PROCEEDINGS OF

INTERNATIONAL MEDITERRANEAN CONGRESS ON SOLAR AND OTHER NEW-RENEWABLE ENERGY RESOURCES

November 14-19, 1988

ANTALYA-TURKEY

THERMAL CHARACTERISTICS OF THE EARTH AND AN EARTH COOLING METHOD COMBINED WITH VENTILATION FOR DWELLINGS

by

Tetsuo HAYASHI, Tadahisa KATAYAMA,
Yoshitaka SHIOTSUKI, Jun-ichiro TSUTSUMI and Qingyuan ZHANG

DEPARTMENT OF THERMAL ENERGY SYSTEM, KYUSHU UNIVERSITY
6-1 KASUGA-KOEN, KASUGA-SHI, FUKUOKA-KEN 816, JAPAN

ABSTRACT

We discuss the utilization of thermal characteristics of the earth as new-renewable energy resources for passive cooling of dwellings in summer.

The thermal characteristics of the earth including buildings are examined by numerical simulations. It is pointed out by these simulations that the ground surface in a crawl space can be cool heat source for passive cooling, because the crawl surface has the lowest temperature among the surfaces in a building by solar shading and water evaporation.

We propose a method to transmit this cool heat to rooms by ventilation. In this method, the outdoor air introduced into the crawl space is cooled by the convective heat exchange with the earth surface; then, it is led to a room and is exhausted eventually through an attic space to the outdoor. This combined effects of earth cooling and ventilation are examined by field experiments and building thermal performance simulations. The feasibility and prospect of our proposal of the passive cooling method are discussed with these results of the experiments and simulations.

1. INTRODUCTION

There are two aspects to discuss the utilization of thermal characteristics of the earth as new-renewable energy resources for passive cooling of dwellings. One is thermal characteristics of the earth as a cooling heat source or sink. The other is devices to transmit the cooling heat from its source to rooms or spaces where it is needed.

In the former part of this paper, we investigate the thermal characteristics of the earth including the influence of buildings by numerical simulations. Two schemes of difference methods are applied to these simulations; single-dimensional scheme and two-dimensional scheme. Latent heat exchange at the ground surface is taken into both schemes, and solar shading effect by buildings is included in the two-dimensional scheme. The phenomenon, that the ground surface temperature in a crawl space is the lowest among the surface temperatures in a building in summer, can be found through these simulations. Therefore the ground surface in the crawl space can be a cooling heat source for passive cooling in summer.

We discuss a method to utilize this cooling heat source. As to the so-called earth cooling, there are a lot of materializing proposals[1]. The method we proposed here is an indirect earth cooling method. It transmit the earth cool heat by ventilation. The outdoor air introduced into the crawl space is cooled by the convective heat exchange with the ground surface. The cooled air is led to a room and is exhausted eventually through attic space to the outdoor. This method would have the same concept as earth cooling tubes in terms of the usage of ventilation, but has completely different cooling source from cooling tubes.

In the latter part of this paper, we examine this combined effect of earth cooling and ventilation on passive cooling of dwellings, by field experiments of model houses and their additional simulations. Thermal performance of two model houses, one of which is applied to our proposing method, is compared with each other. The feasibility and prospect of the proposed passive cooling method are discussed by thermal performance simulations of a dwelling building.

2. BASIC SURVEY ON THERMAL CHARACTERISTICS OF THE EARTH

Thermal characteristics of the earth at surface and in underground is examined by numerical simulations.

2.1 Thermal characteristics of the plain ground

Thermal characteristics of a plain ground are examined by a single-dimensional difference method. The ground is supposed to have plane surface and no obstacle against solar radiation. The following equations are adopted as the difference method.

At ground surface

$$C_e \frac{dx(\theta_{e,n} - \theta_{e,n-1})}{2dt} = \lambda_e \frac{(\theta_{j+1,n-1} - \theta_{e,n-1})}{dx} + H_{e,n} \quad (1)$$

$$H_{e,n} = a_e TH_n + \varepsilon_e (AH_n - \sigma(\theta_{e,n} + 273.16)^4) + \alpha_{co,n}(\theta_{o,n} - \theta_{e,n}) + k_e \frac{\alpha_{co,n}}{C_{ea,n}}(X_{o,n} - X'_{e,n})L_{e,n} \quad (2)$$

$$\begin{aligned} \alpha_{co,n} &= 4.0 + 1.625V_n \quad (v_n \geqq 2.0) \\ \alpha_{oo,n} &= 7.25 \quad (v_n < 2.0) \end{aligned} \quad (3)$$

$$C_{ea,n} = 0.24 + 0.441 \frac{(X_{o,n} + X_{e,n})}{2} \quad (4)$$

$$X'_{e,n} = 0.622 \frac{f_{e,n}}{760. - f_{e,n}} \quad (5)$$

$$\log_{10} f_{e,n} = 8.10765 - \frac{1750.29}{\theta_{e,n} + 235.} \quad (6)$$

In underground

$$C_e \frac{dx(\theta_{j,n} - \theta_{j,n-1})}{dt} = \lambda_e \frac{(\theta_{j+1,n-1} + \theta_{j-1,n-1} - 2\theta_{j,n-1})}{dx} \quad (7)$$

Where

AH :atmospheric radiation, kcal/m^{2}h
a :solar absorptance
C :constant-volume specific heat, kcal/m^3°C
dt :difference of time, h
dx :difference of vertical length, m
f :vapor pressure, mmHg

k :evaporation ratio
L_w :evaporative heat of water at temperature θ_w, kcal/kg
TH :global solar radiation, kcal/m²h
v :outdoor wind velocity, m/s
X :absolute humidity, kg/kg'
X'_w :saturated absolute humidity at temperature of θ_w, kg/kg'
α :convective heat transfer coefficient, kcal/m²h°C
ε :emissivity
θ :temperature, °C
λ :thermal conductivity, kcal/mh°C
σ :constant of black body 4.88×10^{-8}kcal/m²hK⁴

And suffices denote
co :outdoor surface
e :the earth or soil
j :calculation step of length in the direction of x
n :calculation step of time
o :outdoor air
s :ground surface
sa :moist air near ground surface

As well known, thermal properties of soil such as thermal conductivity and specific heat are variable according to its proportion of water content, but they are regarded here as constant all round the year. Evaporative heat exchange at the surface is basically obtained by Lewis's law which assumes the completely wetted surface and an analogy of convective heat transfer and mass transfer. It is corrected with evaporation ratio, k, in the case of incompletely wetted surface. Since Equation (1) is a nonlinear equation, a bisection method is applied to obtain the solution as a convergent procedure.

The Standard Weather Data of Fukuoka, Japan, are adopted as the input data of weather condition for this simulation. The boundary condition at the bottom area in underground is a constant soil temperature at the depth of 20m. It is 16.2°C and it is the annual average temperature of the outdoor air in this case of Fukuoka. The specific values of this simulation are; a_e=0.8, C_e=376kcal/m³°C, dt=1h, dx=0.1m, ε_e=0.95, λ_e=0.53kcal/mh°C. However, we have to know beforehand the value of k_e to start the calculation. It is given as an annual constant value by solving the following equations.

$$\sum_{n=1}^{365\times24} a_e TH_n + \varepsilon_e (AH_n - \sigma(\theta_{o,n} + 273.16)^4) = k_e \sum_{n=1}^{365\times24} \frac{\alpha_{e,n}}{C_{sa,n}} (X'_{e,n} - X_{o,n}) L_{e,n} \quad (8)$$

$$C_{sa,n} = 0.24 + 0.441 \frac{(X_{o,n} + X'_{o,n})}{2} \quad (9)$$

Equation (8) means that the annual amount value of radiative heat gain and that of evaporative heat loss are balanced at the surface if the surface temperature is the same as the outdoor temperature.

Vertical distributions of monthly average underground temperature are shown in Fig.1. They are the results after ten-year calculation. The maximum monthly surface temperature appears in August and the minimum one does in January. The tendency of the surface temperatures in order of height is according to that of the outdoor air temperature. On the other hand, it is October that the maximum value of monthly average temperatures at 3m depth appears and it is April for the minimum one. There is a three months of temperature phase delay between at the surface and at the depth of 3m. As the temperatures of underground below 1m depth do not excess 24°C all the year round, this area of underground can be utilized as one of natural cool heat resources for passive and active devices. Figure 2 shows the fluctuations of monthly average values of daily maximum temperature, daily average one and daily minimum one. Daily fluctuation of underground temperature can not be found below 50cm.

2.2 Thermal characteristics of the ground including a building

Two-dimensional temperature distribution of the underground is examined including the influence of a building. We suppose a site of 30m width. In the center of the site, there is a building of 8m width and 4.5m height. The building has a crawl space of 1m height and eaves of 1.6m length (see Fig.11 to be exact). The existence of the building and its crawl space needs two different types of equations; one is for outdoor ground surface and the other is for indoor ground surface. In this section, heat conduction from the building to the ground is ignored for simplification. The two-dimensional difference method, which is developed from Eq.(1) and (2) shown above, is adopted as to the calculation of underground temperature distribution.

At outdoor ground surface

$$C_e \frac{dxdy(\theta_{e,m,n} - \theta_{e,m,n-1})}{2dt} = \lambda_e \frac{dy(\theta_{j-1,m,n-1} - \theta_{e,m,n-1})}{dx} + H_{e,m,n} + \lambda_e \frac{dx(\theta_{e,m-1,n-1} + \theta_{e,m+1,n-1} - 2\theta_{e,m,n-1})}{2dy} \quad (10)$$

$$H_{e,m,n} = a_e I_{m,n} + \varepsilon_e (AH_n - \sigma(\theta_{e,m,n} + 273.16)^4) + \alpha_{co,n}(\theta_{o,n} - \theta_{e,m,n}) + k_e \frac{\alpha_{co,n}}{C_{ea,m,n}}(X_{o,n} - X'_{e,m,n})L_{e,n} \quad (11)$$

At indoor ground surface

$$C_e \frac{dxdy(\theta_{e,m,n} - \theta_{e,m,n-1})}{2dt} = \lambda_e \frac{dy(\theta_{j-1,m,n-1} - \theta_{e,m,n-1})}{dx} + H_{e,m,n} + \lambda_e \frac{dx(\theta_{e,m-1,n-1} + \theta_{e,m+1,n-1} - 2\theta_{e,m,n-1})}{2dy} \quad (12)$$

$$H_{e,m,n} = \varepsilon_e \sigma \{(\theta_{w,n} + 273.16)^4 - (\theta_{e,m,n} + 273.16)^4\} + \alpha_{ci,n}(\theta_{i,n} - \theta_{e,m,n}) + k_e \frac{\alpha_{ci,n}}{C_{ea,m,n}}(X_{i,n} - X'_{e,m,n})L_{e,n} \quad (13)$$

In underground

$$C_e \frac{dxdy(\theta_{j,m,n} - \theta_{j,m,n-1})}{dt} = \lambda_e \frac{dy(\theta_{j+1,m,n-1} + \theta_{j-1,m,n-1} - 2\theta_{j,m,n-1})}{dx} + \lambda_e \frac{dx(\theta_{j,m-1,n-1} + \theta_{j,m+1,n-1} - 2\theta_{j,m,n-1})}{dy} \quad (14)$$

Where

dy :difference of horizontal length, m

I :solar radiation, kcal/m^{2}h

And suffices denote

ci:indoor surface in the crawl space

i :air of the crawl space

m :calculation step of length in the direction of y

w :wall surface in the crawl space

The solar radiation incident upon a calculating mesh point, I, changes according to the direction of the sun and the distance from the building to its point. Therefore, we use the average value of four kinds of solar radiation incident upon four points, the same distance from the building but four different directions; southern, western, eastern and northern, respectively. On the other hand, the long-wave radiation emitted from the surface of the building is regarded to the same value from the sky. As for the air in the crawl space, the following equation is conducted.

$$C_i V \frac{(\theta_{i,n} - \theta_{i,n-1})}{dt} = C_o VI(\theta_{o,n} - \theta_{i,n}) + S\alpha_{ci,n}(\theta_{w,n} - \theta_{i,n}) + \sum_m \alpha_{ci,n}(\theta_{s,m,n} - \theta_{i,n})dy \qquad (15)$$

Where

S :area of wall in the crawl space, m^2

V :volume of the crawl space, m^3

VI :airflow volume from the outdoor to the crawl space, m^3/h

The temperature of the wall including the reverse side of the floor, θ_w, is supposed here to be the mean value of the average ground surface temperature and the air temperature in the crawl space. The specific values in this section, they are different from the section 2.1 mentioned above or have not mentioned yet, are; dt=2h, dx=0.2m, dy=0.2m, S=10m^2, V=8m^3, VI=80m^3/h. The convective heat transfer coefficient in the crawl space, α_{ci}, is supposed to be 3.5kcal/m^{2}h all the time. The boundary condition in the underground is heat insulation at the depth of 5m for horizontal boundary, and the vertical temperature distribution calculated in section 2.1 (See Fig.1) is applied to the perpendicular boundary at the border of the site. As the site and the building is symmetrical, only the left side half of the ground is simulated.

Daily average temperature distribution in the ground on the 15th of every two months are shown in Fig.3. Underground temperature distribution is affected by the existence of the building and its solar shading. Its isothermal lines are remarkable changed jut at the outside of the building. The underground temperature at 1m depth under the building is 13°C in June and 19°C in August, the under ground below this depth is usable for a kind of the earth cooling such as the cooling tubes.

Figure 5 shows daily temperature deviation of the crawl air, the crawl ground surface and the outdoor ground surface from the outdoor air. The daily average temperature of the outside ground surface is higher than that of the outdoor air in spring and autumn. The daily average temperature of the crawl ground surface is lower than that of the outdoor air all the year round, even the higher maximum temperature of the crawl ground is lower than that of the outdoor air in summer. As cooled by the crawl ground surface, the daily average temperature of the crawl air in August is lower than that of the outdoor air by about 2°C. These results have been obtained under the assumption that the convective heat transfer coefficient in the crawl space is 3.5kcal/m^{2}h. If the convective heat exchange between the crawl surface and the crawl air could be promoted more than this assumption, the crawl air would probably become more low than the results of this simulation.

2. EXPERIMENT OF THE EARTH COOLING METHOD COMBINED WITH VENTILATION

Two experimental houses of the same structure, named Model A and Model B, were built. One of them, Model B, has been reformed to utilize the earth cooling combined with ventilation. The effect of this passive cooling method is examined by the comparison of thermal performance of these two experimental houses.

2.1 Structure of the model houses

Two experimental houses were built in the campus of Kyushu University in Kasuga-shi, on the outskirts of Fukuoka, Japan. The bird-eye view of the experimental houses is shown in Fig.5. Each experimental house is divided into 3 spaces; the attic space, the room space and the crawl space.

The plan of the room space is shown in Fig.6. Figure 7 shows the section of the house in addition to its measuring points of the air temperatures, surface temperatures, globe temperature and relative humidity. Each space has two windows or openings on its southern side and northern one. The floor and the ceiling have each ventilation opening, from the crawl to the room and from the room to the attic, respectively. All of the windows and the openings can be closed and air-tightened. The temperatures in the experimental house are measured with thermo-couples, and the relative humidity of the room space is measured with a high-polymer hygrometer. On the roof of a 5-story building adjacent to the experimental houses, weather condition was observed; its items were global solar radiation, atmospheric radiation, outdoor air temperature, dew point temperature, wind direction and wind velocity.

One of the experimental houses, Model B, has been re-formed to examine the effect of the earth cooling combined with ventilation. The air flow route in Model B is shown in Fig.8. The crawl space of Model B was divided into two areas by guide plates, installed at 8 cm height above the ground surface, to promote the convective heat exchange between the air and the ground surface. The outdoor air flows into the crawl space through the northern crawl opening and goes through the narrow space between the guide plate and the ground surface to be cooled by convective heat exchange with the earth. In this process, the water in the soil can evaporate to the air, absorbing latent heat from the ground surface. Therefore the ground surface temperature can be maintained low. After cooled by the ground surface, the air enters the room space through the opening on the floor. The air in the room space enters the attic space through the ceiling opening, and finally goes out to the outdoor by way of the southern opening of the attic space. To obtain this air flow route, the southern crawl opening and the northern attic one in Model B are closed. A small electric fan(30W) was fitted at the ceiling opening to provide driving force for the air movement. It caused about 150m^3/h of ventilation rate.

2.2 Experimental results

We show here the results of an experiment in which all of the windows and openings in Model A were closed.

The results of the experiment from 14th to 15th of September in 1987 are shown in Fig.9. As Model A has well heat insulated walls and ceiling, and no transmitted solar heat gain, its fluctuation of the room air temperature is similar to that of the outdoor air but somewhat higher in the daytime with the one hour of time lag. In Model B which is applied to the passive cooling method, the maximum air temperature in the room space on Sept.14 is 28°C, which is lower than that in Model A (32°C) and that of the outdoor air(31.5°C) by about 4°C. This indicates the passive cooling effect of the combination of earth cooling and ventilation.

The air temperature in the room space mentioned in the previous paragraph was measured in the central part of the room, point ③ in Fig.3. There were two other measuring points of air temperature in the room space, point ② (14cm above the floor) and point ④ (14cm below the ceiling) as shown in Fig.7. As the room space in Model A is a closed space, temperature stratification is promoted by free convection, the temperature difference between point ② and point ④ is about 1°C when the temperature of point ③ is 30°C. In the room space of Model B, notable temperature difference among these measuring points cannot be found because of the forced ventilation.

As to the fluctuations of humidity, the relative humidity of the room space in Model A is more moderate than that in Model B. On the other hand, the absolute humidity in Model A is not constant but varied remarkably, it is high in the daytime and low in the night in accordance with the fluctuation of the room air temperature. This indicates moisture absorption and emission of porous materials in Model B. However the fluctuation of absolute humidity in Model B is similar to that of outdoor air because the outdoor air is introduced into the room space through the crawl space. There is water evaporation at the ground surface in the crawl space, but it hardly increase the humidity in the room space of Model B.

3. SIMULATION OF THE EARTH COOLING WITH VENTILATION

We have shown some experimental results to estimate the combined effect of earth cooling and ventilation. Field experiments are affected by weather condition. In fact, it was rainy summer in 1987 especially in August, therefore we adopt simulation method from now on to examine the passive cooling effect of the earth cooling with ventilation in mid summer. The thermal performances of Model B and a model dwelling is simulated by using the PSSP/MV1[2),3)]. The PSSP/MV1 is a computer simulation program to calculate thermal performance and airflow distribution in multi-room buildings, and is somewhat transformed to apply to these simulations. The basic concept of the PSSP/MV1 is a state transition equations, they are expressed as simultaneous equations of surface temperatures and room air temperatures.

The accuracy of the simulation is confirmed to compare the predicted values and measured ones in Model B. The measured temperatures in the experiment mentioned in section 2 and the predicted ones using the same weather condition are shown in Fig.10. The measured temperatures and the predicted ones are accorded within the range of 1°C. As to the comparison of conductive heat flux at crawl ground surface, the accordance of the measured values and predicted ones are fairly well but there would be some problems in the measurement. The heat flow meter, a thermo-pile to be exact, shown in Fig.6 was buried in the soil at the depth of 5mm to prevent the influence of radiative and convective heat flux . Thus, there is a possibility that the heat flow meter could not indicate the actual conductive heat flux just at the crawl ground surface. We can conclude from these results that the simulation describe precisely the thermal performance of Model B.

The thermal performance and the effect of our proposed passive cooling method are simulated concerning to a model house shown in Fig.11. The model house is made of laminated panels of 9mm plywood and 100mm of glass-wool. The crawl of the model house are divided into two spaces as same as the experimental house, Model B. The lower space of the crawl is 8cm high. A electric fan, capacity of 1200m^3/h, are equipped at the ceiling to cause the airflow we propose. The windows facing east and west are supposed to be drawn curtains to prevent transmitted direct solar radiation.

The simulation results in mid summer are shown in Fig.12, which is obtained by using the Standard Weather Data of Fukuoka. The room air temperature in the day time is lower than that of the outdoor air by about 3～4°C. As the air in the room is moved by force ventilation, effective temperature, thermal sensation of human body in other words, must be lower than the air temperature. The passive cooling capacity of this method can be defined as the cooled amount of the outdoor air passing through the crawl space. It is about 21 kcal/m^{2}h as all-day-long average and about 30kcal/m^{2}h as in the daytime (from 8 a.m. to 7 p.m.) one by a crawl area. It is about 2000kcal/h in the daytime for the room of this dwelling.

4. CONCLUSIONS

We examined the thermal characteristics of the earth as new-renewable energy resources and propose a passive cooling method for dwellings to utilize combined effect of earth cooling and ventilation.

To clarify the thermal characteristics of the earth, two types of difference methods have been presented, which include latent heat exchange at ground surface.

As the air in the crawl spaces in buildings is cooled with convective heat exchange at the ground surface, it can be cool heat source for passive cooling of dwellings.

We have proposed a method to convey the cooled air by ventilation. The effect of this passive cooling method was examined by field experiments of model houses and thermal performance simulations.

Our proposing passive cooling method can maintain the room air temperature 3～5°C lower than the outdoor air temperature and has 2000kcal/h of cooling capacity regarding the dwelling which we suppose in mid summer of Fukuoka, Japan.

5. REFERENCES

1) ABRAMS,W.,D.:"LOW-ENERGY COOLING", Publication of Van Nostrand Reinhold Company Inc., 1986, pp.256-278.

2) HAYASHI,T., URANO,Y., WATANABE,T. and RYU,Y.: " PASSIVE SYSTEM SIMULATION PROGRAM 'PSSP' AND ITS APPLICATION", Proc. of Building Energy Simulation Conference,1985, pp.346-353.

3) HAYASHI,T., URANO,Y., KATAYAMA,T., SUGAI,T., WATANABE,T., SHIOTSUKI,Y. and ZHANG,Q.: "PREDICTION OF AIR DISTRIBUTION IN MULTIROOM BUILDINGS", Proc. of Roomvent'87, 1987, Session 4b, pp.28-47.

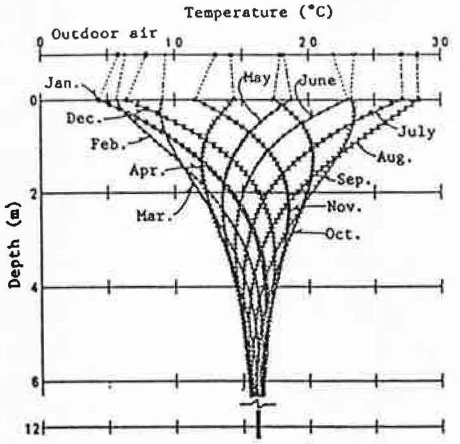


Fig. 1 Monthly average temperature distribution of a plain ground in Fukuoka, Japan.

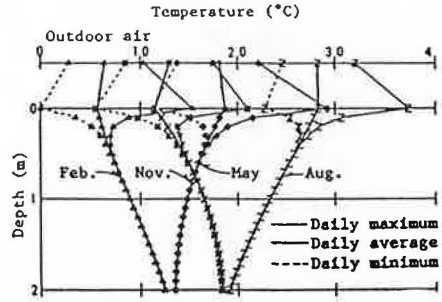


Fig. 2 Monthly average temperature of daily average, daily maximum, and daily minimum of a plain ground in Fukuoka, Japan

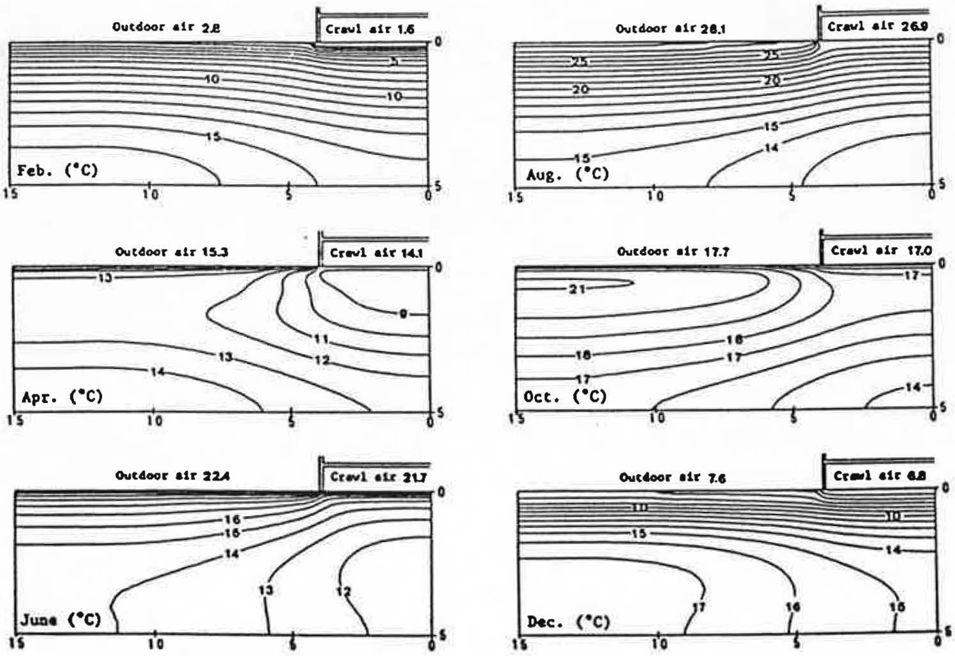


Fig. 3 Daily average temperature distributions of a ground including a building on 15th of every 2 months in Fukuoka, Japan. Vertical axis is the depth from the ground surface and horizontal axis is the distance from the center of the site.

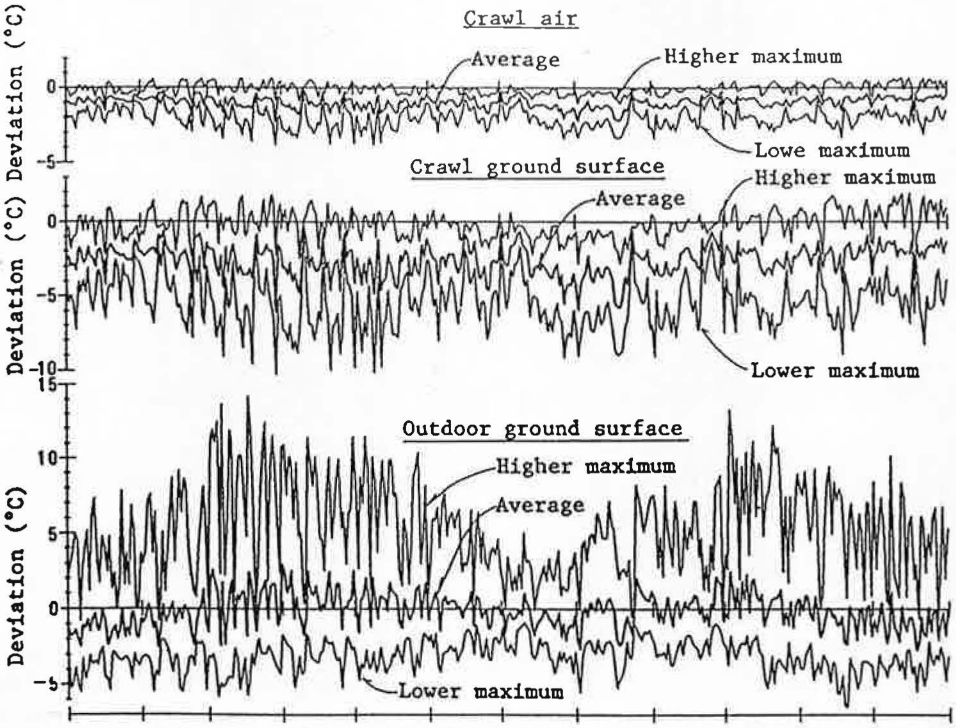


Fig. 4 Daily temperature deviations of the outdoor ground surface, the crawl ground surface and the crawl air from the outdoor air on a site and in a building in Fukuoka, Japan.

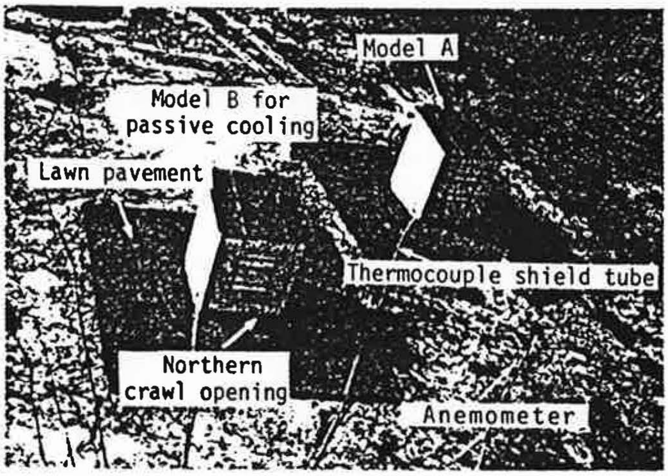


Fig. 5 The bird-eye view of two experimental houses for comparison of the passive cooling effects.

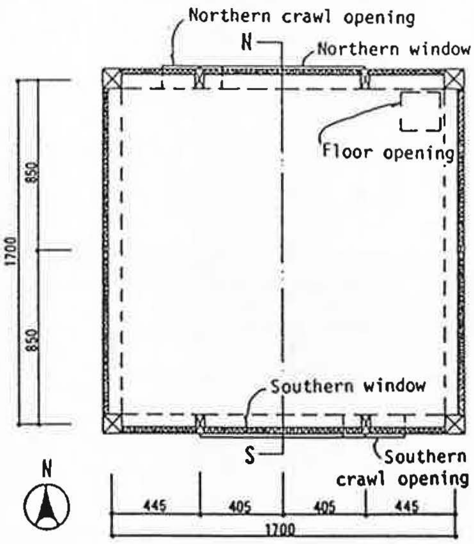


Fig. 6 The plan of the experimental house

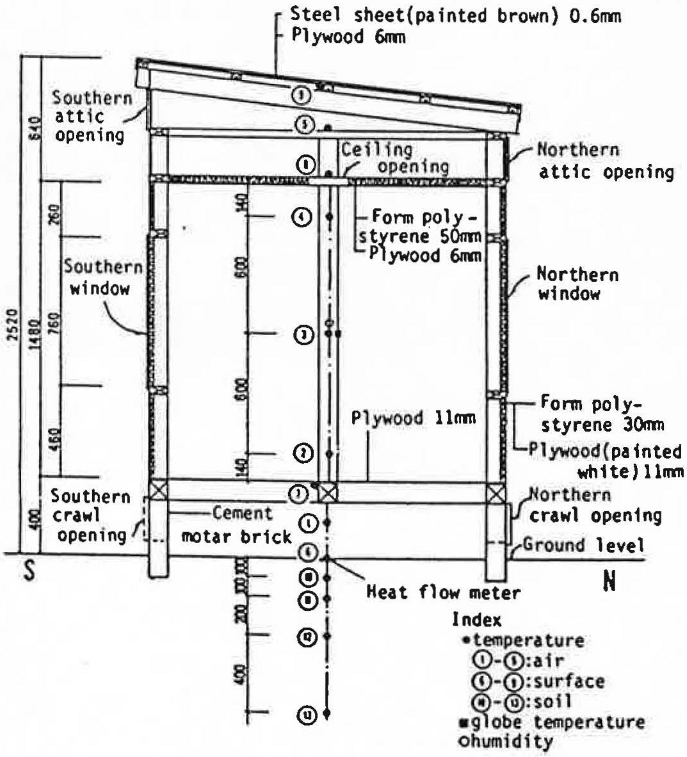


Fig. 7 The section of the experimental house

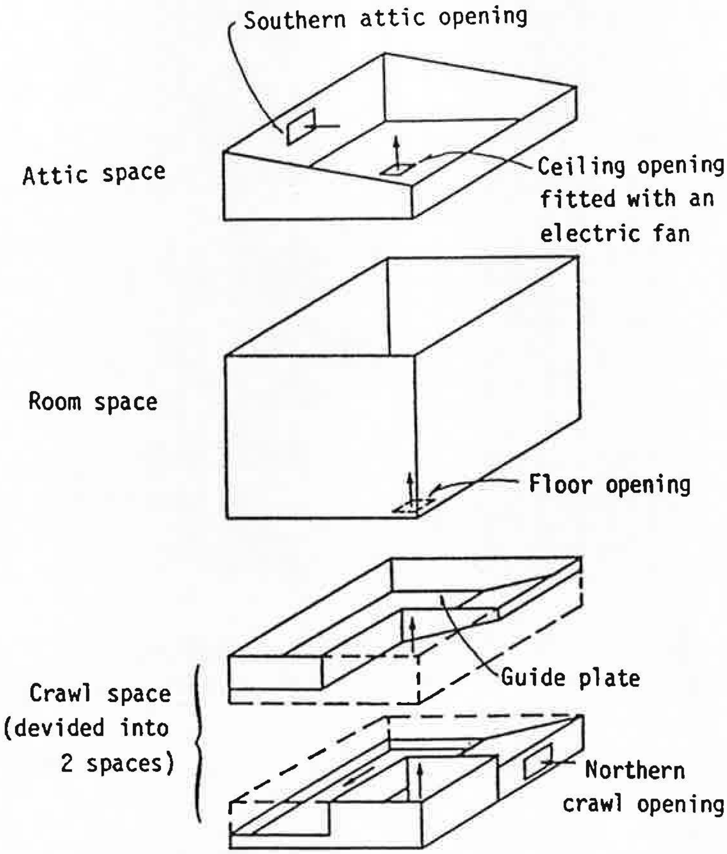
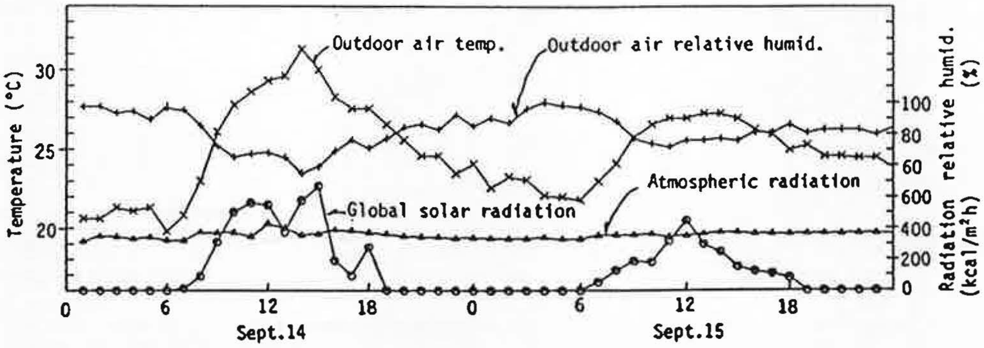
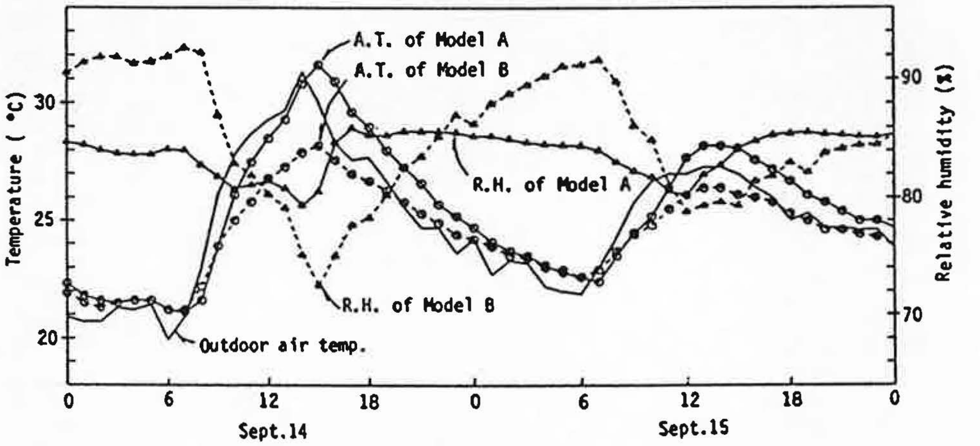


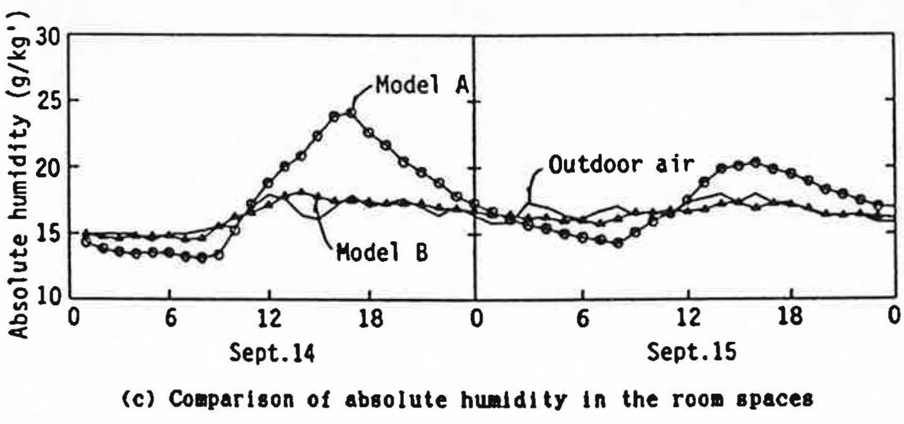
Fig. 8 An illustration of the air flow route in the experimental house for the passive cooling combined with ventilation.



(a) Weather condition during the experiment

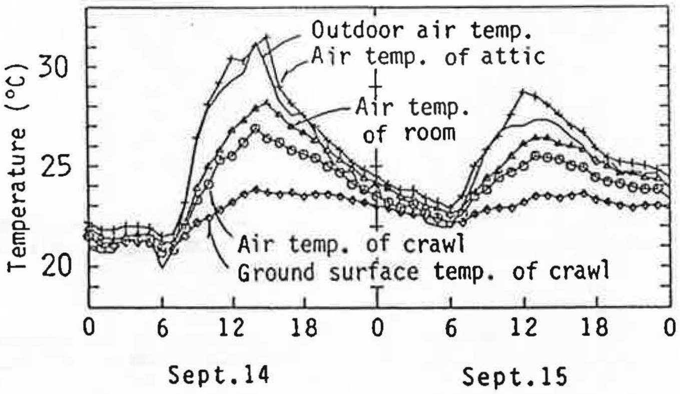


(b) Comparison of air temperature and relative humidity in the room spaces

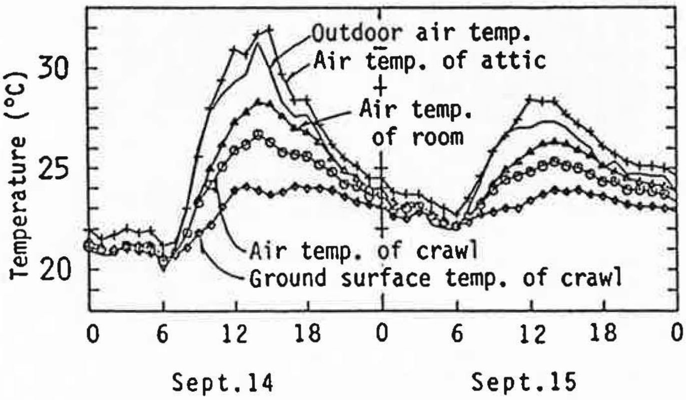


(c) Comparison of absolute humidity in the room spaces

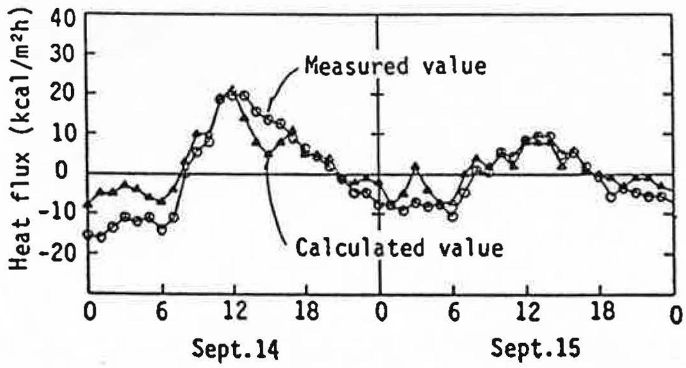
Fig. 9 The experimental results for the passive cooling combined with ventilation.



(a) measured air temperatures in the experimental house



(b) predicted air temperatures in the experimental house



(c) Measured and predicted conductive heat flux at the crawl ground surface

Fig. 10 Comparisons between the measured values in the experiment and predicted values by the PSSP/MV1

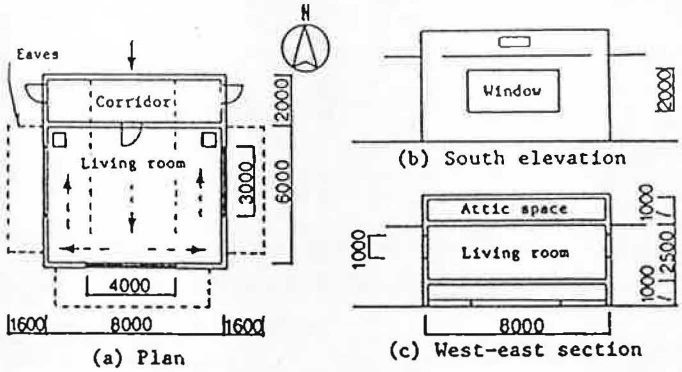
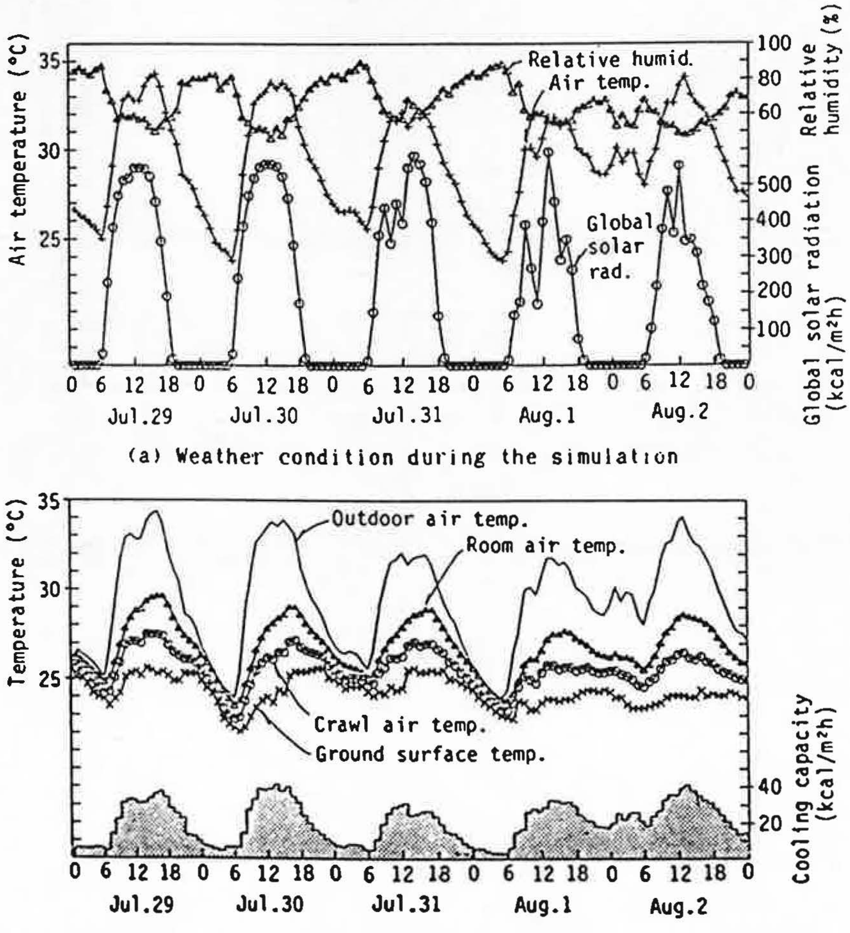


Fig. 11 The plan, section and elevation of a dwelling for passive cooling combined with ventilation



(b) Calculated air temperatures and passive cooling capacity

Fig. 12 The simulation results of the passive cooling combined with ventilation for a dwelling in Fukuoka, Japan