NUMERICAL SIMULATION ON NATURAL VENTILATION SYSTEM COMBINED WITH SOLAR CHIMNEY AND UNDERGROUND COOLTH

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ABSTRACT The results of numerical simulation on the effects of solar chimney and underground cooling system for ventilation and heating in the new building of Faculty of International Environmental Engineering Kitakyushu University, Japan are described. It was found interesting to see the air flow rates with and without the effects of wind during the cooling period and air temperature during the heating period due to the solar chimney.

1 Introduction

In recent years natural ventilation is recommended for buildings to avoid an excess amount of ventilation and air conditioning in summer and solar chimney is often used to promote natural cooling and ventilation. There are insufficient air flow volumes in the Trombe wall in summer. It was reported by Awbi and Gan (1992) that solar chimneys were used in the Trombe walls to gain air flows. Sanjay Kumar et al. (1998) reported indoor air quality in such a system equipped with solar chimney and ground-cooling system that cooled the indoor air from underground of a temperature less than the outdoor (Awbi 1994). However, there are no clear design guidelines of solar chimney in terms of its optimum geometry and ventilation effectiveness.

The solar chimney for natural ventilation designed in the main building of the Faculty of International Environmental Engineering of Kitakyushu University, Japan is combined with the underground crawl space through which the outside air is to be induced. The purpose of this study is to examine the characteristics of a hybrid system with ground cooling and solar chimney to produce passive cooling and heating. The air flow from the temperature difference at the top and bottom in the solar chimney was simulated by CFD simulation. It predicts the effects of energy reduction and the results of simulation for indoor environment with this hybrid system.

2 Weather conditions of the region

The building concerned is to be located at the west end of Kitakyushu city at the latitude of 34°N and the longitude of 130°E.

In summer, the average temperature is about 26° with the highest temperature of 35.4° and the relative humidity is 70-80%. The wind velocity is 2-4.5 m/s and the wind direction is north-west in June and south and south-west in July, August and September.

In winter, the average temperature is 6.7°C and relative humidity is about 63%.Wind velocity is 2- 4.5 m/s and wind direction is south-west.

3 Solar chimney combined with underground cooling

Natural ventilation is performed using wind and buoyancy forces, though the necessary ventilation rate could not always be obtained only by those forces. A large temperature difference between the top and bottom of the solar chimney produces the buoyancy force. A minaret-like tower with holes, can be regarded as a solar chimney, as it is generally used to cool indoors, thus inducing the room air while the outdoor air enters through the opening to be circulated in the indoors. The air heated by solar energy rises within the tower to be discharged to the outdoor. The larger the temperature differences between the top and bottom, the greater the induction effect.

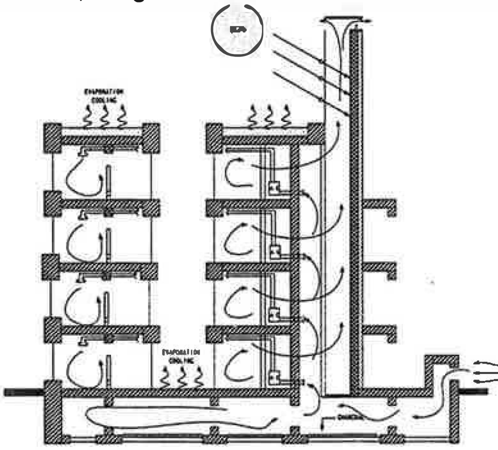


Fig 1. Cooling Mode

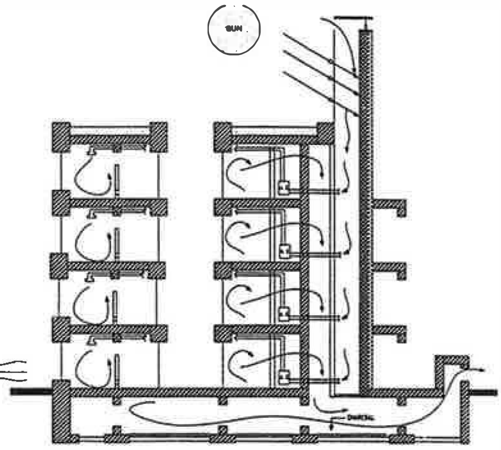


Fig 2. Heating Mode

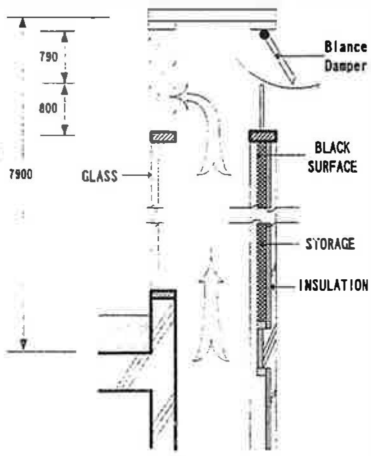


Fig 3. Solar chimney in detail

The indoor is cooled by the intake air from outside through the underground space with a large thermal storage of the underground concrete structure, that has a lesser temperature variation, thus it can act as an underground cooling system. The induced air is to be brought into the room space and discharged to the outdoor through the solar chimney by, stack effect.

In summer, charcoal will be placed in the underground pit to get ride of humidity of the outside air (see Fig 1). As shown in Fig.3 the solar chimney has a glass surface facing south in order to get a higher temperature at the blackened surface inside of solar chimney. In winter, there are many windows to get direct solar heat gain and thermal storage to heat the indoor spaces. Warm air in the solar chimney is used to heat the indoor spaces by fans (see Fig 2). While the underground spaces are to be cooled by cold outside air naturally brought into the underground space, to store the coolness for next summer.

4 Heat transfer in the solar chimney

4.1 Heat conduction

Heat conduction occurs in the building materials of solar chimney effected by outside air temperature and solar radiation. The inside surface temperature of solar chimney is determined by the heat conduction at the surface balanced with heat convection and radiation heat exchange at the surface.

4.2 Heat convection

Heat convection occurs between a heated surfaces and the air within the solar chimney. Gravity, flow viscosity and thermal diffusion influence on the convective heat transfer. The relationship can be expressed by a combination of dimensionless numbers depending on the characteristics of fluid and the space configuration.

a. Vertical - Parallel Isothermal Plates (Handbook 1985, ASHRAE 1993, JSME 1989)
For parallel isothermal plates of surface temperatures T1 and T2 , where T1=T2 or T1≠T2, the Nu number and that in the fully developed flow (Nufd) are expressed by eq.(1). For Ra>10 the observed values of Nu depart from the value of Nufd. For Ra≥10^3 the Nu values follow eq.(2), while for Ra≥10^5 the subsequent heat transfer eq.(3) is recommended (ASHRAE 1993)

$$Nu_{fd} = \frac{4T^{*2}+7T^{*}+4}{90\left(1+T^{*}\right)^{2}} Ra \approx \frac{Ra}{24}$$ eq.(1)

$$Nu = c \cdot Ra^{1/4}$$ for laminar flow eq.(2)

$$Nu = \left[\left(Nu_{fd}\right)^{m} + \left(c \cdot Ra^{1/4}\right)^{m}\right]^{1/m}$$ m=-1.9 eq.(3)

where $T^{*} = \frac{T_2 - T_A}{T_1 - T_A};\ T_1 \geq T_2;\ 0 \leq T^{*} \leq 1$ eq.(4)

Aung and Elenbaas proposed c=0.62 for air (Handbook 1985).This value is 17% higher than the value of a vertical isolated plate. In the case of widely spaced vertical surfaces, the heat transfer relation is similar in form to that for a vertical plate.

b. Uniform-Heat -Flux Parallel Plates (Handbook 1985)
If the heat fluxes are denoted as q1 and q2 , the relationship between heat flux and Nusselt number for the vertical plates are given by

$$Nu = c \cdot (Ra^{*})^{1/5}$$ for $10^{2} \leq Ra^{*} \leq 10^{4}$ in the laminar flow eq.(5)

where $Ra^{*} = \frac{g\beta q_m S^4}{\nu\alpha k}\frac{S}{h}$ eq.(6) $q_m = 1/2(q_1 + \square q_2)$ eq.(7)

For air, an analysis by Aung suggests c= 0.72 while the data by Sobel et al. yielded c=0.67. Further, the Nu number of laminar flow in the parallel and vertical surfaces is given in the ASHRAE Handbook of Fundamentals (1993)

$$Nu = 0.56(Ra)^{0.25}$$ $10^{4} \leq Ra \leq 10^{8}$ eq.(8) for laminar flow

$$Nu = 0.13(Ra)^{0.33}$$ $10^{8} \leq Ra \leq 10^{12}$ eq.(9) for turbulent flow

4.3 Radiation exchange among the inside surfaces (JSME 1989)

Radiative heat transfer occurs among the surfaces within the solar chimney. The rate of radiative transfer from surface 1 to surface 2 is expressed by

$$q_{r12} = h_r\ (T_1 - T_2)$$ eq.(10)

5. Energy balance

The air temperature variation within the solar chimney is brought by heat transfer by convection to the air from the wall and glazing surfaces the temperatures of which are governed by radiation exchange between them q_r, solar radiation absorbed by the respective surfaces q_s and heat conduction through building materials of solar chimney at the respective surfaces q_d. The energy balance at each surface is given by the following equations:

$$q_T = q_d + q_s + q_r \qquad \text{eq.(11)}$$

The convective heat transfer from all side surfaces of solar chimney contributes to the temperature rise of the air dT_A ($=T_{A2}-T_{A1}$) while passing through the incremental height dz at the velocity of w. Thus, referring to Fig 4,

$$q_c(2W+2S)dz = C_p \gamma \; w BSdT_A \qquad \text{eq.(12)}$$

In the case of a rectangular solar chimney, q_c may be expressed by

$$q_c(2W+2S)dz = h_c Bdz\,(T_1-T_A)+h_c Bdz\,(T_2-T_A)+ h_c Sdz\,(T_3-T_A)+h_c Sdz\,(T_4-T_A) \qquad \text{eq.(13)}$$

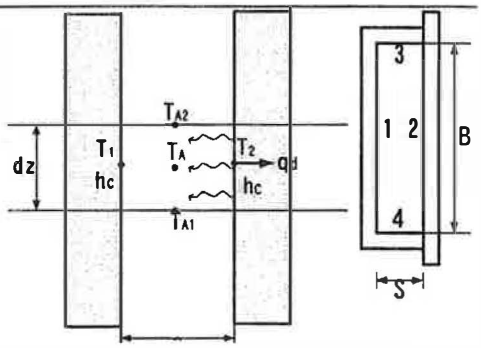


Fig.4 Section of the solar chimney

From these energy balance equations, the surface temperature, air temperature and air velocity in the solar chimney can be obtained from the analysis combined with CFD. In the later calculation, however, the surface temperatures were assumed as one constant value for simplicity under steady state conditions.

6 Stack effect (Awbi 1994, Awbi & Gan 1992, Allard 1998)

A pressure by stack effect at the reference position

$$P_s = P_0 - \rho g z \qquad \text{eq.(14)}$$

The pressure difference between the top and bottom can be given by the following equation:

$$dP = -\rho g z dz = -\rho_0 g \frac{T_0}{T} dz \qquad \text{eq.(15)}$$

$$dP = \rho_0 T_0 g H\left(\frac{1}{T_i}-\frac{1}{T_e}\right) \qquad \text{eq.(16)}$$

7 Airflow through openings

The flow rate through the opening can be obtained from the continuity and Bernoulli equations.

$$Q = A_i V_i = A_e V_e \qquad \text{eq.(17)}$$

$$P_i + \frac{\rho V_i^2}{2} = P_e + \frac{\rho V_e^2}{2} \qquad \text{eq.(18)}$$

where velocity(v) is expressed by

$$V = \sqrt{\frac{2(P_i - P_e)}{\rho\left(1-\left(\frac{A_e}{A_i}\right)^2\right)}} \qquad \text{eq.(19)}$$

The swirling flow and turbulent motion near the orifice introduce a non-ideal effect. To account for these effects the discharge coefficient C_d is introduced by Awbi (1994) and Allard (1998) and equation (22) becomes

$$V = C_d \sqrt{\frac{2(P_i - P_e)}{\rho}} \qquad \text{eq.(20)}$$

The pressure difference from equation(16) and taking the reference temperature as $T_0=T_m=1/2(T_i+T_e)$,

$$V = C_d \sqrt{2ghT_m\left(\frac{1}{T_i}-\frac{1}{T_e}\right)} \qquad \text{eq.(21)}$$

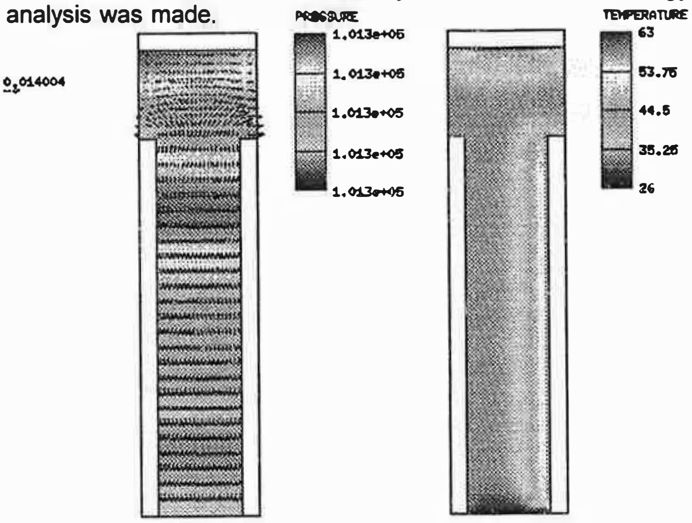
The discharge coefficient is a function of the temperature difference, wind speed and opening geometry. For steady state and buoyancy driven flow, the discharge coefficient for internal openings is given by

$$C_d = (0.4 + 0.0075\Delta T) \qquad \text{eq.(22)}$$

(ASHRAE 1993)

8 Results of air flow in solar chimney by CFD

CFD is used for predicting the air flow for natural ventilation in a solar chimney. The dimensionless version of continuity, momentum and energy equation were set up and analysis was made.



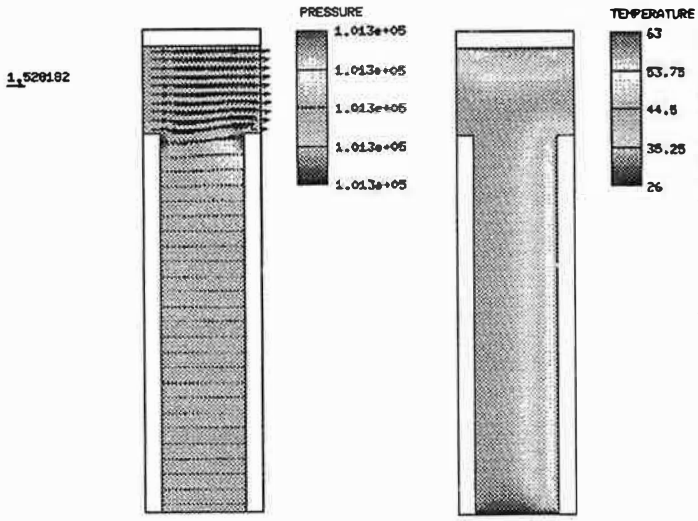
a.Velocity and Pressure b.Temperature

Fig 5.Results of CFD analysis on the solar chimney of cooling mode without the effect of wind

8.1 Cooling mode

The temperature was set at 34°C for the glass surface and 60°C in the opposite wall surface. The velocity boundary conditions of inlet and outlet were free and initial temperature was 33°C. Fig 5 shows the results of CFD simulation for cooling mode without wind and the solar chimney effects are clearly expressed in (a) velocity and pressure and(b) temperature. Fig6 shows the results for cooling mode with wind where the air within the solar chimney is rising upward intensified by sucking force by wind.

The pressure distribution does not change so much with the effects of winds, while pressure variation is fairly effected by wind within the solar chimney. This was especially manifested by a high pressure in the middle of the solar chimney, though the temperature did not vary so much.



a.Velocity and Pressure b.Temperature

Fig 6.Results of CFD analysis on the solar chimney of cooling mode with the effect of wind

8.2 Heating mode

The temperature was set at 4°C for glass surface and 24°C for the opposite wall surface with the wind velocity at 2m/s. The velocity boundary conditions of inlet and outlet were free and initial temperature was set at 2.5°C. High pressure and low velocity appeared in the corner of the solar chimney. But, the pressure distribution did not change greatly within the solar chimney. The air in the chimney was 3-4 K higher than outdoor air.

9. Conclusion

Pressure, air velocity and temperature distribution within the solar chimney were examined using CFD simulation for cooling and heating. The results showed the advantage of solar chimney for ventilation in summer. Also, In winter a considerable amount of energy reduction is anticipated by the inlet temperature higher than the outside temperature.

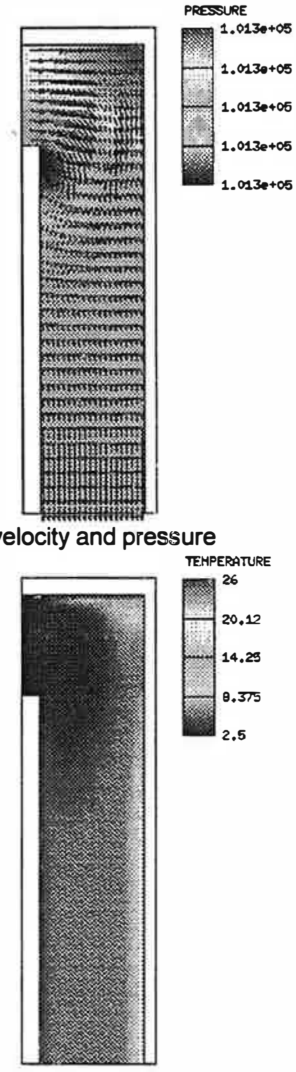
Nomenclature

A: area[m^2]
B: breadth of solar chimney[m]
Cp: specific heat of air [J/kg.K]
g: gravity [=9.865m/s^2]
hc: convective heat transfer coefficient [W/m^2K]
hr: radiative heat transfer coefficient [W/m^2K]
H: height of solar chimney[m]
k: thermal conductivity of air[W/m.K]
Po: reference pressure[Pa]
Ps: pressure by stack effect pressure [Pa]
q: heat flux [W/m^2]
Q: air flow rate[m^3/h]
S: width of solar chimney[m]
T : temperature [°C, interval: K]
T_A: air temperature [°C, interval: K]
V: velocity at opening [m/s]
w: velocity of rising air [m/s]

α: thermal diffusivity [m^2/s]
β: coefficient of thermal expansion[K^{-1}]
ρ: density of air[kg/m^3]
ρ_o :reference density[kg/m^3]
ν: viscosity [m^2/s]
σ: Stefan-Boltzmann number [=5.67×10^{-8} W/(K^4.m^2)]

subscript

1,2 : wall number
i, e: inlet and exit
m: average



a.velocity and pressure

b.temperature

Fig 7. Results of CFD analysis on the solar chimney for heating

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