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3-D MODELLING OF SOLAR CHIMNEY-BASED VENTILATION SYSTEM FOR BUILDING

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ABSTRACT

A computer model for predicting natural ventilation in buildings by solar chimney alone is presented. The simulations are based on the solution of the 3-D steady laminar conservation equations of mass, momentum and thermal energy with an appropriate set of boundary conditions. The equations are discretized using a finite difference formulation and solved by the Marker and Cell (MAC) scheme. Indoor airflow fields and temperature distributions are discussed with respect to human comfort at the living level, 1 m above floor. The simulation results show that solar chimney alone can induce a sufficient ventilation rate for ensuring residents' thermal comfort, when the outdoor temperature is moderate (below 37 C).

KEYWORDS

Laminar flow; natural ventilation; openings; thermal comfort; tropical climate.

INTRODUCTION

Today, with increasing awareness about environment and energy conservation, an energy-conscious design of building has become a necessity. By far, natural ventilation is the most attractive choice for achieving a low-cost cooling energy building design. Most buildings have rather poor ventilation. Outdoor heat is stored inside and, then, makes occupant uncomfortable. In the past, the easiest way to solve this problem was to close the building envelope and use air conditioning which for free running buildings, the simplest way was to open houses' openings such as door and windows in order to allow breezes to flow through the house. Its effectiveness depends, mainly, on surface area of openings, positions and wind. Thus, with one side ventilation, the ventilation is reduced considerably. A number of computer models for predicting the induced rate of ventilation is available (Allard, 1998) which combines both wind and simplified scheme of stack effect or solar chimney. Under tropical climate, the need for cooling is very high during summer where wind is quasi non-existing that limits the efficiency of wind-induced ventilation. Therefore, solar chimney-based ventilation seems to be the unique way. Investigation was reported by Khedari *et al.* (1999, 2000) with a limited number of openings and for a single-room house of 25 m^3 volume. It was concluded that window-door-based ventilation is less efficient than that with solar chimney as the room temperature was only 2 C above ambient. With regard to designing purpose, a computer model has to be developed for predicting the ventilation induced by solar chimney. Discussing the model outputs, namely, indoor airflow fields and temperature distributions with respect to human comfort at the living level, about 1 metre above, would help in identifying openings' size and position for a given house design. This is being the objective of this research work.

The main assumptions can be summarized as follows:

- 3-D model
- Flow is steady and laminar.
- Radiation exchange between solid surfaces inside the room is neglected.
- Flow is only due to buoyancy driven force.
- By accepting Boussinesq approximation, i.e., all thermal properties of air except density are constant. Thus, the buoyancy driven force is caused to due a density gradient.
- The density does not directly depend on pressure, it depends on temperature. That means the buoyant flow could be expressed in terms of temperature gradient rather than density gradient.

GOVERNING EQUATIONS AND BOUNDARY CONDITIONS

The conservation equations of mass, momentum components, and thermal energy in Cartesian coordinates are as follows

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \tag{1}$$

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}=-\frac{1}{\rho}\frac{\partial(p-p_o)}{\partial x}+\nu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right) \tag{2}$$

$$u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}=-\frac{1}{\rho}\frac{\partial(p-p_o)}{\partial y}+\nu\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial z^2}\right) \tag{3}$$

$$u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}=-\frac{1}{\rho}\frac{\partial(p-p_o)}{\partial z}+\nu\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2}{\partial z^2}\right)+g\beta(T-T_o) \tag{4}$$

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}+w\frac{\partial T}{\partial z}=\alpha\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right) \tag{5}$$

where g = acceleration of gravity, m/s^2
p, p_o = pressure and atmospheric pressure, N/m^2
T, T_o = temperature and ambient temperature, K
u = velocity component in x direction, m/s
v = velocity component in y direction, m/s
w = velocity component in z direction, m/s
α = thermal diffusivity, m^2/s
β = volumetric coefficient of thermal expansion ($\beta = 1/T_o$), 1/K
ν = kinematic viscosity, m^2/s
ρ = density, kg/m^3

At all solid boundaries, velocity components are equal to zero and temperatures are equal to solid temperatures. For the inlet and outlet boundary conditions, they are somewhat more difficult as the exact velocity profile is unknown. One approach to handle the opening boundary is to deal with an appropriate extended domain (Yu and Joshi, 1997). Another method that is used here is to fix the values of the pressure at both inlet and outlet, to neglect the kinetic energy head at inlet and to assume a buoyant jet at chimney exit (Barozzi *et al.*, 1992). Thus, the pressure boundary conditions at openings are set equal to the atmospheric pressure. At the inlet opening "lower one", by considering ambient temperature and assuming no lateral velocities (i.e. v, $w = 0$), the continuity equation yields zero gradient of normal velocity (i.e. $\partial u/\partial x = 0$). At the exit opening "upper one", the extrapolation procedure for all variables is suitable. The solution technique for solving these equations is based upon the Marker and Cell (MAC) algorithm. This method was first used by Harlow and Welch (1965) for the free surface flow. In this paper the upwind differencing scheme for convection terms is used (Ozisik, 1994). The detail of the procedure can be found in Nakamura (1977).

RESULTS AND DISCUSSION

In this paper, the house geometry was rectangular (2.5 × 4 × 6 m). Two openings are located on the northern-facade (0.5 × 1 m) and the ceiling (0.4 × 1 m). Two positions of inlet and three positions of ceiling openings were considered. The six geometries studied and their numerical results are shown in Fig. 1 and 2 which show velocity vector plots and temperature distributions for the cross-section of the middle of room, respectively. The temperatures for simulations were as follows: ambient temperature = 30 C, floor, ceiling, northern, eastern, southern and western walls temperature = 30, 37, 35, 37, 40 and 37 C, respectively. Such conditions would, qualitatively, represent noon. Since no wind enters the building then the airflow is only due to stack effect. Fig. 1 shows that the incoming induced air stream moves through the living level and another part moves upward along the walls resulting from the buoyancy force. Near the ceiling, it turns toward the ceiling aperture. This demonstrates that the ventilation rate and the streamlines depend on openings' position. Therefore, by changing, mainly, the inlet and ceiling apertures' position, improvement of ventilation may be obtained with respect to the desired level of comfort. From Fig. 2, the average room temperature is 2 C above ambient, which is in good agreement with experimental results given by Khedari *et al.* (2000) that validated the model developed here.

CONCLUSIONS

The numerical result shows that using a solar chimney alone to induce the airflow within the building can not only work but also be controlled according to resident comfort and building design. At moderate outdoor temperature, solar chimney could provide sufficient ventilation rate for occupant's comfort, which is very suitable for buildings in the tropics. A complete version of the software is under development and will be published sooner.

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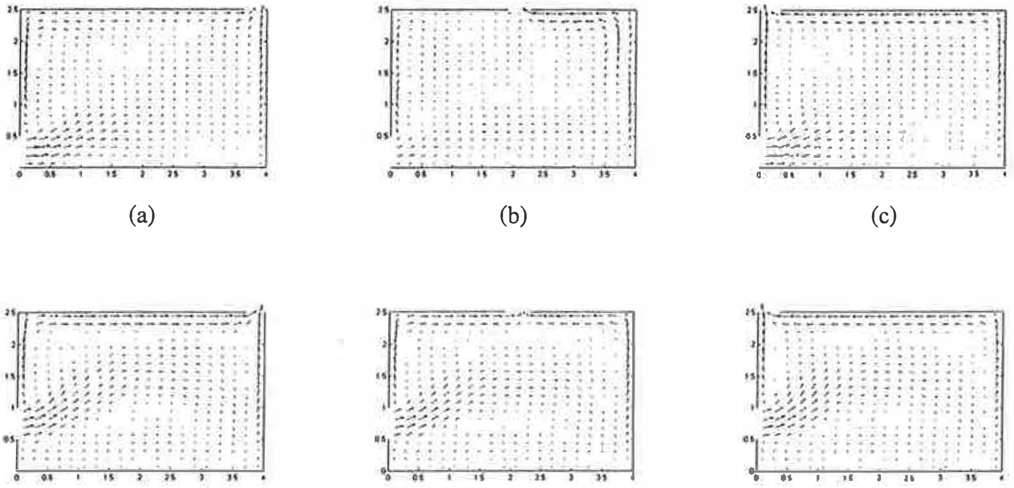
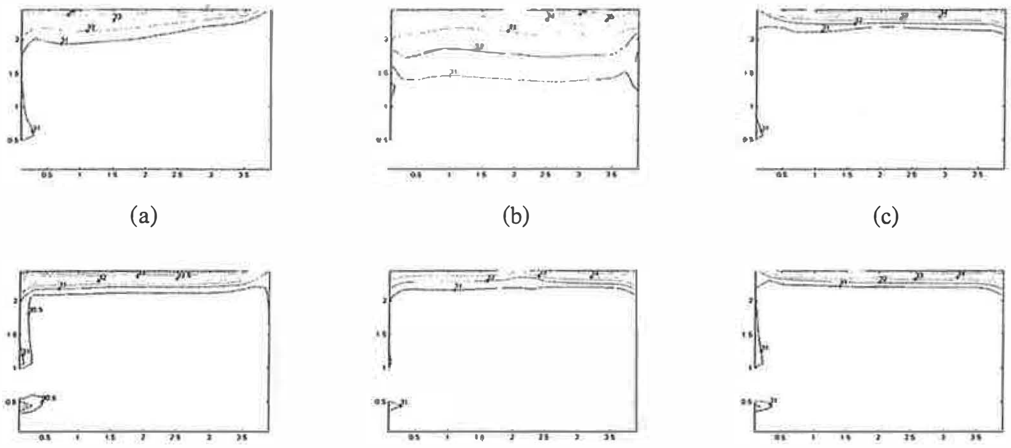


(a) (b) (c)

(d) (e) (f)

Fig. 1. Velocity vector plot on the middle plane of buildings at different opening positions. (The right wall is faced to the south direction.)



(a) (b) (c)

(d) (e) (f)

Fig. 2. Temperature distribution on the middle plane of buildings.