTRODUCTION

To ensure an acceptable indoor environment in a non-airconditioned building in a hot climate, certain rates of natural ventilation are required to remove heat, odours, moisture and undesirable contaminants from the building. These rates can be estimated for a building at the design stage if the expected temperature and wind-induced pressures are known. However, the first step in assessing the expected indoor environment of a proposed naturally ventilated building is usually the prediction of its thermal performance (Mathews (1)). If the predicted indoor air temperature in a hot, arid climate is below 28,5°C, the indoor thermal environment may, in many cases, be deemed acceptable (Wentzel et al (2)). When the predicted indoor air temperature is above 28,5°C the building should preferably be re-designed or mechanical ventilation or even airconditioning provided. Should it be decided that the building will be naturally ventilated, the thermal predictions can be used to estimate the temperature-induced pressures that may give rise to natural ventilation.

The prediction of the thermal performance of a naturally ventilated building is a difficult task, as reliable information on flow rates of natural ventilation are seldom available (Loudon (3)). A semi-empirical thermal analysis method for naturally ventilated buildings was therefore developed (1). Although empirical constants in some equations account for typical expected rates of natural ventilation in conventional South African buildings, the procedure is primarily based on theory and can therefore be extended to include the thermal analysis of other buildings in other climates.

A further obstacle to estimating natural ventilation flow rates is the lack of information on wind-generated pressure distributions around buildings. Boundary layer wind tunnels can be employed to obtain these distributions (Bowen (4)), but many researchers and designers do not have economical access to such tunnels. It was therefore decided to exploit the increased accessibility of computing power by developing a program to compute the necessary pressure values (1). The partial differential equations which describe motion of turbulent atmospheric air were discretised and the resulting finite difference equations implemented in a computer program.

To complete the integrated procedure for natural ventilation calculations, a technique for flow network analysis was developed. For this purpose the Hardy Cross computational procedure (Streeter and Wylie (5)) for analysing pipe networks was adapted to natural ventilation networks (1).

The aim of this paper is to present the three computational methods which can be integrated to predict natural ventilation flow rates in buildings. The three methods are not embodied in a single computer program, as each method can be used for other applications as well.

THERMAL ANALYSIS

Theory

For the purpose of calculating natural ventilation flow rates, the temperature induced pressure difference (ΔP_{TI}) acting across an opening at height (y) in a building can be estimated from the following equation, which is valid for SI units (1):

$$\Delta P_{TI} = \frac{yP_a}{29(T_iT_o)}(T_o - T_i) \qquad (1)$$

where (P_a) is the atmospheric pressure and (T_o) and (T_i) the outdoor and indoor air temperatures respectively. Since the atmospheric pressure and the outdoor air temperature are known, the pressure difference can be estimated if the indoor air temperature can be predicted.

The equations that are needed to predict the indoor air temperature are based on a simple electrical analogue for heat flow through the building shell (1) as shown in Figure 1. As natural ventilation is primarily of importance in summer, it was assumed that direct sun penetration and heat generation inside the building would be negligible. Direct sun penetration will be prevented in summer if enough roof overhang is provided. However, the effect of gains on the indoor air temperature can be included if necessary (1).

The air temperature (T_i) inside a completely passive building is the result of the interaction of its thermal properties with the outdoor air temperature (T_o) and the sol-air temperature (T_{sa}) on the different exterior surfaces. In the electrical analogue, the thermal properties of the building are described by the ventilation resistance (R_v), the shell resistance per unit shell area ($R_s/\Sigma A$) and the total active thermal capacity (ΣC) of the building. The ventilation resistance is dependent on the flow rate of outdoor air entering the building shell. The total active capacity of the building is that portion of its thermal capacity that is effective in storing heat. The active capacity is calculated down to a depth of 300mm below ground level, where the temperature has a negligible diurnal swing (Wentzel et al (6)). The one leg of the active capacity shown in Figure 1 is therefore referred to a "constant" earth temperature (T_E) which is measured at 300mm below ground level. As with an electrical capacitor, the thermal capacitor will not be ideal. Tiny leakage heat flow will occur "around" its two junction points, through a very large resistance, that is the non-ideal capacitor resistance (R_{NI}).

By using a single forcing temperature (T_{ff}) instead of two, namely (T_o) and (T_{sa}), the analogue in Figure 1 may be further simplified. As a first simplifying approximation, the magnitude of (T_{ff}) was taken as the average of (T_{sa}) and (T_o) and is thus given by the following equation:

$$T_{ff} = 0,5(T_{sa} + T_o) \qquad (2)$$

Equation (2) will be exactly satisfied (1) when (R_v) equals ($R_s/\Sigma A$).

The amplitude ratio of the indoor air ($|\tilde{T}_i|$) and forcing ($|\tilde{T}_{ff}|$) temperatures can be derived from Figure 1 and simplified by means of empirical constants (1), resulting in the following equation:

$$\frac{|\tilde{T}_i|}{|\tilde{T}_{ff}|} = \frac{150}{\Sigma C} \qquad (3)$$

The amplitude of the indoor air temperature is therefore dependent on an empirical constant, the amplitude of the forcing temperature and the active capacity. The empirical constant accounts for the relationship between shell resistance, exposed shell area and ventilation rates (1), while the active capacity is dependent on the mass and resistance of the building elements, their position relative to each other, and on the shell resistance.

The equation for the mean response ($\bar{T}_i$) to the mean value of the outdoor forcing temperature ($\bar{T}_{ff}$) can also be derived from the simplified electric analogue and is given by (1)

$$\frac{\bar{T}_i}{\bar{T}_{ff}} = 1 \qquad (4)$$

The maximum indoor air temperature can now be calculated by the following equation:

$$(T_i)_{max} = \bar{T}_i + \tfrac{1}{2}|\tilde{T}_i| \qquad (5)$$

If the predicted $(T_i)_{max}$ is lower than the maximum acceptable indoor air temperature, airconditioning will be unnecessary.

The temperature difference between the indoor and outdoor air can now be estimated (1) from the following equation:

$$(T_i - T_o) = \bar{T}_i - \bar{T}_o + \frac{|\tilde{T}_i|}{2}\sin[0,26t - \phi - \arctan(\frac{\Sigma C}{150})] - \frac{|\tilde{T}_o|}{2}\sin[0,26t - \beta] \quad \text{..........(6)}$$

where ϕ is approximated as 2,04 radians and β is approximated as 2,43 radians for South African conditions (1).

All the unknowns in Equations (5) and (6) can be calculated from building plans and from design weather data. Equation (6) can be substituted into Equation (1) to obtain the temperature-induced pressures needed for the prediction of natural ventilation flow rates.

Computer program, test results and discussion

The method was implemented as an interactive program in BASIC on an APPLE IIE microcomputer (1). The program is extremely easy to use and is therefore ideally suited for use by building designers. Although the thermal analysis method and the computer program were developed to predict the thermal performance of naturally ventilated buildings, the method can easily be extended to predict heat loads in airconditioned buildings (1).

The thermal analysis method and computer program were verified against experiments. Measurements were done in six buildings which covered a range of thermal properties. Predictions by Equations (3) and (4) as well as measured values for these buildings are presented in Figures 2 and 3. Temperature differences between the indoor and outdoor air are shown for only one of the buildings (Figure 4). Fair agreement between measured and predicted amplitude ratios was found, as shown in Figure 2. The agreement between predicted and measured ratios for mean values was less favourable (see Figure 3). The most important reason being that the forcing temperature (Equation (2)) has an assumed value. An empirical value of 1,05 rather than the theoretical value of 1,0 for the ratio of the mean temperatures must be used for calculation purposes. The error in the amplitude values of the forcing temperature in Equation (3) and Figure 2 was compensated for by the empirical constant of 150. The difference between measured and predicted temperature differences presented in Figure 4 is primarily caused by the assumption that all the temperatures can be approximated as consisting of only one frequency component. Predictions by this thermal analysis method should however be acceptable for design purposes.

WIND ANALYSIS

Theory

The partial differential equations that govern the movement of a viscous fluid are the Navier-Stokes equations and the continuity equation. These equations in vector notation are given by

$$\rho \frac{D\vec{V}}{Dt} = -\text{grad } P + \mu\nabla^2\vec{V} \quad \text{..........(7)}$$

and $$\text{div } \vec{V} = 0 \quad \text{..........(8)}$$

where ($\vec{V}$) is the velocity vector, (P) the pressure, (μ) the viscosity, and (ρ) the density of the fluid.

Finite difference equations are derived from the partial differential Equations (7) and (8). A line-by-line numerical solution method is used to solve the algebraic finite difference equations. Unknown variables along each grid line are calculated by the application of a tridiagonal matrix algorithm. The converged solution provides statistical mean values for all the variables. To account for the fluctuating nature of fluid flow, the k-ε turbulence model was incorporated into the computational procedure (1).

Computer program, test results and discussion

The finite difference equations were implemented as a FORTRAN 5 program on a CDC 750 mainframe computer (1). The main aim of this program was to investigate the use of computed pressure distributions for estimating natural ventilation flow rates. Little effort was therefore spent on developing an efficient, user-friendly program. Although work in this field was initiated, the potential of numerical techniques was not fully exploited.

The program was used to investigate turbulent wind flow around a tall building. Although flow around a tall building is sensitive to the vertical velocity gradient, a two-dimensional approach was assumed to be acceptable (1). Predicted velocity profiles around the building (dimension

HxH) are presented in Figure 5. The predicted pressure coefficient distribution resulting from the flow around the building is compared with the measured distribution (Barriga et al (7)) in Figure 6. A reasonable agreement between measured and predicted pressure coefficients was found.

The present computer program can be extended to analyse more complex shapes, as well as clusters of buildings (1). Although the program was developed to aid in the prediction of natural ventilation, predicted flow fields (such as in Figure 5) can also be used to study wind comfort around buildings (Taesler and Andersson (8)).

INTERNAL FLOW ANALYSIS

Theory

The flow rate (Q), for fully turbulent flow, resulting from a pressure difference (ΔP) across an opening (area A) in a building, can be estimated from the following equation:

$$Q = C_d A (2\Delta P/\rho)^{\frac{1}{2}} \qquad (9)$$

where (C_d) is the discharge coefficient of the opening and (ρ) is the air density.

The flow rate through an opening can therefore be estimated if the pressure difference across it is known. For a naturally ventilated building, the temperature- and wind-generated pressures around its shell can be predicted by the methods proposed in the previous two sections. Although the internal pressures are usually not known, the air flow in the networks of airpaths in the building can be predicted by a network analysis procedure, provided that the external pressures are known. One possible computational procedure for solving flow networks is to estimate an initial flow rate distribution that satisfies continuity at each node in the network. By ensuring that the pressure loss in a closed loop remains zero, corrections to the flow rates are made. The process is repeated until convergence is reached. The Hardy Cross computational procedure (5) for pipe network analysis is an example of such a procedure. This procedure was successfully adapted to analyse natural ventilation networks (1). It can in its present form, also be used to design mechanical air-supply networks.

Computer program, test results and discussion

The ventilation network analysis method was implemented as a fairly user-friendly program in FORTRAN 5 on a CDC 750 mainframe computer (1).

Although natural ventilation network analyses are often verified against measurements in a wind tunnel, an inexpensive experiment was carried out to verify the present computer program (1). This was done by attaching "false" rooms to the exterior of the model into which compressed air was blown. Generation and control of the exterior pressures were therefore easy, inexpensive and could be closely controlled. The difference between measured and predicted flow rates was less than 3%.

No single, all-embracing experiment was carried out to verify the three procedures in combination as the associated costs would be prohibitive. It was reasoned that, if the different methods that constitute the integrated procedure were singly verified, the integrated procedure could be deemed verified as well. A complete example calculation is however, given in reference (1).

SUMMARY AND CONCLUSIONS

Three computational methods were presented, which may be combined to form an integrated procedure to predict natural ventilation flow rates for a building while it is still at a design stage. The integrated procedure exploits the increased accessibility of computing power available to building designers, environmental engineers and researchers. Each of the discussed computational methods can be refined and extended. The potential of numerical techniques for the computation of wind generated-pressure distributions was for example not fully exploited.

It is concluded that the three methods can be used not only for the prediction of natural ventilation, but also for many other environmental engineering applications, namely the calculation of heat loads in buildings, the prediction of the wind environment around buildings and the design of mechanical air-supply networks.

ACKNOWLEDGEMENTS

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SYMBOLS USED

Symbols

A = area of opening (m^2)

ΣC = total active thermal capacity of the building ($kJ/°Cm^2$)

C_d = discharge coefficient for opening

C_p = pressure coefficient

H = buiding dimension (m)

I = turbulence intensity

L = length scale of turbulence (m)

P = pressure (Pa)

Q = flow rate (m^3/s)

R_s = thermal shell resistance ($°Cm^2/W$)

R = all other resistances (°C/W)

t = time (hours)

T = temperature (°C) or (K)

V = velocity (m/s)

y = height of opening above ground level (m)

β = phase of outdoor air temperature (radians)

μ = viscosity (kg/ms)

ρ = density (kg/m^3)

ϕ = phase of forcing temperature (radians)

Superscripts

∿ = alternating variable

\- = mean part of alternating variable

→ = vector quantity

Subscripts

1 = x-direction

a = atmospheric

E = earth

ff = forcing temperature

i = indoor air

NI = non-ideal

o = outdoor air

sa = sol-air

TI = temperature-induced

v = ventilation

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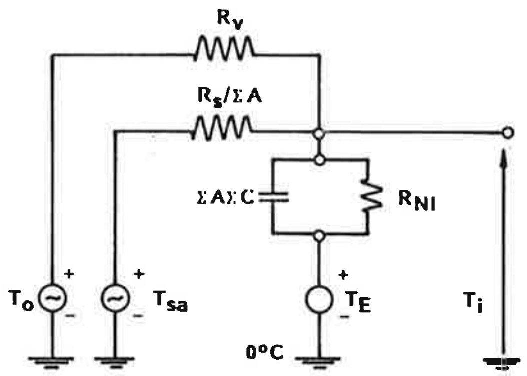

Figure 1 Electrical analogue

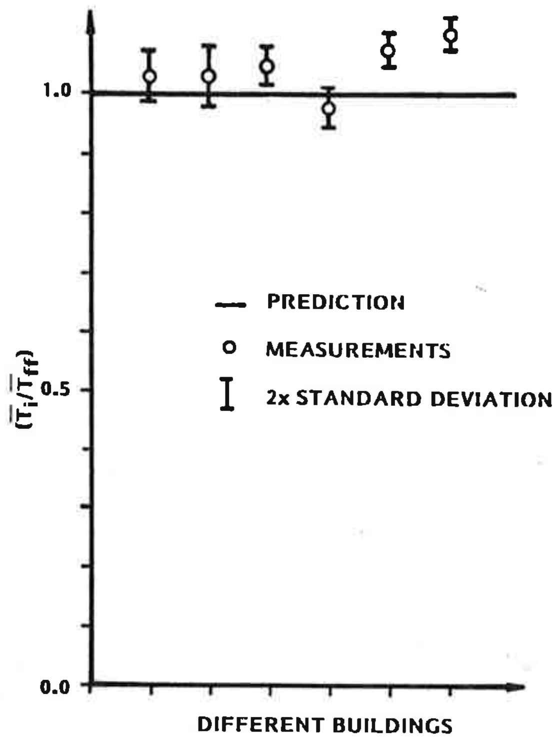

Figure 3 Ratios of temperature means

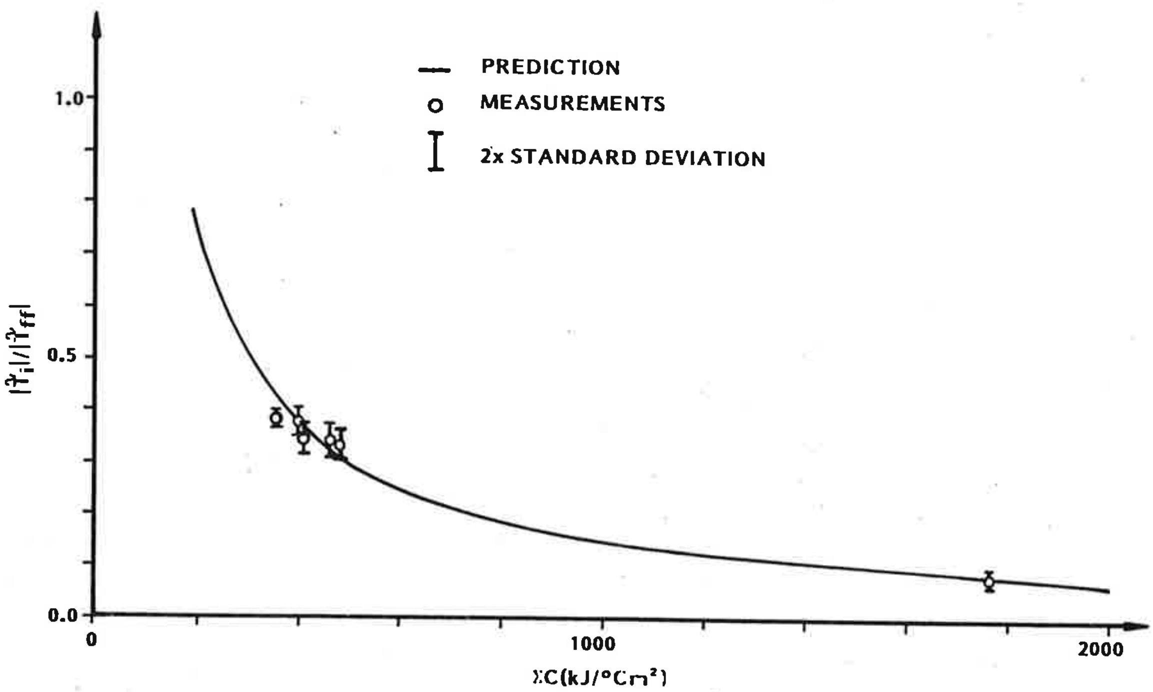

Figure 2 Measured and predicted amplitude ratios

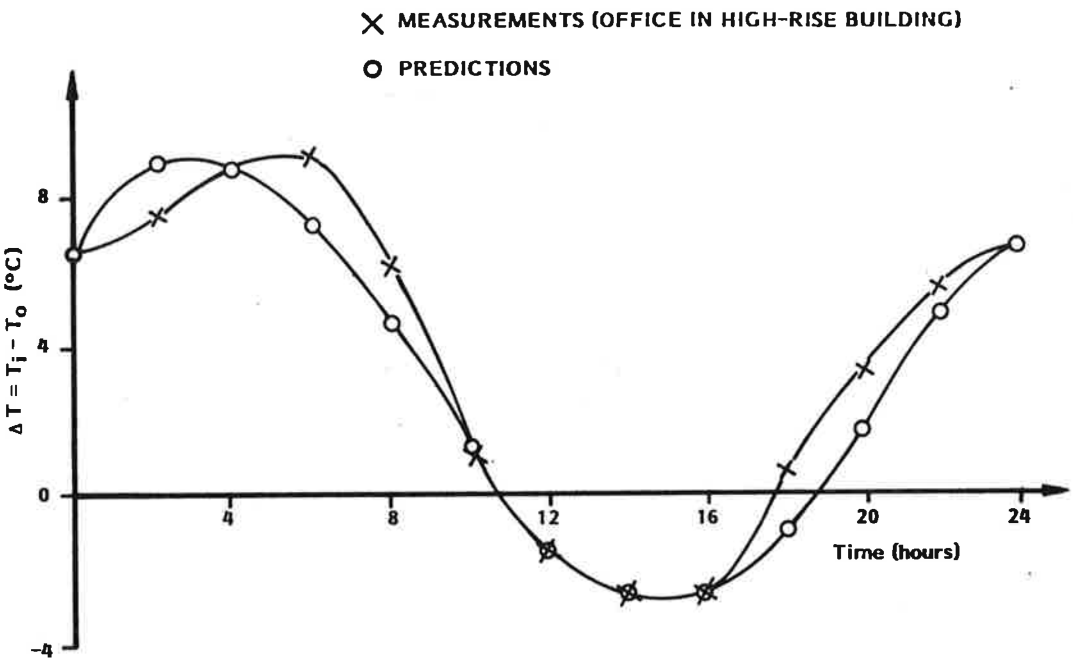

Figure 4 Temperature difference between indoor and outdoor air

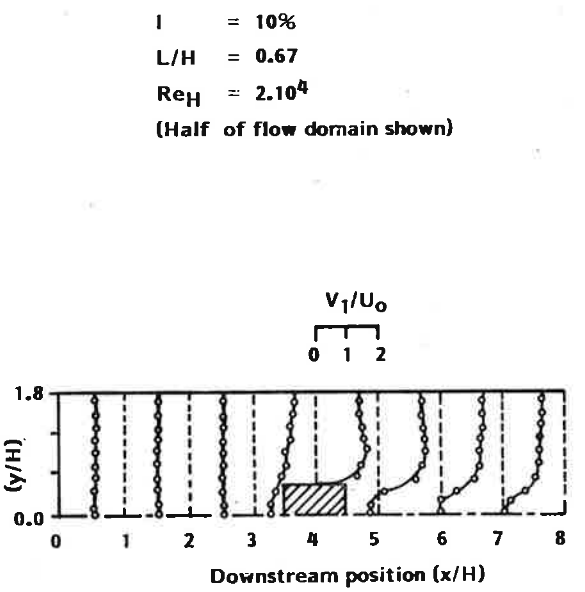

Figure 5 Velocity profiles

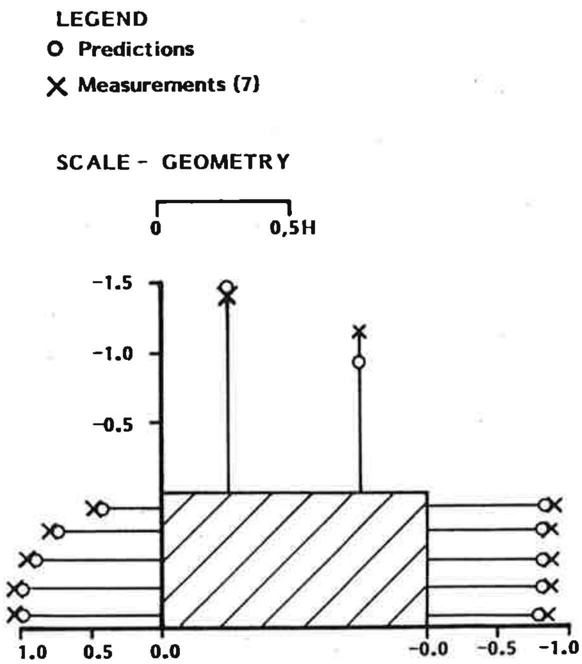

Figure 6 Mean pressure coefficients