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USE OF SOLAR ENERGY FOR VENTILATION COOLING OF BUILDINGS

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SYNOPSIS

This paper discusses summer cooling of buildings by means of natural ventilation. Computational fluid dynamics is used to predict the ventilation rate in a room with a Trombe wall. The effect of Trombe wall insulation on the room thermal environment is investigated. It is shown that to maximise the effect of ventilation cooling, the interior surface of a Trombe wall should be insulated.

1 INTRODUCTION

A Trombe wall system consists of a massive storage wall and glazing. The massive storage wall serves to collect and store solar energy. The stored energy is transferred to the inside building for winter heating or enhances room air movement for summer cooling. Fig. 1 shows a Trombe wall for summer cooling of a room. During the operation, the buoyancy effect of air in the channel between the solar heated storage wall and glazing draws room air to the bottom vent. The air in the channel exits to the ambient through the top vent while cool outdoor air is drawn into the room through an open window in the opposite wall. Depending on the ambient temperature, this operation can be either for daytime ventilation or night cooling. If the summer temperature of outdoor air is not very high such that indoor air is warmer than outdoor air due to high heat loads through lighting and other sources, the Trombe wall can be used for ventilation cooling during daytime to reduce or eliminate the need for energy intensive refrigerative cooling. If the outdoor air is hot during the day, the Trombe wall can be used for night cooling by drawing the cool ambient air into the space and so removing heat from the interior of the building.

In this work computational fluid dynamics (CFD) is used to investigate the potential of a Trombe wall for summer ventilation of a room with solar heat gains and conduction heat transfer. The effect of insulation of Trombe wall on the indoor thermal comfort is assessed.

2 CFD TECHNIQUE

The CFD model consists of a set of governing equations representing the mean and turbulent velocities and enthalpy. The time-averaged steady-state air flow equations can be written in the following form

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

where ϕ is the flow variable, U_i is the mean velocity component in x_i direction, ρ is the air density, Γ_ϕ is the diffusion coefficient and S_ϕ is the source term.

The solution of the flow equations is based on the finite-volume TEAM code [1] and is validated against the experimental data for enclosures with Trombe wall geometries [2].

The CFD technique is applied to simulating ventilation cooling of an occupied room with a

Trombe wall system (see the schematic of the room in Fig. 1). The room is a test chamber at the University of Nottingham which has dimensions of 5 m long, 3 m wide and 2.4 high. The simulated Trombe wall is assumed to include a double glazing unit and a 0.3 m thick concrete wall with thermal conductivity of 1.4 W/m-K and insulated on the interior surface. It has the same width and height as the room and is situated at the south end of the room. The distance between the glazing and wall is 0.1 m. There are five 0.4 m X 0.1 m slots near the bottom of the storage wall and one single 3 m X 0.1 m slot at the top of glazing. Other room walls are insulated. In the north wall there is an openable window. In the summer ventilation mode, the outdoor air at a temperature of 20°C is assumed to enter the room through the window with an opening level of 1 m high and 0.5 m wide. It is further assumed that stack effect [3] is the sole driving force for air exchange between indoors and outdoors.

The storage wall solar heat gain is calculated from the daily mean total solar irradiance and mean solar gain factor on July 23. The daily mean solar irradiance on south wall is 165 W/m^2 [3] and mean solar gain factor for double glazing is 0.64. The room is occupied by two people with heat generation. The occupants' metabolic rate is taken to be 1.2 met and clothing level 0.6 clo. The heat gain due to lighting is 20 W/m^2 of floor area and uniformly distributed on the floor. The room is symmetrical and so only half of the room is used for simulation.

Solution of the flow field is considered to have converged when the sum of normalized residuals is less than 10^{-6} for enthalpy and less than 10^{-3} for other flow equations. Convergence is achieved after 10000 iterations. For a grid size of 68 x 40 x 27 for room length, height and half width, the CPU time for computation is 25 seconds per iteration on a Sun ULTRA server (Enterprise E3000 with three 250 MHz processors of 1 GB memory).

3 RESULTS AND DISCUSSION

Figures 2 and 3 show the predicted thermal environment on two vertical planes - symmetry plane and the plane through one of the occupant. It is seen from Fig. 2a that the outdoor air is drawn into the room through the window. The cool incoming air drops down to the floor due to the negative buoyancy effect and spreads over the floor. The buoyancy forces of air in the Trombe wall channel induce room air towards the bottom openings in the storage wall and eject the heated air in the channel through the outlet opening at the top of glazing. Because there is no strong air movement in the upper region of the room, the thermal plume created by the occupant reaches the ceiling (Fig. 3a and Fig. 3b). The predicted ventilation rate for the room is 103 l/s. This is well above the minimum fresh air requirement for two persons [3]. The predicted mean air velocity in the occupied zone (from floor to 1.8 high and 0.15 from walls) is 0.08 m/s. There exists a temperature gradient in the room but the mean gradient between 1.1 m and 0.1 m above the floor is only 1.1 K. The predicted mean air temperature in the occupied zone is 24.2°C. The mean radiant temperature varies from floor to ceiling due to heat gain from the floor but the variation is small (25.4°C on average) because of wall insulation (Fig. 2c and Fig. 3c). The predicted mean vote (PMV) [4] for the occupied zone is close to zero and the predicted percentage of dissatisfied (PPD) is 6.5%, within the comfort limit of 10% [5]. Thus, the average room environment is acceptable. Along the incoming air stream, air is slightly cool (PMV < -0.5) (Fig. 2d). This can be alleviated by adjusting the window opening level since the predicted ventilation rate is very high under the simulated conditions. However, since the air in the area where the occupant is situated is close to a neutral temperature (i.e. PMV = 0) (Fig. 3d), such an operation may not be needed.

When the insulation on the interior surface of the storage wall is removed, part of the solar heat gain on the wall is transferred to the room through conduction and so less heat is utilised for generating the buoyancy forces in the channel of Trombe wall. The predicted mean air temperature in the occupied zone is increased to over 30°C due to the reduced ventilation rate and heat transfer from the storage wall by convection and radiation. The room is consequently far too hot for thermal comfort. However, the room thermal environment can be improved by opening extra vents in the north or other walls. Fig. 4 and Fig. 5 show the predicted room air conditions with the non-insulated Trombe wall and a slot vent near the top of the north wall whose size is the same as the outlet vent for the Trombe wall. The non-insulated warm storage wall induces an upward thermal plume inside the room (Fig. 4a) and when air flows towards the vent in the north wall it distorts the thermal plume created by the occupant (Fig. 5a). The predicted ventilation rate is increased to 167 l/s, of which 54% is induced by the Trombe wall. The mean air velocity in the occupied zone is also increased slightly to 0.09 m/s. The mean air temperature in the occupied zone is 23.6°C, which is slightly lower than that under the original room and Trombe wall conditions due to the increased ventilation heat loss over heat gain from the storage wall. Also, the vertical temperature gradient is increased, however it is still within the comfort limit of 3 K [5]. The average value of mean radiant temperature for the occupied zone remains the same as for the room with insulated storage wall but the distribution is not so uniform. The mean radiant temperature near the Trombe wall is higher than that near the north wall, resulting in the variation of mean radiant temperature principally along the horizontal rather than vertical direction. This is due to the increased temperature of the interior surface of storage wall. The mean temperature of the interior surface is 31.4°C compared with 24.6°C when the surface is insulated. The PPD value for the occupied zone is 7.1%. The room as a whole is also comfortable but the cool incoming air stream disperses to a larger area due to the higher air flow rate.

The above predictions are based on the occupants' clothing level of 0.6 clo. The clothing level could be reduced to 0.5 clo or lower for summer conditions. Hence the occupants could tolerate slightly higher outdoor air temperatures (e.g. 21°C) or internal heat gains (say 25 W/m^2) than used for the predictions without causing thermal discomfort provided that the interior surface of storage wall is insulated. In addition, opening more air vents can induce higher air exchange rates and thus allows the system to operate at even higher outdoor air temperatures. For example, with the storage wall insulated, when a vent is opened in the north wall in the same way as for the case with the non-insulated storage wall, the occupants with clothing level 0.4 clo will feel comfortable at outdoor air temperatures as high as 24°C. The predicted ventilation rate at the outdoor air temperature of 24°C is 160 l/s. The predicted mean air and radiant temperatures in the occupied zone become 26.4° and 27.5°C, respectively. The mean value of PPD for the occupied zone is 11.9% for the clothing level of 0.5 clo and decreases to 9.2% when the clothing level is taken to be 0.4 clo. If the clothing level has to be fixed at 0.5 clo, the maximum outdoor air temperature for acceptable indoor thermal comfort is 23°C (with the predicted mean air and radiant temperatures and PPD in the occupied zone of 25.5°, 26.7°C and 7.9%, respectively).

To demonstrate the effectiveness of the insulated Trombe wall for ventilation cooling, further predictions are made with the Trombe wall system removed but with the same amount of heat gain imposed in the south wall as that from the non-insulated storage wall and with the slot vent opened at the top of both south and north walls. At an outdoor air temperature of 24°C, the predicted ventilation rate is reduced to 105 l/s (compared with 160 l/s for the room with insulated Trombe wall). The predicted mean air and radiant temperatures in the occupied zone reach 27.7°C and 28.7°C, respectively, and PPD is over 23% for clothing level 0.5 clo. However, when the outdoor air temperature is reduced by 4°C to 20°C, the predicted room thermal environment is acceptable with mean air and radiant temperatures reduced to 23.8°C and 24.9°C, respectively, and PPD for the occupied zone of 7.4%. Therefore, insulating the storage wall can provide ventilation cooling at higher outdoor air temperatures than without insulation (23°C compared with 20°C for instance).

4 CONCLUSIONS

In moderate sunny days, Trombe walls can be used for ventilation cooling. To maximise ventilation cooling, the interior surface of storage wall should be insulated. Additional vents should be provided to increase ventilation rates for high outdoor temperatures.

Trombe walls are however designed principally for winter heating. If ventilation cooling is the main purpose, it would be more effective to enhance and control the ventilation rate by using a solar chimney than a Trombe wall [2].

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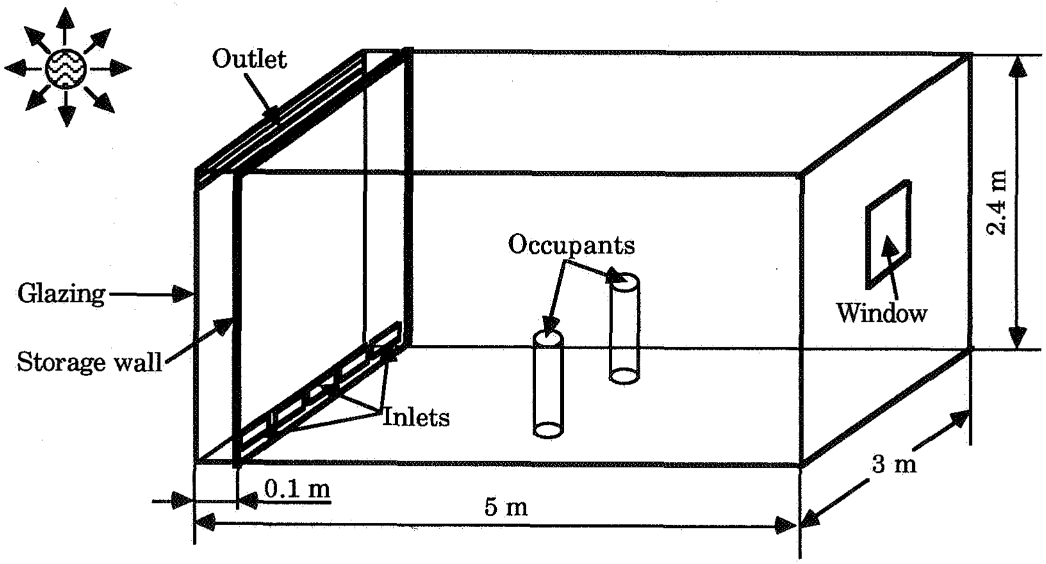
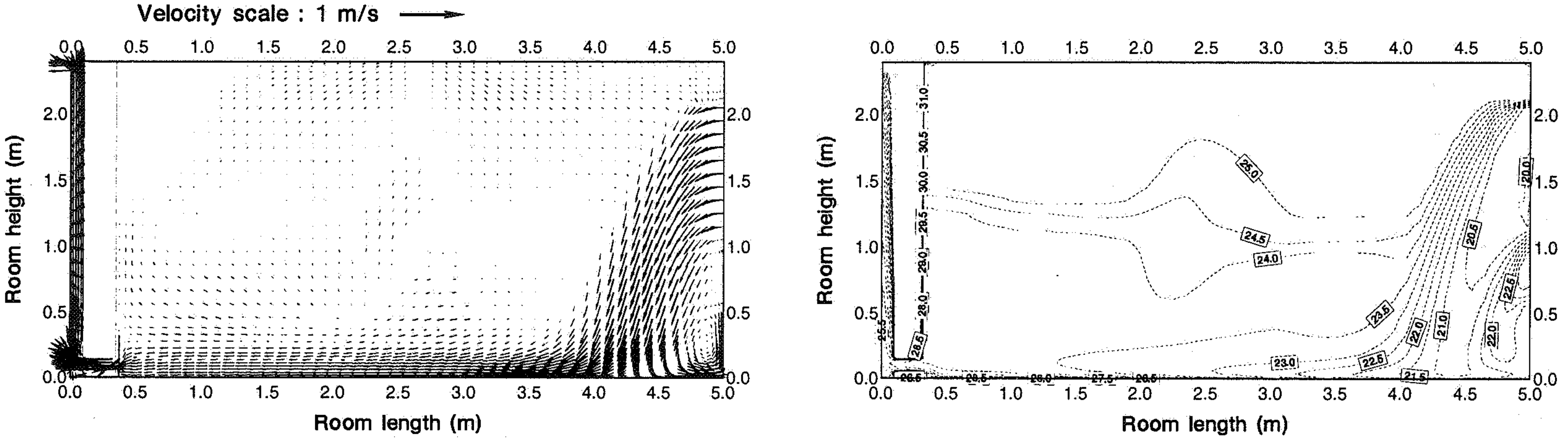
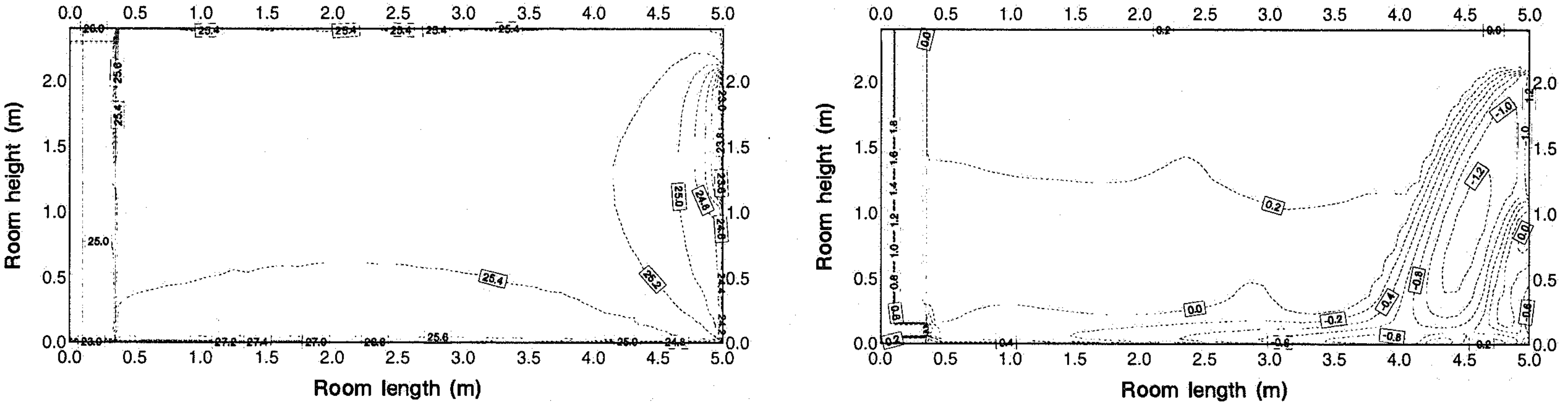


Fig. 1 Schematic diagram of a Trombe wall for ventilation cooling of a room



(a) Air velocity (m/s)

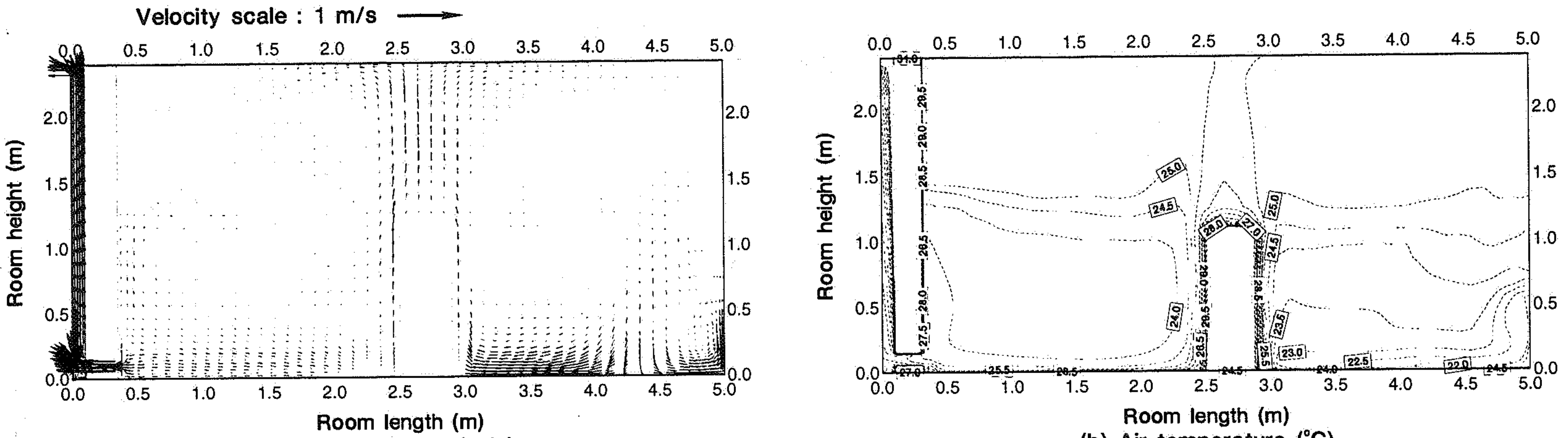
(b) Air temperature (°C)



(c) Mean radiant temperature (°C)

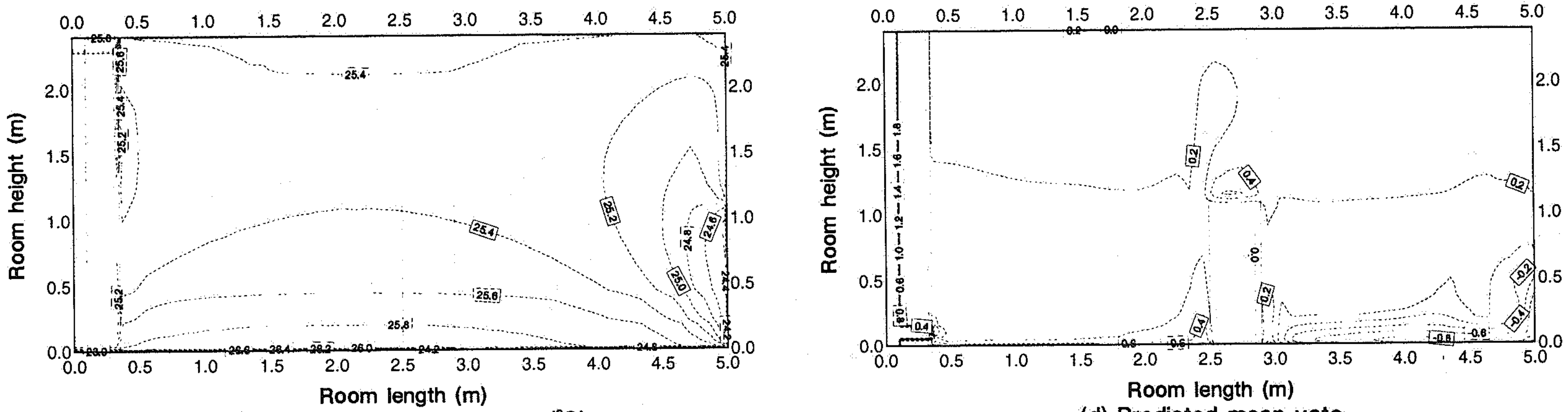
(d) Predicted mean vote

Fig. 2 Predicted air flow pattern and thermal environment on the symmetry plane in the room with insulated Trombe wall



(a) Air velocity (m/s)

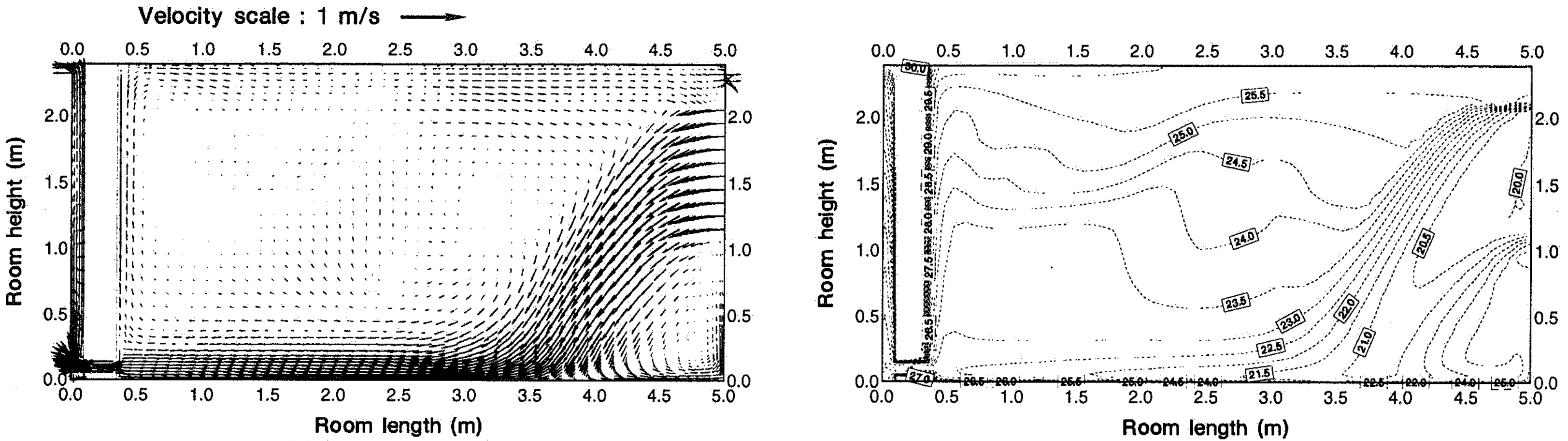
(b) Air temperature (°C)



(c) Mean radiant temperature (°C)

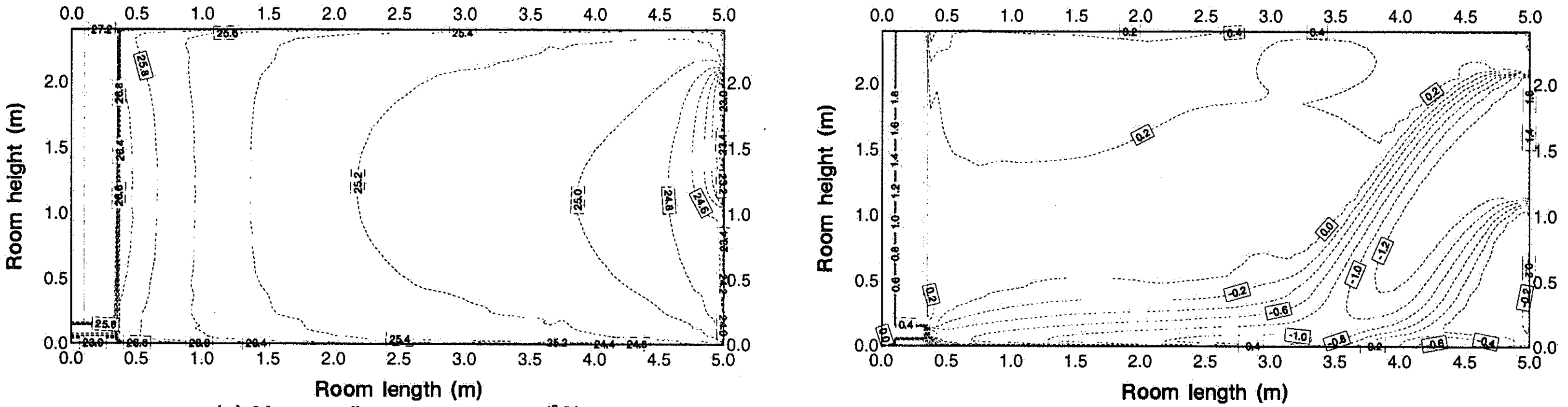
(d) Predicted mean vote

Fig. 3 Predicted air flow pattern and thermal environment on the plane through occupant in the room with insulated Trombe wall



(a) Air velocity (m/s)

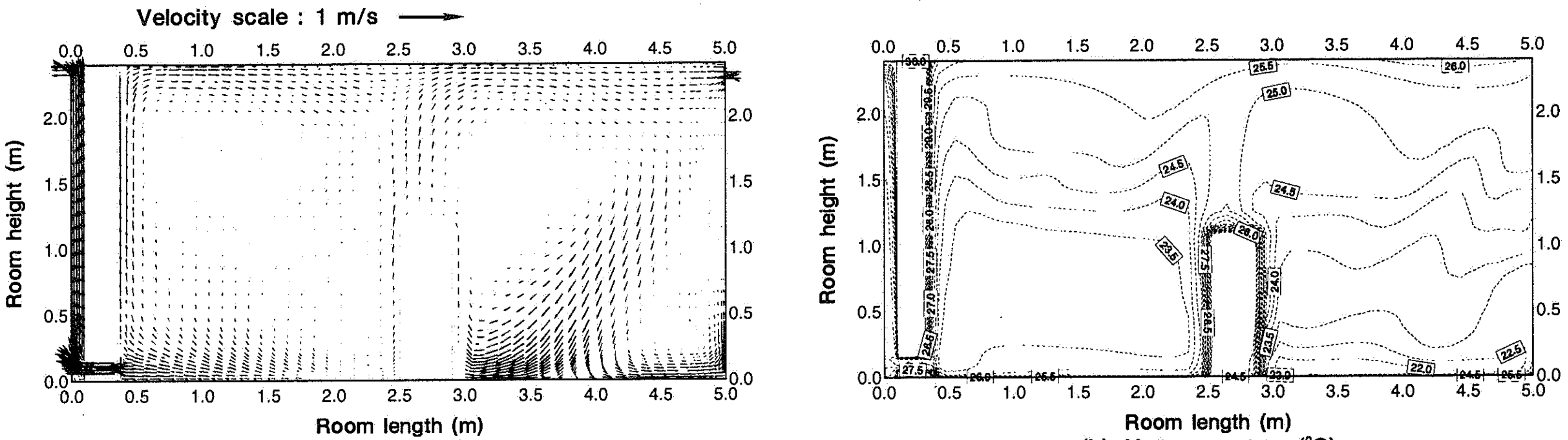
(b) Air temperature (°C)



(c) Mean radiant temperature (°C)

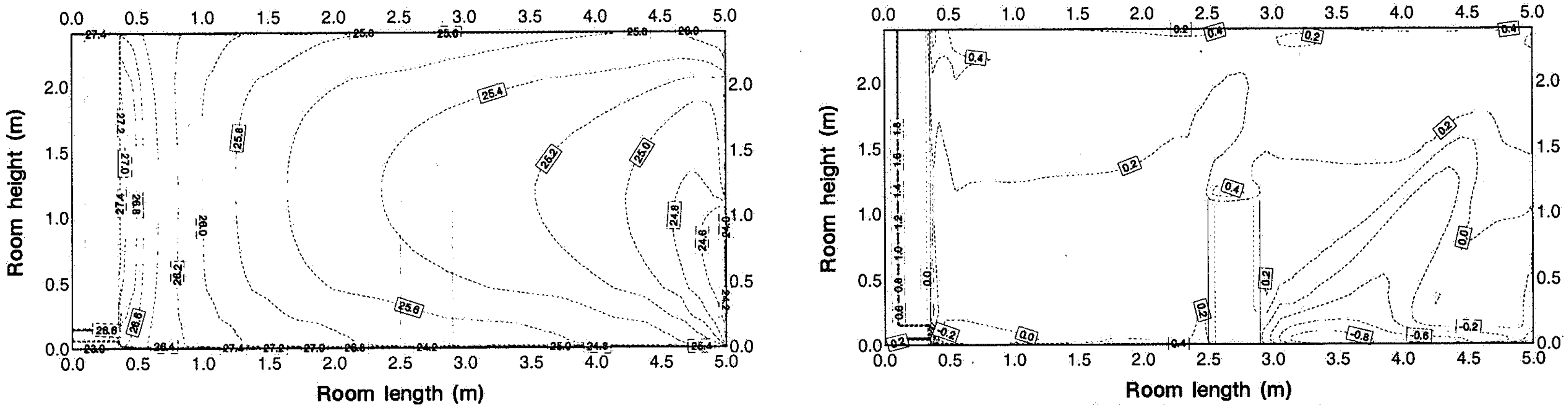
(d) Predicted mean vote

Fig. 4 Predicted air flow pattern and thermal environment on the symmetry plane in the room with non-insulated Trombe wall



(a) Air velocity (m/s)

(b) Air temperature (°C)



(c) Mean radiant temperature (°C)

(d) Predicted mean vote

Fig. 5 Predicted air flow pattern and thermal environment on the plane through occupant in the room with non-insulated Trombe wall