NUMERICAL DETERMINATION OF THE EFFECTIVE DEPTH FOR SINGLE-SIDED NATURAL VENTILATION

Guohui Gan

Institute of Building Technology, School of the Built Environment, University of Nottingham, Nottingham NG7 2RD, UK

ABSTRACT

This paper describes a numerical method for the determination of the effective depth of fresh air distribution in rooms with single-sided natural ventilation. The numerical method involves predicting air flow and the local mean age of air. The renormalisation group two-equation model of turbulence is used with the conservation equations of mass, momentum and energy to predict turbulent buoyancy-induced room air flow. The local mean age of air is then obtained from the solution of air flow equations together with the transport equation for the age of air. The predicted air flow pattern, temperature distribution and local mean age of air are used to determine the effective depth for a room with a window opening for summer cooling. The effect of window opening level on the effective depth is investigated.

Keywords: CFD, Cooling, Natural ventilation, Thermal comfort, Window.

INTRODUCTION

Effective distribution of fresh ventilating air within an occupied space is essential to achieve good indoor air quality and thermal comfort. The supply of fresh air can be accomplished by mechanical or natural means. Natural ventilation is preferable to mechanical ventilation with regard to energy conservation. Natural ventilation can be in the form of single-sided or cross flow. Cross ventilation is generally more effective in promoting room air movement than single-sided ventilation. However, buildings for offices or classrooms in urban environments are often designed to make use of single-sided natural ventilation by which air exchange between indoors and outdoors takes place through openings on one side of a space.

The effective depth for single-sided natural ventilation is the longitudinal distance that fresh air travels from the inlet opening to where stagnant air prevails. The end of the fresh air penetration depth can be characterised numerically by a decay in the velocity component for the fresh air stream along the inflow direction to zero. For buoyancy-induced natural ventilation in summer, the mean velocity of air through a large opening is often very low and the incoming air stream may not be clearly distinguishable from the room air movement. Nevertheless, the temperature distribution of the incoming air stream would differ from that of the room air and so their interface could be used as an indicator of the depth of fresh air penetration. Another method to evaluate the effective depth of fresh air distribution is by means of the local mean age of air. The local mean age of air [1] is the average time for air to travel from an inlet to any point in a room. It can be determined experimentally using tracer gas measurement or numerically using computational fluid dynamics (CFD). Walker and White [2] described tracer gas measurements of the local mean age of air at different locations within a 10 m deep single-sided naturally-ventilated office room. The results were used to give guidance to the depth of room over which ventilation would be effective. They also carried out measurements over a wide range of realistic conditions in several deep office rooms with single-sided ventilation to address the effects of window location and partitions on air distribution and internal climate [3]. It was found that local ventilation rates were generally evenly spread in rooms up to 10 m deep but air movement away from windows might not be adequate for thermal comfort in such deep offices.

Air flow in naturally-ventilated buildings is invariably influenced by wind forces. It is therefore difficult to isolate wind from buoyancy forces and so to determine experimentally the effective depth of fresh air distribution under less favourable outdoor conditions - buoyancy alone. One of the advantages of numerical simulation of room air movement over experimental measurement is that such parameters as wind and buoyancy effects can be evaluated individually and collectively. In this study, the CFD technique is used to predict the air movement in single-sided naturally-ventilated rooms. The predicted air flow pattern, temperature distribution and local mean age of air are used to evaluate the effective depth of fresh air distribution in an office room for summer cooling.

MATHEMATICAL MODEL

The air flow pattern and temperature distribution in single-sided naturally-ventilated rooms are predicted using a fundamental air flow model involving turbulence and buoyancy. The fundamental air flow model consists of a system of governing equations of continuity, momentum, turbulence and energy. For natural ventilation of a space due to the buoyancy effect, air turbulence is represented by the renormalisation group turbulence model developed by Yakhot, et al. [4]. The prediction of the local mean age of air is based on the fundamental air flow model in combination with the transport equation for the age of air. The complete set of equations for an incompressible steady-state flow can be written in the following form

$$\frac{\partial}{\partial x_i}(\rho U_i \phi) = \frac{\partial}{\partial x_i}(\Gamma_\phi \frac{\partial \phi}{\partial x_i}) + S_\phi \tag{1}$$

where ρ is the air density, ϕ represents the mean velocity component U_i in x_i direction, pressure, turbulent parameters, mean enthalpy and local mean age of air, Γ_ϕ is the diffusion coefficient and S_ϕ is the source term for variable ϕ.

The local mean age of air is a passive quantity and so can be decoupled from the fundamental air flow equations. Details of the model equations and validation are given elsewhere [5].

Air flow through a large opening

Ideally, the air flow through a large opening for single-sided ventilation can be simulated by coupling the indoor air flow to the outdoor flow as demonstrated by Schaelin, et al. [6] and Li and Teh [7]. However, because such simulations require an enlarged computational domain, a very large grid size has to be used. Also, for the simulation of a room that may be located at any level of a building, the coupling of indoor and outdoor flows would involve an uncertain computational domain for the height. For these reasons, the flow domain used in this study is restricted to the room enclosure and the velocity in the opening with inflow and outflow is calculated from the buoyancy effect.

Fig. 1 illustrates the buoyancy-induced air flow through a large opening with a total height of h. It is known that, without the wind effect, air flow through large external openings can be described in the same way as for internal openings [8]. The ideal velocity profile for the flow through a large internal opening bounded by isothermal air with different temperatures on either side is parabolic according to the Bernoulli theory. Assuming that there is no mixing between the incoming and outgoing flow, the velocity distribution across the opening is given by the following expression

$$V = -C_d \frac{y - h_n}{|y - h_n|} \sqrt{2g \frac{|\Delta\rho|}{\rho_r} |y - h_n|} \tag{2}$$

where V is the horizontal component of air velocity at a vertical distance y; C_d is the discharge coefficient for the opening; h_n is the neutral level at which the air velocity and pressure are zero; g is the gravitational acceleration; $\Delta\rho$ is the difference in air density between outdoors ρ_o and indoors ρ_i; ρ_r is the reference density ($\rho_r = \rho_o$ for the incoming air stream and $\rho_r = \rho_i$ for the outgoing air stream); for complete mixing flow ρ_i is the mean density of indoor air but for flows with short-circuiting ρ_i is taken to be the density of outgoing air stream.

The flow velocity through an opening is theoretically parallel only at the 'vena contracta' of the air stream but here the parallel velocity is prescribed for the section at the opening. Hence, the discharge coefficient is included in the expression to account for streamline contraction and viscous losses that would be incurred at the 'vena contracta'. In this way, the air flow rate through the opening can be obtained directly by numerical integration of the velocity over the opening area either for the inflow or outflow air.

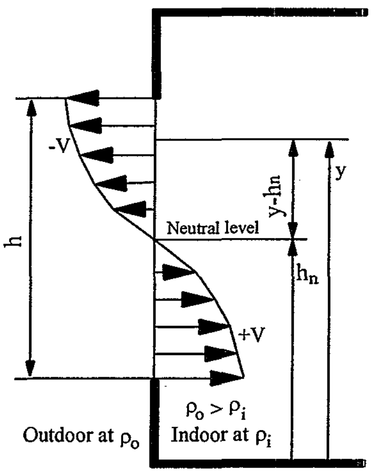

Fig. 1 Schematic diagram of air flow through a large opening

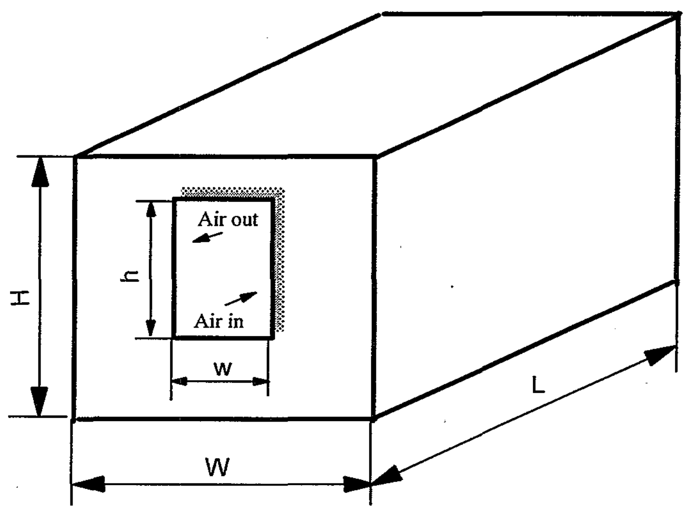

Fig. 2 Schematic diagram of the simulated room

RESULTS AND DISCUSSION

Simulations are performed for a room 3 m wide, 3 m high and 15 m deep under the steady-state summer conditions. Fig. 2 shows the schematic of the room. The room depth is set as a value much larger than the commonly-encountered dimension so that the incoming air flow stream in the empty room would not be diverted by the opposite wall. There is a large openable window in one of the walls, with a maximum opening area of 1.5 m high and full width (3 m). The room has an internal heat input of 15 W/m^2, uniformly distributed over the floor. This heat input would be equivalent to 67.5 W/m^2 for a typical office of 10 m^2 floor area. The outdoor air is set at 20°C. It is assumed that there is no conduction heat transfer or air infiltration through the room envelope. Besides, only buoyancy-induced ventilation is considered while the wind effect is ignored. This is appropriate because in summer the greatest risk of overheating and problems of poor indoor air quality may be expected to coincide with days of low wind speeds [2].

The configuration of the room is symmetrical along the vertical plane of the mid-width and so only half of the room is used for simulation with a computational grid size of 80 x 60 x 30 for room depth, height and half width.

Figure 3 shows the air flow pattern and distributions of air temperature and local mean age of air in the room with full-width window opening. The local mean age of air is normalised by the value at the air exit. The air velocity and temperature are environmental parameters for thermal comfort whereas the local mean age of air is taken as an index for indoor air quality.

It is seen from Fig. 3 that the outdoor air that is cooler than the room air is induced in through the lower part of the window and the cool incoming air immediately drops onto the floor. The air flows along the floor and picks up heat from it. In an occupied room, the air would rise when it encounters a concentrated heat source or an obstruction as in the case of displacement ventilation. Here, the incoming air flows forwards up to about 11 m distance from the window. At a level about half of the room height and above, the room air flows towards the window and then exits through the upper part of the window opening. The air temperature between the window and 9 m distance is stratified with cool incoming air distributed on the floor. The mean air temperature in the room is 22.1°C with the area along the incoming air stream being cooler than the area beyond. The temperature distribution shows that the effective depth of incoming air penetration is about 9.5 m. The predicted air change rate for the room is 7.5 1/h. The local mean age is less than the exit value (i.e., the normalised local mean age of air is less than unity) in the air stream for a distance of 11.2 m from the window. Beyond this distance, the local mean age of air is higher than the exit value and air is essentially stagnant, resulting in poor air quality. The distributions of air temperature and local mean air age indicate that the effective depth of the room with the full-width window opening is between 9.5 m and 11.2 m depending on the requirements for thermal comfort and air quality.

When the width of window opening is reduced to 1 m, for the same heat generation rate in the room, the mean indoor air temperature increases to 24.1°C. This increases the buoyancy effect and results in an increase in the maximum inlet air velocity by 45%. However, the total air flow rate (= 3.6 1/h) decreases as a result of the reduced opening area. The mean air temperature at head level is over 24°C and so the thermal environment would not be satisfactory although below the head level and for a distance of 11 m from the window the air temperature is less than the mean value. The fresh air can reach a longer distance (12 m according to the local mean age) than the room with the full-width window opening but the height of fresh air diffusion is only about 1 m. Therefore, the air at high level (breathing zone) would not be very fresh, nor thermally comfortable.

The increased effective depth at low level (11 m to 12 m deep and 1 m high) for the reduced window opening is due to the increased inlet air velocity. This is confirmed by a further prediction for the room where the window opening is still 1 m wide but the magnitude of inlet velocity distribution is set the same as that for the fully-open window, i.e., the maximum inlet

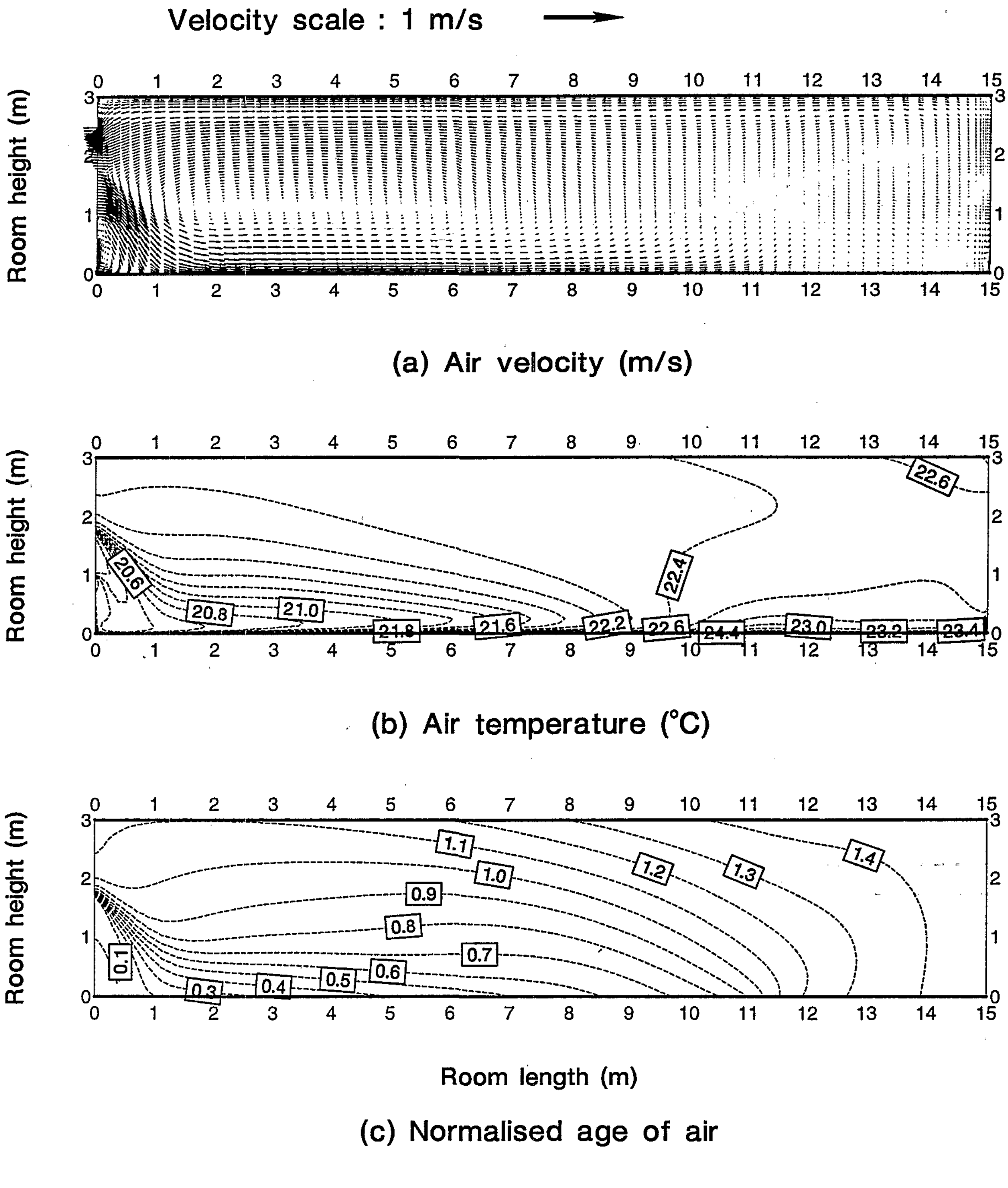

Fig. 3 Predicted indoor environment on the symmetry plane of the room with single-sided natural ventilation

velocity is reduced by 45%. To achieve such a reduced velocity requires a reduction of the heat generation rate in the room by 2/3 approximately, i.e., from 15 to 5 W/m^2, according to Equation (2). This heat generation rate is still a reasonable value for a 15 m deep room; in terms of total amount of heat generation it is equivalent to a rate of 15 W/m^2 for an office room 5 m deep. Besides, the reduced window opening level would likely be employed at times when room heat gains are low for thermal comfort. The incoming air under the reduced heat generation rate influences the temperature distribution for a distance of 7 m, compared with 11.2 m for the heat generation rate of 15 W/m^2. The mean air temperature in the room becomes 22°C. The local mean age of air is less than the exit value for a distance of 7.5 m. Therefore, the effective depth of the room is between 7 m and 7.5 m.

These predictions suggest that the effective depth for single-sided ventilation based on the air temperature distribution differs from that based on the local mean age of air. In rooms with uniform heat generation, the effective depth for thermal comfort is smaller than that for indoor air quality. This agrees with the experimental finding of White and Walker [3] for office rooms where the spread of acceptable local ventilation rates was deeper than that of adequate air movement for thermal comfort.

CONCLUDING REMARKS

It has been illustrated that CFD is a useful tool for the determination of the effective depth of fresh air distribution in rooms with single-sided natural ventilation. The effective depth is influenced by the degree of window opening and heat gains. The effective depth for thermal comfort may not be coincide with that for indoor air quality. For summer cooling, the requirement for thermal comfort is the limiting factor to the effective room depth.

REFERENCES

1. Sandberg, M. 1981. What is ventilation efficiency?. *Building and Environment*. 16(2), 123-135.
2. Walker, R.R. and White, M.K. 1992. Single-sided natural ventilation - How deep an office. *BSER&T*. 13(4), 231-236.
3. White, M.K. and Walker, R.R. 1996. The efficiency of single-sided and cross ventilation in office spaces. *Proc. 17th AIVC Conference - Optimum Ventilation and Air Flow Control in Buildings*. Vol. 2, 487-496.
4. Yakhot, V., Orszag, S.A., Thangam, S., Gatski, T.B. and Speziale, C.G. 1992. Development of turbulence models for shear flows by a double expansion technique. *Physics of Fluids, Part A*. 4(7), 1510-1520.
5. Gan, G. 1998. Prediction of turbulent buoyant flow using an RNG k-ε model. *Numerical Heat Transfer, Part A: Applications*. 33(2), 169-189.
6. Schaelin, A., van der Mass, J. and Moser, A. 1992. Simulation of airflow through large openings in buildings. *ASHRAE Transactions*. 98(2), 10pp.
7. Li, K. and Teh, S.L. 1996. Two-dimensional numerical study of airflow through large openings. *Proc. Indoor Air '96*. Vol. 2, 1027-1032.
8. van der Mass, J., Bienfait, D., Vandaele, L. and Walker, R. 1991. Single sided ventilation. *Proc. 12th AIVC Conference - Air Movement and Ventilation Control within Buildings*. Vol. 1, 73-98.