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A numerical study of solar chimney for natural ventilation of buildings with heat recovery

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Abstract

The performance of a glazed solar chimney for heat recovery in naturally-ventilated buildings was investigated using the CFD technique. The CFD program was validated against experimental data from the literature and good agreement between the prediction and measurement was achieved. The predicted ventilation rate increased with the chimney wall temperature. The effects of solar heat gain and glazing type were investigated. It was shown that in order to maximise the ventilation rate in a cold winter, double or even triple glazing should be used. Installing heat pipes in the chimney for heat recovery not only increased the flow resistance but also decreased the thermal buoyancy effect. To achieve the required air flow rates in naturally-ventilated buildings with heat recovery, use should be made of wind forces.

Keywords: Solar chimney; Natural ventilation; Heat pipes; Flow resistance; Computational fluid dynamics

1. Introduction

Today, buildings are better insulated and more air-tight than ever in order to reduce heat losses. Most houses are naturally ventilated and many naturally-ventilated buildings utilise chimneys for stack ventilation. The use of more tightly sealed exterior envelopes decreases room air movement and increases the possibility of chimney backdraughting, particularly in mild weather when the stack effect is smallest [1]. To reclaim heat from exhaust air in a naturally-ventilated building, therefore, specific measures need to be adopted to overcome this problem.

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Solar chimneys are used to enhance air movement in naturally-ventilated buildings. A solar chimney can be made of concrete or masonry walls. To increase the solar heat absorption and ventilation rate, a south-facing wall of the solar chimney could be replaced with glazing and the interior of other walls blackened and the exterior insulated. Unlike exhaust chimneys where the purpose of insulation, if any, is to reduce heat loss from exhaust gases, the insulated walls of a solar chimney serve to collect and store solar energy so as to generate the buoyancy effect and enhance stack ventilation.

LeMay and O'Connor [2] tested various types of exhaust chimneys in order to measure the effect of chimney insulation. It was found that from a cold start all chimneys formed a wall condensate but better insulated chimneys had shorter condensation periods and attained operating conditions much faster. Barozzi *et al.* [3] modelled a solar chimney-based ventilation system for buildings. The roof of a building performed as a solar chimney to generate air flow and provide cooling for the living room. Experimental tests were carried out on a 1:12 small-scale model of the prototype. Thermal anemometers were used to measure temperature and velocity distributions and a laser sheet was used to enhance smoke flow visualisation. The experimental results were then used to validate a two-dimensional laminar flow simulation model. Good agreement between the predicted flow pattern and experimental flow visualisation was achieved but it was envisaged that flow predictions could be improved upon by taking account of turbulence and three-dimensional effects as well as employing appropriate boundary conditions. Bansal, *et al.* [4] analytically studied a solar chimney-assisted wind tower for natural ventilation in buildings. The combination of wind tower and solar chimney enabled wind and buoyancy forces to be utilised to generate air flow in the building. The estimated effect of the solar chimney was shown to be substantial in promoting natural ventilation for low wind speeds. Bouchair [5] experimentally and theoretically studied the performance of a typical cavity used as a solar chimney in inducing ventilation into a house. Measurements were made on a full-scale model under steady-state conditions. It was observed that the mass flow rate maximised when the cavity width was between 0.2 m and 0.3 m. The mass flow rate was also found to increase with surface temperature.

The authors have recently been undertaking a project on solar-assisted natural ventilation with heat-pipe heat recovery [6]. In order to promote air exchange in naturally-ventilated buildings, a glazed solar chimney is proposed as an integral part of the system [7]. A heat-pipe heat recovery unit is a heat exchanger consisting of externally-finned sealed pipes containing a volatile fluid such as methanol which has an operating temperature range from −40°–100°C. The unit is divided into evaporator and condenser sections. Heat from exhaust air in the chimney is recovered by the evaporator and transferred to the condenser to pre-heat incoming air in a supply duct. Several types of heat-pipe unit have been tested in a two-zone chamber. One of them consists of two banks of seven heat pipes with plain fins. A strategy to control the flow rate is also developed by employing dampers in the chimney and supply duct. The control system functions according to the levels of indoor and outdoor air temperatures as well as occupancy so that, for example, the dampers are closed and no heat exchange takes place when a building is not occupied on a cold night. A prototype heat exchanger and solar chimney will be tested in a large office in Zurich with a design flow rate of 100 l/s.

The objective of the present study is to apply the technique of computational fluid dynamics (CFD) to simulating air flow and heat transfer in the proposed solar chimney for heat recovery in naturally-ventilated buildings. A CFD program was first validated against experimental data for an isothermally heated chimney. Numerical investigation was then carried out into the performance of the glazed solar chimney.

2. Methodology

In the CFD technique, the time-averaged steady-state flow equations can be written in the following form:

$$\mathrm{div}(\rho\bar{U}\phi - \Gamma_\phi \nabla\phi) = S_\phi, \tag{1}$$

where ρ is the air density, $\bar{U}$ is the mean velocity, ϕ represents the flow variables such as mean velocity, turbulence parameters, mean temperature/enthalpy and moisture concentration, Γ_ϕ is the diffusion coefficient and S_ϕ is the source term for variable ϕ.

Details of the model equations and solution are described by Gan and Riffat [6].

The air flow rate through a solar chimney is given by

$$Q = C_d A\sqrt{\frac{2\Delta P}{\rho}}, \tag{2}$$

where Q is the volume flow rate (m^3/s), C_d is the discharge coefficient, A is the inlet opening area (m^2) and ΔP is the driving pressure due to buoyancy (stack) (ΔP_b) and/or wind (ΔP_w) effects (Pa), i.e. $\Delta P = \Delta P_b + \Delta P_w$.

Because the temperature and to a lesser extent moisture concentration of air in the chimney are not uniform, the inside air density is not constant and so the stack effect is calculated from the following equation:

$$\Delta P_b = g\int_0^H (\rho_o - \rho_h)\mathrm{d}h, \tag{3}$$

where g is the gravitational acceleration (m/s^2), H is the chimney height (m), ρ_o is the density of outdoor air (kg/m^3) and ρ_h is the mean density of air in the chimney at height h (kg/m^3).

The wind effect is given by

$$\Delta P_w = \tfrac{1}{2}\Delta C_p \rho V_w^2, \tag{4}$$

where ΔC_p is the difference in wind pressure coefficient between flow inlet and exhaust openings and V_w is the wind speed at the level of chimney exhaust opening (m/s).

The discharge coefficient is related to the total flow resistance of a system as follows:

$$C_d = \sqrt{\frac{1}{\sum k_i}}, \tag{5}$$

where Σk_i is the sum of pressure loss coefficients for the flow system including entry, exit, bend and obstructions such as heat pipes as well as the friction loss coefficient of straight passages.

The pressure loss coefficients can be determined using measurement and CFD modelling [8]. In air ducts with heat recovery for naturally-ventilated buildings using heat pipes, the duct mean velocity is generally low, typically between 0.5 and 1 m/s. Consequently, the pressure loss coefficient of heat pipes has been found to vary with duct mean velocity. The measured pressure loss coefficient for two banks of heat pipes with plain fins is related to the velocity by

$$k = 4.6261\,V^{-0.4825} \qquad (r = 1.00), \tag{6}$$

where V is the duct mean velocity between 0.4 and 2 m/s and r is the correlation coefficient.

3. Validation

Validation of the program was performed by comparing the numerical prediction with the experimental results for natural convection in a solar chimney by Bouchair [5]. Figure 1 shows the elevation of the chimney.

The chimney was 2 m high and of variable width. The inlet height also varied in the experiment. All the wall faces were isothermally heated by electric heaters to temperatures from 30°C to 60°C. The inlet air temperature was controlled at 20°C. Temperatures were measured with copper–constantan thermocouples. The speed of air movement was measured with a heated thermistor anemometer and air flow patterns were observed with the use of smoke. Details of the experimental measurement and results are given by Bouchair [5].

Figure 2 shows the predicted and measured mass flow rates per unit length of the chimney for channel widths between 0.1 m and 0.5 m and inlet heights of 0.1 m and 0.4 m. It is seen that the agreement between the prediction from the present study and the measurement by

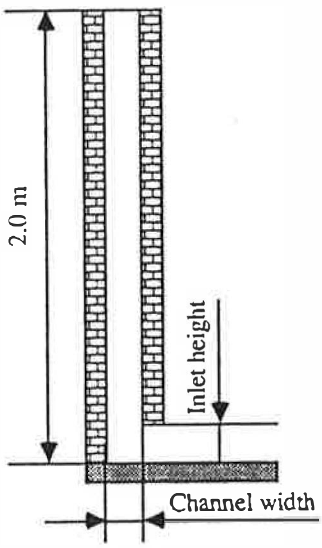


Fig. 1. Elevation of the test chimney.

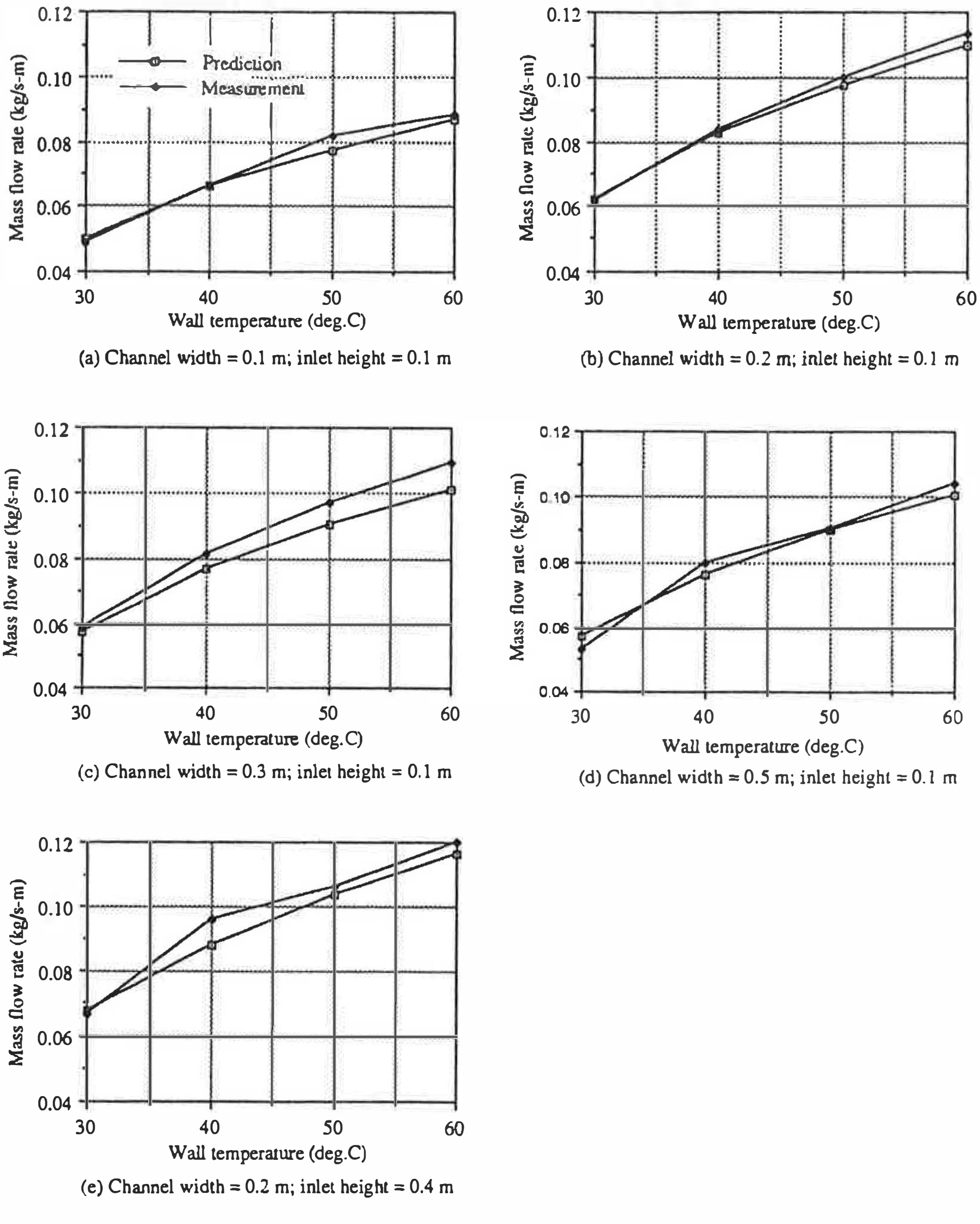
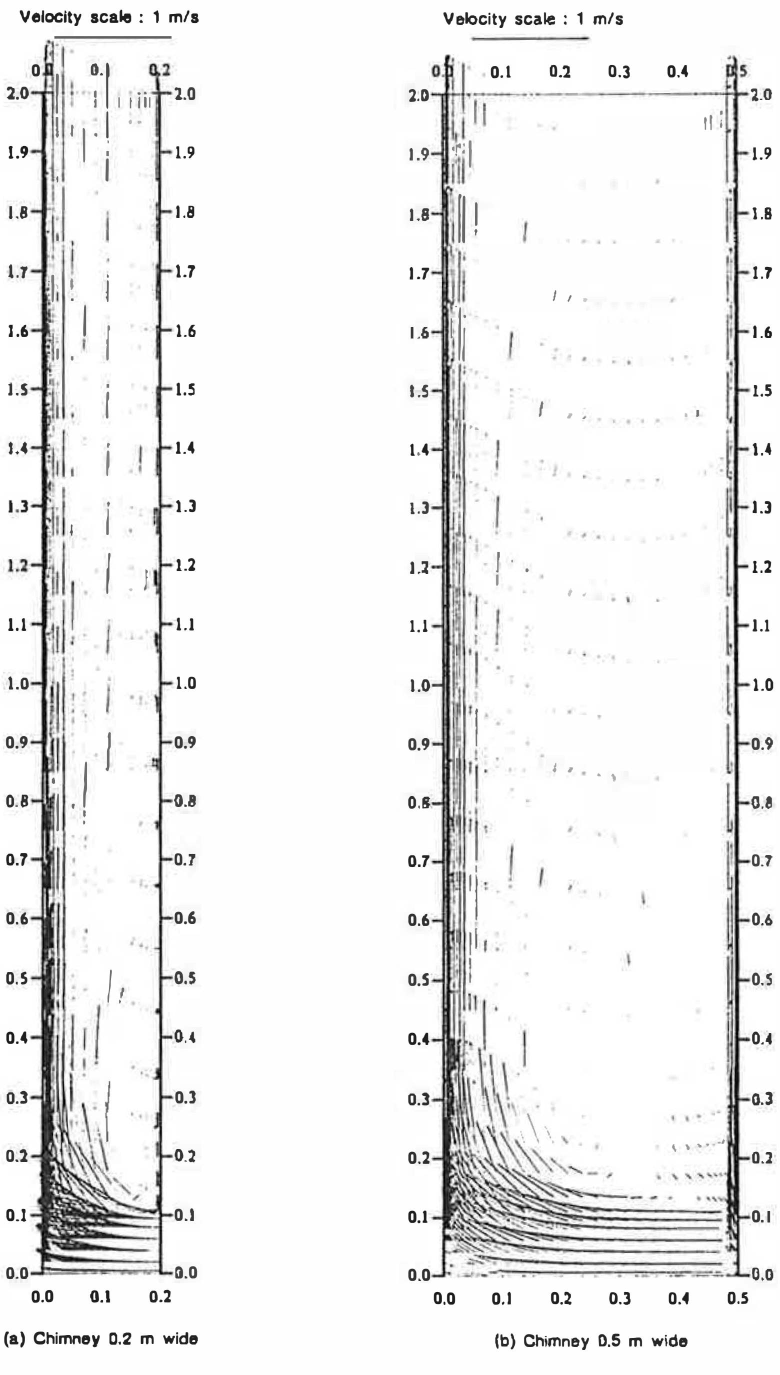


Fig. 2. Comparison of the predicted and measured mass flow rates in the test chimney.



ig. 3. Predicted air flow patterns in the test chimney at two channel widths (wall temperature 50°C; inlet eight 0.1 m).

Bouchair [5] is generally good. The average difference between the prediction and measurement for all the cases was about 3.5%; the maximum difference was 5.6% for the cavity width of 0.3 m and inlet height 0.1 m. This gives confidence in using the computer code to study the air flow and heat transfer in chimneys.

It is also seen from Fig. 2 that the predicted flow rate increased with wall temperature. The flow rate also increased with channel width from 0.1 m to 0.2 m but then decreased as the width increased further. This can be attributed to the reverse flow in the chimney of widths wider than the two boundary layers. Figure 3 shows that when the width of the chimney is small (0.2 m) the flow is upward for the whole width. However, when the width is large (0.5 m), air flows upwards near the heated walls due to the buoyancy effect but near the centre of the chimney air flows downward. This phenomenon was also observed by Bouchair [5].

For a given channel width, the flow rate increased with inlet height due to decreasing entry flow resistance. This can be seen by comparison of Fig. 2(e) with (b).

4. Numerical study of a glazed chimney

Numerical simulation was carried out for the proposed solar chimney for stack ventilation of a large office in Zurich (design air flow rate 100 l/s) with heat-pipe heat recovery in winter.

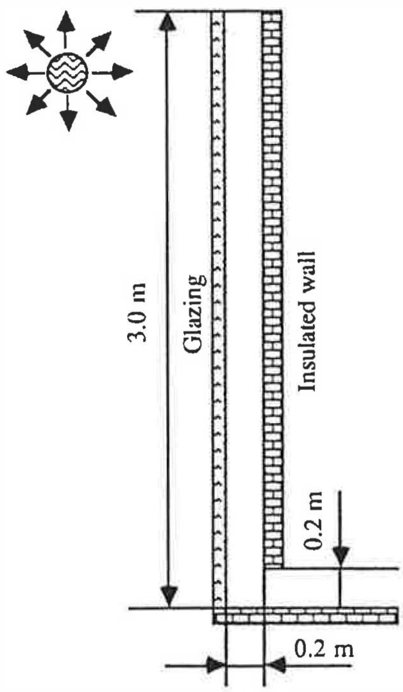


Fig. 4. Dimensions of the glazed solar chimney.

4.1. Simulation conditions

Figure 4 shows the elevation of the chimney. It was 3 m tall and its horizontal cross-section was 0.2 m × 1 m with the major dimension along the east-west orientation. The south face was double glazed and the rest were insulated brickwork. The glazing had an absorptivity for direct solar radiation of 0.2. The inlet opening was also 0.2 m high and 1 m wide. As a base simulation, heat pipes were absent in the chimney. Further simulations were then carried out to study the effect of installing heat pipes on the chimney performance.

The chimney solar heat gain was calculated from the mean total solar irradiance and mean solar gain factor. For a vertical wall with double glazing, the mean solar gain factor was 0.64. The mean solar irradiance on a vertical south surface between 08.00 and 16.00 h sun time on December 21 at 45° north latitude (close to Switzerland) was 438 W/m^2 [9]. The corresponding wall solar heat gain was thus 280 W/m^2. The base outdoor air temperature was taken to be 0°C. A lower outdoor air temperature of −13°C (design winter outdoor temperature for Zurich) was also used to investigate the effect on the chimney performance. The exhaust air from a building that entered into the chimney was assumed at 20°C and 50% relative humidity. It was assumed that in the base simulation stack effect was the sole driving force for air exchange between indoors and outdoors. Wind forces were taken into consideration to achieve high air exchange rates.

5. Results and discussion

Predictions of the performance of the solar chimney were performed for various outdoor conditions (temperature, solar irradiance and wind speed) and chimney components (glazing level and heat pipes with and without heat recovery). The influence of these variables on the chimney performance is discussed below.

Table 1
Predicted performance of 3 m high solar chimney without wind forces and heat pipes

Conditions			Results		
Glazing type	T_o (°C)	q (W/m^2)	T_w (°C)	T_g (°C)	Q (l/s)
Double	0	280	63.2	20.2	106
Single	0	280	65.1	8.6*	98
Single	0	333	71.6	7.1*	103
Double	0	140	46.0	15.6	80
Single	0	167	51.2	5.9*	71
Double	-13	140	47.1	9.6*	73
Triple	-13	140	46.0	15.4	80
Double	0	104	41.1	14.1	70
Single	0	124	45.2	5.0*	45^5

q—wall solar heat gain. T_g—mean temperature of interior surface of glazing. T_w—mean temperature of wall surface facing glazing. *—condensation on the interior surface of glazing. ^{5}—reverse flow near the top of glazing.

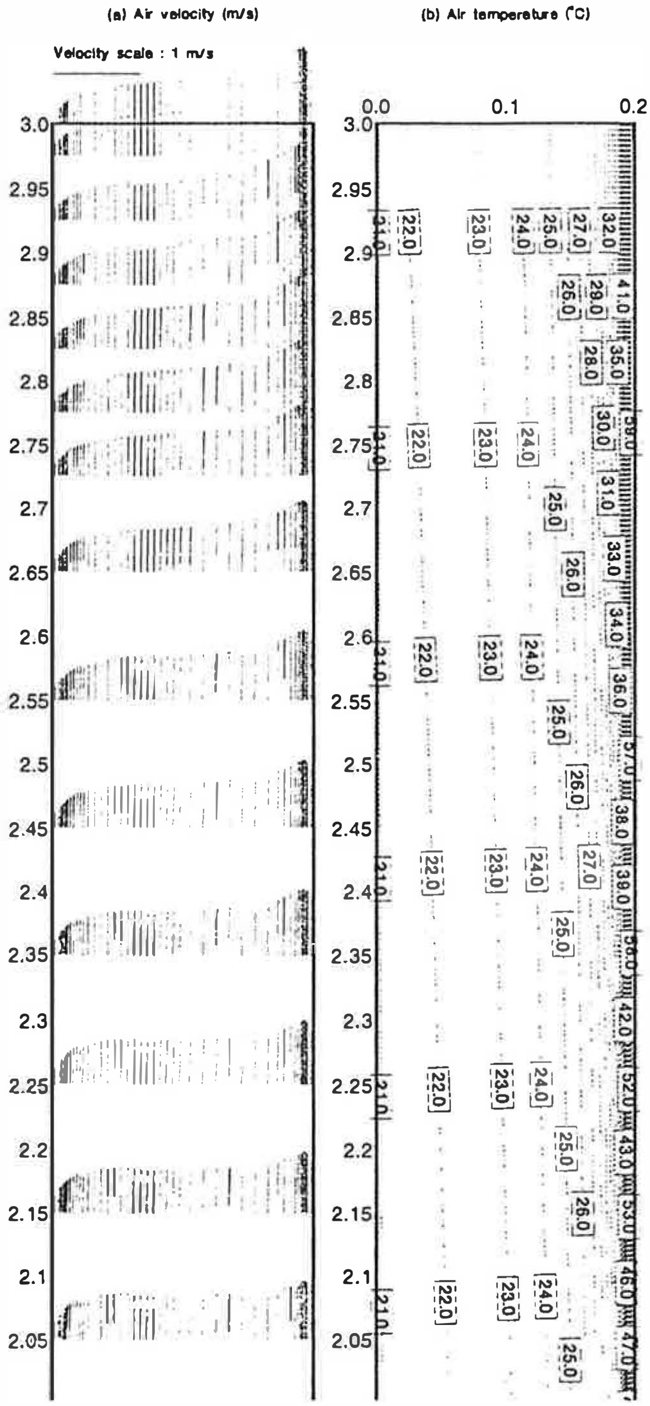


Fig. 5. Predicted centreline air flow pattern and temperature distribution in the double-glazed chimney (wall solar heat gain 280 W/m^2; outdoor temperature 0°C).

5.1. Effect of solar irradiance

The effects of solar irradiance and glazing type on the chimney performance without wind forces and heat pipes are presented in Table 1.

Figure 5 shows the predicted air flow pattern and temperature distribution on the centre plane near the exit of the glazed chimney under the base outdoor and chimney conditions. The predicted ventilation rate through the chimney was 106 l/s. The air temperature near the insulated heated wall was higher than that near the glazing with conduction heat loss. Consequently, the velocity profile showed a peak near the heated wall and low magnitude near the glazing. Nevertheless, air flow in the chimney was upward for the whole width. When the wall solar heat gain was halved (140 W/m^2, corresponding to solar irradiance 219 W/m^2) or further decreased to 104 W/m^2 (corresponding to the daily mean total solar irradiance for Dec. 21 of 163 W/m^2), the predicted ventilation rate was reduced by 24% and 34%, respectively.

5.2. Effect of glazing

The effect of glazing on the predicted ventilation rate depended on the total solar irradiance. For the base outdoor conditions, the ventilation rate decreased from 106 l/s to 98 l/s when double glazing was replaced with single glazing under the same wall solar heat gain. However, when the wall solar heat gain was calculated using the mean solar gain factor for single glazing (0.76 instead of 0.64) and the heat absorption by the glazing was reduced correspondingly, the decrease of the predicted ventilation rate (at 103 l/s) was negligible. At low solar heat gains, the effect of glazing type became significant. Replacing double glazing by single glazing with wall solar heat gains of 167 and 124 W/m^2 led to reductions of the ventilation rate of 11% and 35%, respectively. The large reduction for the lower heat gain (124 W/m^2) was partly due to the flow reversal near the glazing. Figure 6(a) shows the reverse flow of air near the top of the glazing. The reverse flow was caused by the downdraught effect of the glazing. As seen from Fig. 6(b), the temperature of air near the glazing was lower than the inlet air temperature (20°C) due to the higher conduction heat loss than the glazing solar heat absorption. Such flow reversals were also observed by Sparrow, *et al.* [10] for natural convection in a one-sided heated vertical channel. Besides, the use of single glazing led to moisture condensation on its interior surface. The detrimental effect of condensation on the chimney performance would in reality be more serious because the predictions were based on the fixed wall solar heat gains although the latent heat of condensation on the glazing was taken into account. In real situations, the condensate on the glass could have reduced the wall solar heat gains and thus led to even lower ventilation rates than predicted.

Condensation would also occur on double glazing when the outdoor air temperature was reduced to −13°C, resulting in a decrease of the ventilation rate. The risk of condensation was, however, avoided when double glazing was replaced by triple glazing. Besides, using triple glazing increased the ventilation rate to the same level as the chimney with double glazing at the higher outdoor air temperature (0°C) when there was no condensation.

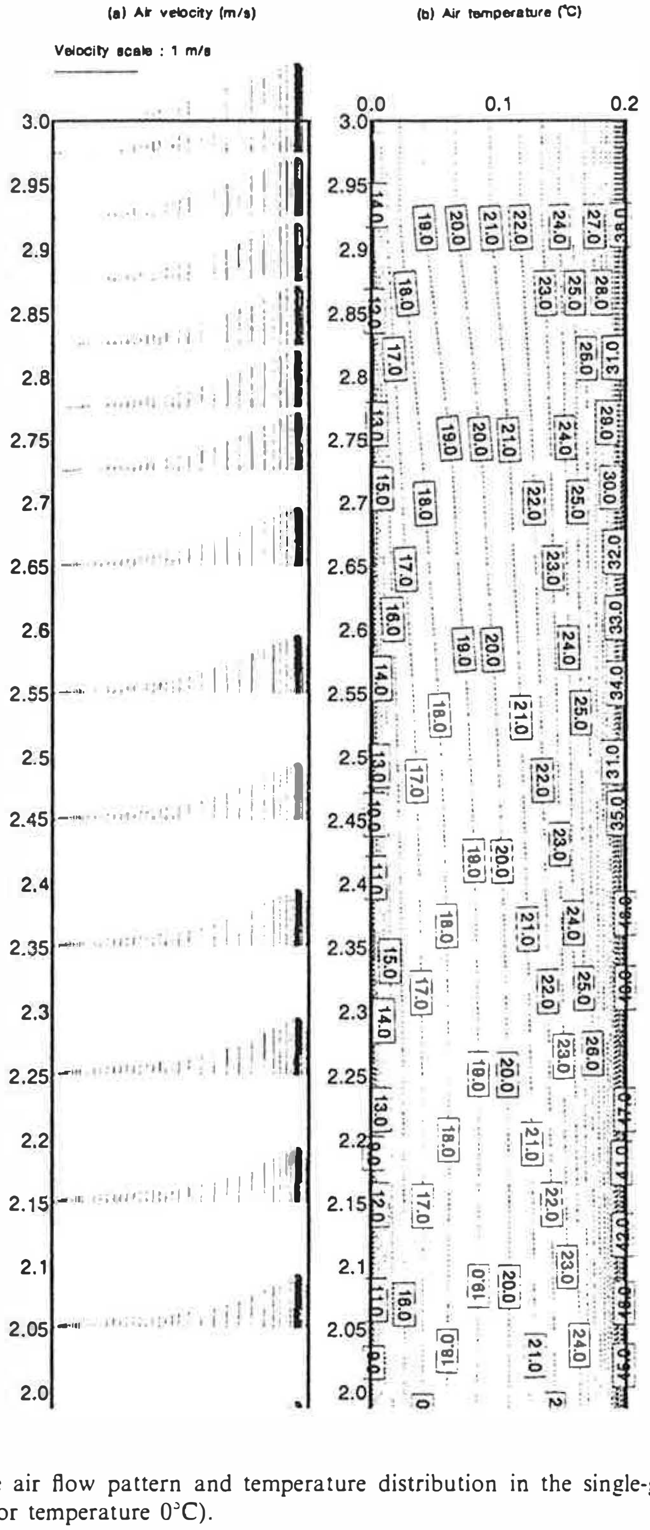


Fig. 6. Predicted centreline air flow pattern and temperature distribution in the single-glazed chimney (wall solar heat gain 124 W/m^2; outdoor temperature 0°C).

5.3. Effect of internal flow resistance

The internal flow obstructions such as dampers and heat recovery systems incur certain flow resistance. The flow resistance due to a unit of two banks of heat pipes with plain fins was accounted for by the pressure loss coefficient—equation (6). In order to study the effect of internal flow resistance alone, the effect of reduced buoyancy of air in the chimney due to heat recovery was ignored. This is equivalent to no heat recovery (heat recovery effectiveness $\epsilon = 0$) and can be achieved by closing the damper in the supply duct while opening a vent or a separate duct without heat pipes to introduce fresh air into the building. Such a circumstance may arise even in heating seasons, for example, when the indoor air temperature exceeds the comfort requirement.

Table 2 presents the predicted ventilation rates with the heat pipes. By comparing with Table 1, it is seen that when the heat pipes were installed in the chimney, the predicted ventilation rate for the base conditions decreased from 106 l/s to 65 l/s, a reduction of nearly 40%. The ventilation rate decreased further to 57 l/s when single instead of double glazing was used. The use of single glazing also led to both condensation on the glass and flow reversal near the glass.

To achieve a higher flow rate through the chimney with heat pipes by natural means, say the design value of 100 l/s, the chimney height should be increased and/or use should be made of wind forces. By increasing the stack effect alone, the height of a glazed chimney should be between 5 m and 6 m with the predicted ventilation rates of 96 l/s and 110 l/s, respectively. Such a tall glazed chimney may however be impractical in use and so it would be more appropriate to make use of the wind effect. To achieve this, the chimney exhaust opening should be located in a region of negative wind pressures under prevailing weather conditions.

Table 2
Predicted performance of solar chimney with heat pipes

Conditions					Results			
Glazing type	Chimney height (m)	Wind speed (m/s)	ϵ (—)	T_o (°C)	q (W/m²)	T_w (°C)	T_g (°C)	Q (l/s)
Double	3	0	0.0	0	280	69.9	21.4	65
Single	3	0	0.0	0	**333**	71.5	6.6^{*}	57^{S}
Double	**5**	0	0.0	0	280	71.6	21.2	96
Double	**6**	0	0.0	0	280	71.8	21.2	110
Double	3	**3**	0.0	0	280	63.0	20.2	107
Double	**2**	**4**	0.0	0	280	58.7	19.7	99
Single	**2**	0	0.0	**-13**	**124**	42.6	-3.7^{*}	2^{S}
Double	**2**	0	0.0	**-13**	**104**	43.1	5.3^{*}	17^{S}
Triple	**2**	0	0.0	**-13**	**104**	42.3	12.6	26^{S}
Double	3	0	**0.639**	0	280	67.0	20.8	45^{S}
Single	3	0	**0.644**	0	333	73.2	5.8^{*}	37^{S}
Triple	**2**	0	**0.663**	**-13**	**104**	41.9	11.1	6^{S}
Double	3	**3**	**0.613**	0	280	58.1	18.9	89

Footnotes as for Table 1

For the simulation, the effect of wind forces was taken account of via the driving pressure in equation (2). Assuming the chimney opening was situated in an area with a pressure coefficient of −0.25 and that the chimney outlet was 6 m from the ground level (3 m room height plus 3 m chimney height), a wind speed at height 10 m above ground in an urban terrain of 3 m/s would be sufficient to generate the required flow rate. The predicted ventilation rate was 107 l/s. If the glazed chimney had to be restricted to a lower height, such a high ventilation rate could only be induced at a higher wind speed and/or higher negative pressure coefficient for the chimney opening. For example, for a chimney 2 m high, the predicted ventilation rate was 99 l/s at a wind speed of 4 m/s (with a pressure coefficient of −0.25). Although the wind speed could not be controlled in practice, the predictions showed under which ambient conditions the required ventilation rate could be attained.

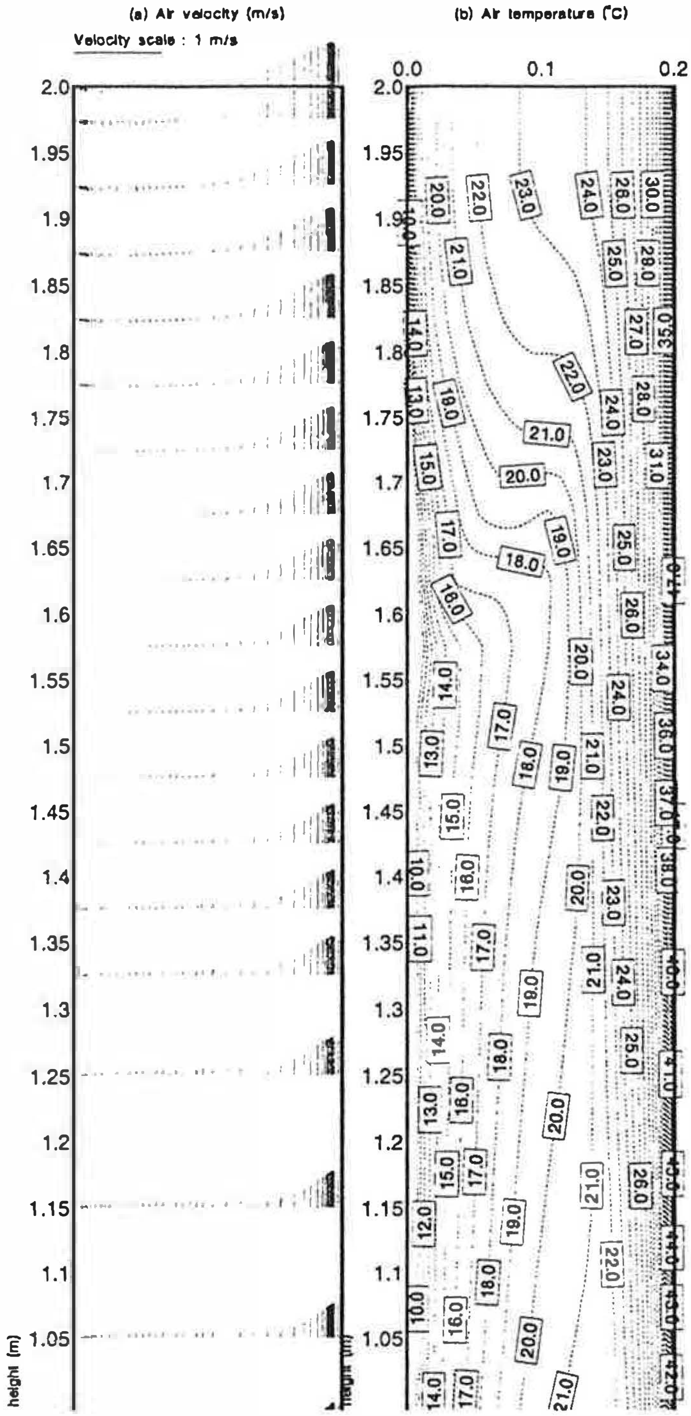
As an illustration, for the worst possible combination of the simulation conditions, i.e., a single-glazed chimney 2 m high with wall heat gain of 124 W/m^2 and at outdoor air temperature of −13°C without the wind effect, the predicted downdraught effect in the chimney was so serious that the downward flow reached the bottom of the glazing and the cold air would flow into the room through part of the chimney inlet opening, thus causing 'backdraughting'. Besides, the temperature of the glazing interior surface was below the freezing point such that any moisture condensed on it would form frost. Even if the chimney was double glazed, there would still exist condensation and flow reversal. The extent of reverse flow was nearly half of the chimney width (Fig. 7) and the predicted ventilation rate was only 17 l/s. Condensation could be prevented by using triple glazing although slight flow reversal near the top of the glazing would still occur. The predicted ventilation rate for the triple glazed chimney increased to 26 l/s.

The case with chimney backdraughting demonstrated the usefulness of the three-dimensional CFD technique in contrast with a one-dimensional flow analysis. A one-dimensional flow model would not be able to predict backdraughting in the chimney simulated. This is because the driving pressure ΔP in equation (2) calculated from a one-dimensional model (equation (7) below) would be positive when the average temperature of air in the chimney was greater than the outdoor air temperature regardless of the chimney insulation level or the amount of solar heat gain. Hence there would always be upward flow in the chimney. The one-dimensional model for calculating thermal buoyancy can be derived from equation (3) for constant air temperature and density across the chimney cross-section as follows:

$$\Delta P = gH\frac{\rho}{\beta}\left(\frac{1}{T_o + 273} - \frac{1}{T_h + 273}\right), \quad (7)$$

where β is the thermal expansion coefficient ($1/K$), T_o is the outdoor air temperature (°C) and T_h is the mean temperature of air in the chimney (°C).

However, the CFD predictions showed that the flow distribution across the chimney was such that cool air could flow downwards while warm air rose within the same duct. Therefore, equation (7) is not appropriate for such situations. Instead, a multi-dimensional analysis which is underpinned in the CFD technique should be used.



[illegible]. 7. Predicted centreline air flow pattern and temperature distribution in the double-glazed chimney with heat [illegible]es (wall solar heat gain 104 W/m^2, outdoor temperature −13°C).