# PASSIVE SYSTEM SIMULATION PROGRAM "PSSP" AND ITS APPLICATIONS

by
Tetsuo HAYASHI, Yoshimi URANO,
Toshiyuki WATANABE and Yuji RYU

Department of Architecture, Faculty of Engineering,
Kyushu University 36
6-10-1 Hakozaki, Higashi-ku, Fukuoka-shi 812, Japan

ABSTRACT-The PSSP, a computer simulation program to predict room temperatures and heat load of buildings has capacity of in-depth investigation into thermal performance of solar houses. At first. the theories of multi-layer wall heat conduction and multi-room heat transfer are presented as a set of successive state transition equations. Secondly. the calculation procedures of radiative heat exchange and natural ventilation are described in detail. At the end. simulation results executed by the PSSP for a hybrid solar house are presented. Various kinds of passive and acti e devices are estimated on their heating and cooling performance. such as direct solar heat gain. earth-contact floor, natural ventilation, floor cooling and heating. etc.

## INTRODUCTION

The Passive System Simulation Program "PSSP" is a computer simulation program for analyzing transient room temperatures of a solar house. Solving heat balance equations at wall surfaces and of room air. the PSSP is capable of estimating effects of various kinds of devices and techniques applied to solar houses.

The PSSP series is started as a simulation program for an experimental house cooled by water evaporation and atmospheric radiation [1], is finalized the multi-room version "PSSP/MV1" and now under its experimental stage. Here, we introduce the theories, calculating procedures and some application examples of the PSSP/MV1 in advance, but its accuracy will be assured in this summer by comparison of the calculated values and the measured ones.

## THEORIES OF TRANSIENT ROOM TEMPERATURE MODEL

The PSSP adopts the theories of transient room temperature model. It consists of successive state transition equations of surface temperature and room air temperature, expressed finally as linear simultaneous equations. We can get the temperatures of every surface and every room air at every time step by solving these equations.

### Heat balance at wall surface and resulting equations

The sensible heat balance equation of outside surface $\bar{j}$ at time $n$ is given by

$$CD_{\bar{j},n} = CV_{\bar{j},n} + NSR_{\bar{j},n} + NLR_{\bar{j},n}, \tag{1}$$

where convective heat flux, $CV_{\bar{j},n}$, net short-wave radiation, $NSR_{\bar{j},n}$, and net long-wave radiation, $NLR_{\bar{j},n}$, are given by

$$CV_{\bar{j},n} = \alpha_{c,\bar{j},n}(T_{o,n} - T_{\bar{j},n}), \tag{2}$$

$$NSR_{\bar{j},n} = a_{\bar{j}} SCDN_{\bar{j},n} \xi_{\bar{j},n} DN_n \cos\theta_{\bar{j},n} + a_{\bar{j}} SCRS_{\bar{j},n} \{F_{\bar{j}s} SH_n + (1 - F_{\bar{j}s})\rho_g TH_n\}, \tag{3}$$

$$NLR_{\bar{j},n} = \varepsilon_{\bar{j}} SCRS_{\bar{j},n} F_{\bar{j}s} AH_n + \varepsilon_{\bar{j}}(1 - SCRS_{\bar{j},n}) F_{\bar{j}s} \sigma T_{o,n}^4 + \varepsilon_{\bar{j}}(1 - F_{\bar{j}s})\sigma T_{o,n}^4 - \varepsilon_{\bar{j}} \sigma T_{\bar{j},n}^4. \tag{4}$$

A solar shading like an overhang is assumed in Eq.(3) that it reflects solar radiation as much as a ground surface. The assumption that the ground surface and the solar shading are black bodies in long-wave range and their temperatures are equal to the outdoor air temperature, leads Eq.(4).

When we introduce $RS_{\bar{j},n}$, $NR_n$ and $\alpha_{r,\bar{j},n}$,

$$RS_{\bar{j},n} = F_{\bar{j}s} SH_n + (1 - F_{\bar{j}s})\rho_g TH_n, \tag{5}$$

$$NR_n = AH_n - \sigma T_{o,n}^4, \tag{6}$$

$$\alpha_{r,\bar{j},n} = 4\varepsilon_j \sigma \{(T_{\bar{j},n} + T_{o,n})/2\}^3, \tag{7}$$

the right hand sides of Eqs.(3) and (4) are reduced to

$$NSR_{\bar{j},n} = a_{\bar{j}}(SCDN_{\bar{j},n} \xi_{\bar{j},n} DN_n \cos\theta_{\bar{j},n} + SCRS_{\bar{j},n} RS_{\bar{j},n}), \tag{8}$$

$$NLR_{\bar{j},n} = \varepsilon_{\bar{j}} SCRS_{\bar{j},n} F_{\bar{j}s} NR_n + \alpha_{r,\bar{j},n}(T_{o,n} - T_{\bar{j},n}). \tag{9}$$

On the other hand, the heat balance at inside surface $j$ at time $n$ is given by

$$CD_{j,n} = CV_{j,n} + NSR_{j,n} + NLR_{j,n}, \tag{10}$$

where convective heat flux $CV_{j,n}$ is

$$CV_{j,n} = \alpha_{c,j,n}(T_{i,n} - T_{j,n}). \tag{11}$$

In order to clarify a method for modeling net short-wave radiation, $NSR_{j,n}$, and net long-wave radiation, $NLR_{j,n}$, it is necessary to analyze solar radiation transmitted through fenestration, absorbed, reflected and reemitted by the interior surfaces. We assume that the interior surface is gray and diffusive for short- and long-wave radiation, respectively.

First, short-wave radiation transmitted through fenestration $f$ are given as follows

$$TDN_{f,n} = \tau_f SCDN_{\bar{j},n} SCDN_{f,n} DN_n, \tag{12}$$

$$TRS_{f,n} = \tau_f SCRS_{\bar{j},n} SCRS_{f,n} RS_{\bar{j},n}. \tag{13}$$

Secondly, let us think that surface $l$ of area $S_l$ accepts the transmitted direct solar radiation shown by Eq.(12). The heat absorbed at the surface $l$ comes to $a_l \xi_{l,n} TDN_{f,n} \cos\theta_{l,n}$, and the rest is reflected. The idea of the absorption factor proposed by Gebhart [2] may be applied to this reflected component. The short-wave absorption factor is given by

$$\gamma_{lj} = F_{lj} a_j + \sum_k F_{lk} \rho_k \gamma_{kj}. \tag{14}$$

Thirdly, when $ADE_{j,n}$ denotes the heat absorbed at surface $j$ of area $S_j$ owing to transmitted direct solar radiation, $TDN_{f,n}$, it is given by

$$ADE_{j,n} = TDN_{f,n} \sum_l (a_l + \gamma_{lj} \rho_l S_l / S_j) \cos\theta_{l,n}. \tag{15}$$

Finally, reciprocity relation, $a_l S_l \gamma_{lj} = a_j S_j \gamma_{jl}$, and assumption that there are plural fenestrations change Eq.(15) into

$$ADE_{j,n} = \sum_f \sum_l a_j (1 + \gamma_{jl} \rho_l / a_l) \xi_{l,n} TDN_{f,n} \cos\theta_{l,n}. \tag{16}$$

In the same manner, for transmitted diffuse solar radiation, $TRS_n$, the following equation will be obtained

$$ARE_{j,n} = \sum_f a_j \gamma_{jf} TRS_n / a_f. \tag{17}$$

As for short-wave radiation from lights, $ASL_{j,n}$, it may be approximated with

$$ASL_{j,n} = \sum_k a_j \gamma_{jk} SL_{k,n} / a_k. \tag{18}$$

Using Eqs.(16),(17) and (18), net short-wave radiation, $NSR_{j,n}$ reduces to

$$NSR_{j,n} = ADE_{j,n} + ARE_{j,n} + ASL_{j,n}. \tag{19}$$

Next, we describe a method for modeling net long-wave radiation $NLR_{j,n}$. When $\beta_{lj}$ denotes the long-wave absorption factor, $\beta_{lj}$ is given by

$$\beta_{lj} = F_{lj} \varepsilon_j + \sum_k F_{lk} (1 - \varepsilon_k) \beta_{kj}. \tag{20}$$

Long-wave radiative heat exchange between surface $j$ and other surfaces, $ALR_{j,n}$, is given by

$$ALR_{j,n} = \sum_k (\beta_{kj} \varepsilon_k \sigma T_{k,n}^4 S_k / S_j) - \varepsilon_j \sigma T_{j,n}^4. \tag{21}$$

Applying reciprocity relation, $\varepsilon_k S_{k,n} \beta_{kj,n} = \varepsilon_j S_{j,n} \beta_{jk,n}$, and energy preservation law, $\sum_k \beta_{jk,n} = 1$, we can rewrite Eq.(21) as

$$ALR_{j,n} = \sum_k \varepsilon_j \beta_{jk} \sigma (T_{k,n}^4 - T_{j,n}^4)$$

$$= \sum_k \beta_{jk} \alpha_{r,jk,n} (T_{k,n} - T_{j,n}), \tag{22}$$

re

$$\alpha_{r,jk,n} \fallingdotseq 4 \varepsilon_j \sigma \{ (T_{k,n} + T_{j,n})/2 \}^3. \tag{23}$$

As for long-wave radiation from lights and so on, $ALL_{j,n}$, it may be approximated with

$$ALL_{j,n} = \sum_k \varepsilon_j \beta_{jk} LL_{k,n} / \varepsilon_k. \tag{24}$$

Using Eqs.(22) and (24), net long-wave radiation, $NLR_{j,n}$, reduces to

$$NLR_{j,n} = ALR_{j,n} + ALL_{j,n}. \tag{26}$$

## Successive state transition equations of surface temperature

We give the approximate indicial response [3] of a wall heat conduction system for $m = j, o, \bar{j}$ as

$$\Phi_m(t) = A + \sum_k A_{m,k} \exp(-\alpha_k t) + Q_m \delta(t). \tag{27}$$

Then, conductive heat flux, $CD_{j,n}$, at inside surface $j$ can be shown [4] as

$$CD_{j,n} = a_j T_{j,n} - a_o T_{\bar{j},n} + D_{j,n-1}, \tag{28}$$

where

$$D_{j,n-1} = b_j T_{j,n-1} - b_o T_{\bar{j},n-1} + \sum_k \varphi_k x_{j,k,n-1}, \tag{29}$$

$$x_{j,k,n} = \varphi_k x_{j,k,n-1} + p_k (A_{j,k} T_{j,n-1} - A_{o,k} T_{\bar{j},n-1}) + q_k (A_{j,k} T_{j,n} - A_{o,k} T_{\bar{j},n}), \tag{30}$$

$$\left.\begin{aligned} \varphi &= \exp(-\alpha_k \Delta), \\ a_m &= A + \sum_k A_{m,k} (1 + q_k) + Q_m / \Delta, \\ b_m &= \sum_k A_{m,k} p_k - Q_m / \Delta, \\ p_k &= \varphi_k - (1 - \varphi_k) / (\alpha_k \Delta), \\ q_k &= -p_k - (1 - \varphi_k). \end{aligned}\right\} \tag{31}$$

Substituting Eq.(28) into Eq.(10), we obtain the successive state transition equation of the inside surface temperature,

$$(a_j + \alpha_{c,j,n} + \sum_k \beta_{jk,n} \alpha_{r,jk,n}) T_{j,n}$$

$$- a_o T_{\bar{j},n} - \alpha_{c,j,n} T_{i,n} - \sum_k \beta_{jk,n} \alpha_{r,jk,n} T_{k,n}$$

$$= NSR_{j,n} + ALL_{j,n} - D_{j,n-1}. \tag{32}$$

The unknown values at time $n$ as $T_{j,n}$, $T_{\bar{j},n}$, $T_{i,n}$ and $T_{k,n}$ are taken place in the left hand side of Eq.(32). On the other hand, the known values are taken place in the right hand side.

Conductive heat flux at outside surface, $CD_{\bar{j},n}$, is obtained by replacing $j$ and $\bar{j}$ with each other in Eq.(28). Substituting $CD_{\bar{j},n}$ into Eq.(1), we obtain,

$$(a_{\bar{j}} + \alpha_{c,\bar{j},n} + \alpha_{r,\bar{j},n}) T_{\bar{j},n} - a_o T_{j,n}$$

$$= NSR_{\bar{j},n} + \varepsilon_{\bar{j}} SCRS_{\bar{j},n} F_{\bar{j}s} NR_n$$

$$+ (\alpha_{c,\bar{j},n} + \alpha_{r,\bar{j},n}) T_{o,n} + D_{\bar{j},n-1}. \tag{33}$$

### Successive state transition equations of room air temperature

The heat balance equation of room air is a state equation of room air temperature $T_{i,n}$. Through trapezoid hold function [4] for sampled data of each input and Z-transform of the state equation, the successive state transition equation [5] of $T_{i,n}$ is obtained as

$$\frac{T_{i,n}}{q_{i,n}} - \sum_k \alpha_{c,k,n} S_{k,n} T_{k,n} - \sum_{\blacksquare} \Lambda_{\blacksquare,n} VI_{\blacksquare,n} T_{\blacksquare,n}$$
$$= TA_{n-1} + \Lambda_{o,n} VI_{o,n} T_{o,n} + \Lambda_{e,n} VI_{e,n} T_{e,n}$$
$$+ CL_n + H_n, \quad (34)$$

where

$$TA_{n-1} = \varphi_n \frac{T_{i,n-1}}{q_n}$$
$$+ \frac{p_n}{q_n} \left( \sum_k \alpha_{c,k,n} S_k T_{k,n-1} + \sum_{\blacksquare} \Lambda_{\blacksquare,n} VI_{\blacksquare,n} T_{\blacksquare,n-1} \right)$$
$$+ \frac{p_n}{q_n} \left( \Lambda_{o,n} VI_{o,n} T_{o,n-1} + \Lambda_{e,n} VI_{e,n} T_{e,n-1} \right)$$
$$+ \frac{p_n}{q_n} \left( CL_{n-1} + H_{n-1} \right), \quad (35)$$

$$\left. \begin{aligned} \varphi_n &= \exp(-B_n \Delta / RQ_n), \\ B_n &= \sum_k \alpha_{c,k,n} S_{k,n} + \sum_{\blacksquare} \Lambda_{\blacksquare,n} VI_{\blacksquare,n} \\ &\quad + \Lambda_{o,n} VI_{o,n} + \Lambda_{e,n} VI_{e,n}, \\ p_n &= -\{\varphi_n - RQ_n(1-\varphi_n)/(B_n \Delta)\} / B_n, \\ q_n &= -p_n + (1-\varphi_n)/B_n. \end{aligned} \right\} \quad (36)$$

## CALCULATING PROCEDURES

### Situational correlations among inside surfaces

The successive state equations of surface temperature are shown in Eqs.(32) and (33). In these equations, inside surface temperatures, $T_{j,n}$, $T_{k,n}$, and outside surface temperature, $T_{\bar{j},n}$, appear. The situational correlations among surface $j,k$ and $\bar{j}$ have to be exactly denoted to estimate radiative and conductive heat flux.

To confirm the situational correlations among surfaces, each room in a building is declared for its own serial room number. All surfaces of the room are divided into six sections (south wall, west wall, north wall, east wall, floor and ceiling). Each section is divided into several parts according to its material, finish and structure. Both sections and parts have their own serial numbers (shown in Fig.1).

According to the serial number, a computer gets the inside part's input data which contain solar absorptance, solar reflectance, long-wave emittance, the wall structure number and the opposite part's serial number. All of wall structures in a building are named their own serial number in advance. Referring these numbers, wall structure data are input to calculate the multi layer wall indicial response.

If the opposite part of the concerned part is outside, outside part data are input following to the inside part data. Besides radiative data, outside part data contain overhang data which consist of the depth, the width and the situation on the wall.

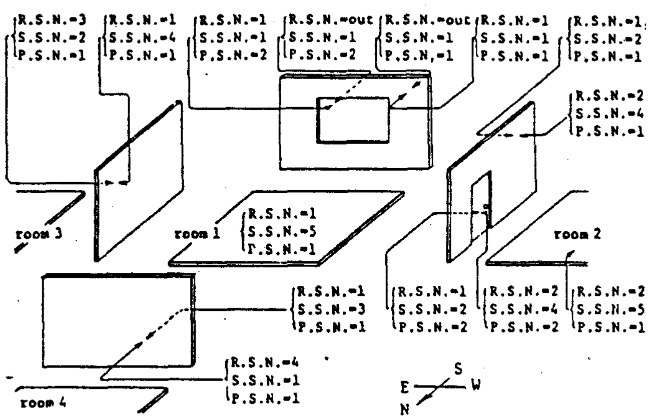



Fig.1 Numbering of rooms, sections and parts.

### Outside and inside sunlit area ratio

Sunlit area ratio means the ratio dividing sunlit area by total surface area which is added sunlit area to shaded area. Outside sunlit area ratio is obtained by the overhang data and solar position.

The procedure to get inside sunlit area ratio is divided into three stages. At the first stage, area and shape of shadow on a fenestration is calculated. Through this sunlit part on the fenestration, direct solar radiation is transmitted into the room. Ordinarily the shape of this sunlit part is an irregular polygon.

At the second stage, the shape of the sunlit part on the fenestration is transformed into a rectangle for convenience (shown in Fig.2). Through this transformation, the area of the sunlit part is not changed.

At the third stage, inside sections (walls and floor) of the room are projected on this sunlit rectangle according to the azimuth and altitude of the sun (shown in Fig.3). Calculating the projected area on the sunlit rectangle, the sunlit area ratio of the inside section or total amount of transmitted solar radiation incident upon the inside section can be obtained geometrically.

Radiative heat exchanges among interior sections are calculated at first. Each section's solar

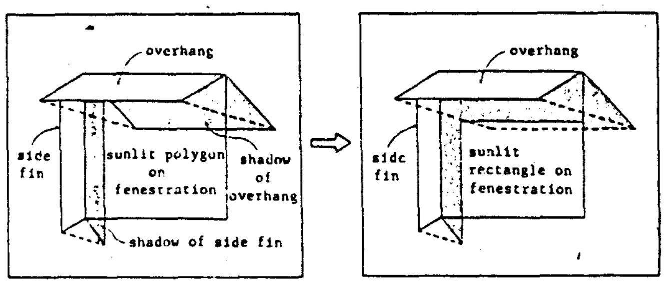



Fig.2 Shadow on wall and fenestration.

absorptance, solar reflectance, long-wave emittance and surface temperature are counted out as the average values of its containing parts. After that, the heat balance equations at each part are composed. The coefficients and values of each part connected with radiative heat exchange in Eq.(32) are given as weighted values of area and solar absorptance or long-wave emittance.

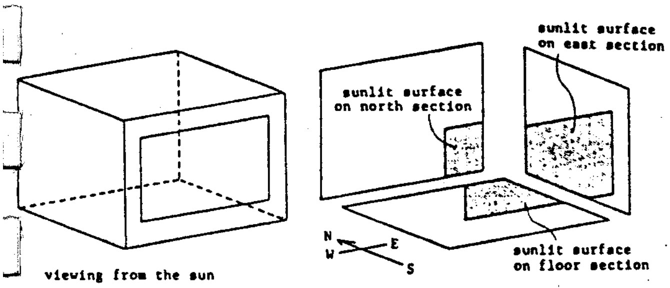



Fig.3 Sunlit area on inroom sections.

## Ventilation and infiltration

The successive state equation of room air temperature is shown in Eq.(34), where incoming air flow, $VI_{o,n}$ and $VI_{m,n}$, appear. Incoming and outletting air flow is classified in two sorts. One is flow through a opening and the other is through a crack as following :

$$V_{j,n} = 3600\mu_j A_j \frac{\pi_{j,n}}{|\pi_{j,n}|} |\pi_{j,n}|^{1/2} \text{(for opening)}, \quad (37)$$

$$V_{j,n} = \nu_j L_j \frac{\pi_{j,n}}{|\pi_{j,n}|} |\pi_{j,n}|^{2/3} \text{(for crack)}. \quad (38)$$

If opening or crack $j$ in room $i$ exists on the envelope, pressure difference $\pi_{j,n}$ is given

$$\pi_{\bar{j},n} = C_{\bar{j},n}\frac{G_{o,n}}{2g}WV_n^2 + h_{\bar{j}}(G_{o,n}-G_{i,n})+P_{i,n}, \quad (39)$$

where $h_j$ is height of leakage and $P_i$ is static pressure of room $i$ at standard level. First term of the right hand side means wind force and second term means thermal force or stack effect. On the other hand, pressure difference at inroom wall is taken into account only stack effect as

$$\pi_{j,n} = h_j(G_{m,n}-G_{i,n})+P_{i,n}-P_{m,n}. \quad (40)$$

Figure 4 shows these relation in simple model room. Air specific gravity, $G$, is connected with its temperature $T$ and obtained simply as

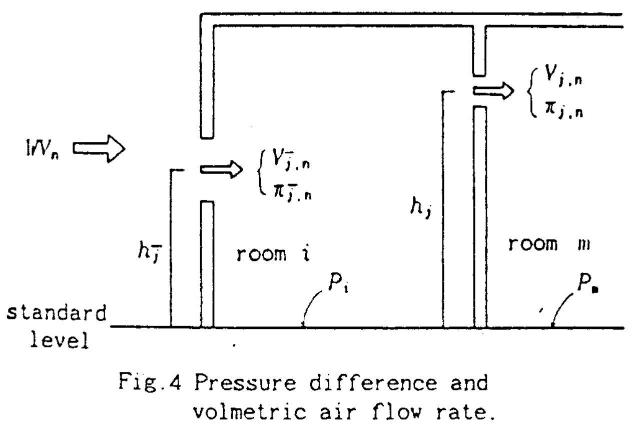



Fig.4 Pressure difference and volmetric air flow rate.

$$G \fallingdotseq 353/T. \quad (41)$$

Regarding room air temperature, $T_{i,n}$ and $T_{m,n}$, at time $n$ are nearly equal to those of at time $n$-1, we can get incoming air flow from other rooms, $VI_{m,n}$, and outdoor, $VI_{o,n}$.

At first, room static pressures, $P_{i,n}$ and $P_{m,n}$, are presumed as initial values. Next, incoming and outletting air flow rate are counted out by Eq.(37) and Eq.(38). Then, air flow balances of each room are checked, in which air flow from air-handling unit and fan are included, and they must be satisfied at every room. If they are not satisfied, initial value of each room's static pressure is exchanged to complete its air balance and the calculation loop is restarted. If all of them are applicable within an admittable limit, the loop is stopped and incoming air flows are summed up.

## Convective and radiative heat transfer coefficient

Convective heat transfer coefficient of outside surface, $\alpha_{c,\bar{j},n}$, is decided according to velocity and direction of outdoor wind, for vertical walls [5] as

$$\alpha_{c,\bar{j},n} = 4.7+7.6v_{\bar{j},n}, \quad (42)$$

where

$$\left.\begin{aligned} v_{\bar{j},n} &= 0.25WV_n,\ WV_n>2 \quad \text{(for windward)},\\ v_{\bar{j},n} &= 0.5;\quad WV_n\leqq 2 \quad \text{(for windward)},\\ v_{\bar{j},n} &= 0.3+0.05WV_n, \quad \text{(for leeward)}, \end{aligned}\right\} \quad (43)$$

and for roofs [6] as

$$\alpha_{c,\bar{j},n} = 8.7+2.3v_{\bar{j},n}, \quad (44)$$

where

$$v_{\bar{j},n} = 0.3+0.05WV_n. \quad (45)$$

Wind pressure coefficient, $C_{\bar{j},n}$, is also decided as a function of velocity and direction of outdoor wind, it is as same manner as HASP/ACLD [7].

Natural convective heat transfer coefficient of inside surface, $\alpha_{c,j,n}$, is given as an exponential function of difference between the surface temperature and the room air temperature at time $n$ [8]. But these values are unknown until Eqs.(32),(33) and (34) have been solved. So we use the values of at time $n$-1 in place of the values of at time $n$,

$$\left.\begin{aligned} \alpha_{c,j,n} &= 1.8|T_{j,n-1}-T_{i,n-1}|^{0.25} \text{(for horizontal)},\\ \alpha_{c,j,n} &= 2.5|T_{j,n-1}-T_{i,n-1}|^{0.25} \text{(for upward)},\\ \alpha_{c,j,n} &= 1.3|T_{j,n-1}-T_{i,n-1}|^{0.25} \text{(for downward)}. \end{aligned}\right\} \quad (46)$$

On the other hand, forced convective heat transfer coefficient of inside surface is given as constant, $\alpha_{c,j,n}$ = 7.3. This value is acquired by Jurges's equation [9] assuming that adjacent wind velocity is 0.5m/s.

Radiative heat transfer coefficients at time $n$ in Eq.(7) and Eq.(23) can get also in advance using surface temperatures at time $n$-1 instead of those of at time $n$.

## APPLICATION OF THE PSSP TO A SOLAR HOUSE

An experimental hybrid solar house called the "Clean House" has been built in Fukuoka (Japan), April 1985. The Clean House is named as it uses only electric power and solar heat as its energy resource, and aims reduction of energy consumption and comfortable environment of modern living life. The PSSP was used for the pre-investigation of thermal performance of the Clean House.

The perspective view of the Clean House is shown in Fig.5, the plans of two storied house made of woods in Fig.6, and the diagram of air-conditioning and hot water supplying in Fig.7. Table 1 shows the wall structures of the Clean House. The usage of thermal insulation materials and pair glass, and pair glass window, confirms the heat insulation and air tight system of the Clean House.

### Passive_devices_of_the_Clean_House

Solar shading is necessary to prevent room temperatures from over heating in summer, but it should not disturb solar heat gain in winter. The Clean House has sliding overhangs, outside movable blinds and vertical pergolas for solar control.

The opening on the ceiling of 1st floor's utility room and fenestration on north wall are effective on natural ventilation caused by wind force. When they are opened in summer, the sea breath from north sweep away the hot air in the Clean House.

Earth-contact floor is adopted to utilize the heat capacity of soil and it prevents excessive fluctuation of room temperatures and enhances the efficiency of floor heating in winter and floor cooling in summer. The heat capacity of 50mm thick mortar cement at second floor slab is expected to give the same efficiency.

Fig.5 Perspective view of the Clean House.

Table 1 Wall structures.

| section | material | thickness (mm) | section | material | thickness (mm) |
|---|---|---|---|---|---|
| roof | plywood | 12 | envelope | plaster board | 12 |
| | asbestos slate | 12 | | glass wool | 100 |
| 2F ceiling | glass wool | 200 | | plywood | 9 |
| | plaster board | 12 | | form polystiren | 30 |
| 2F floor | carpet | 7 | | air | - |
| | mortar cement | 50 | | asbestos slate | 12 |
| | plywood | 12 | inroom wall | plaster board | 12 |
| | air | - | | air | - |
| | plaster board | 12 | | plywood | 9 |
| 1F floor | flooring | 12 | single glass | glass | 3 |
| | mortar cement | 30 | | | |
| | concrete | 120 | pair glass | glass | 3 |
| | gravel | 300 | | air | - |
| | soil | - | | glass | 3 |

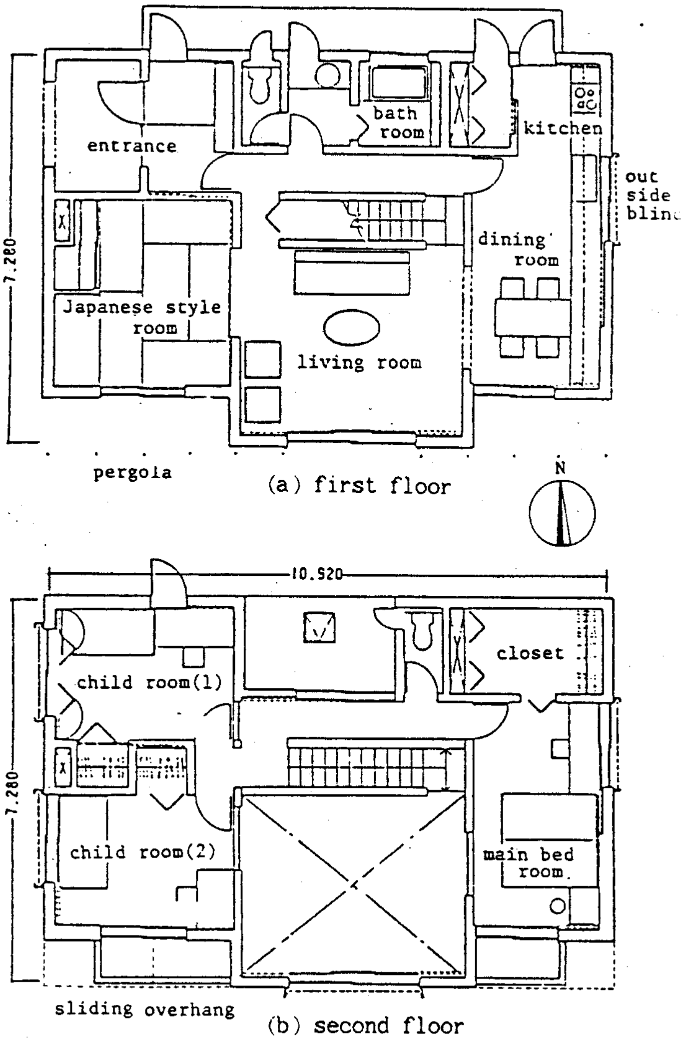



Fig.6 Plans of the Clean House.

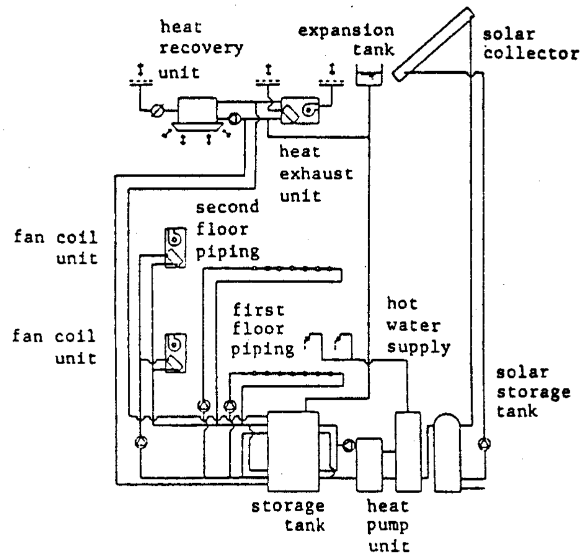
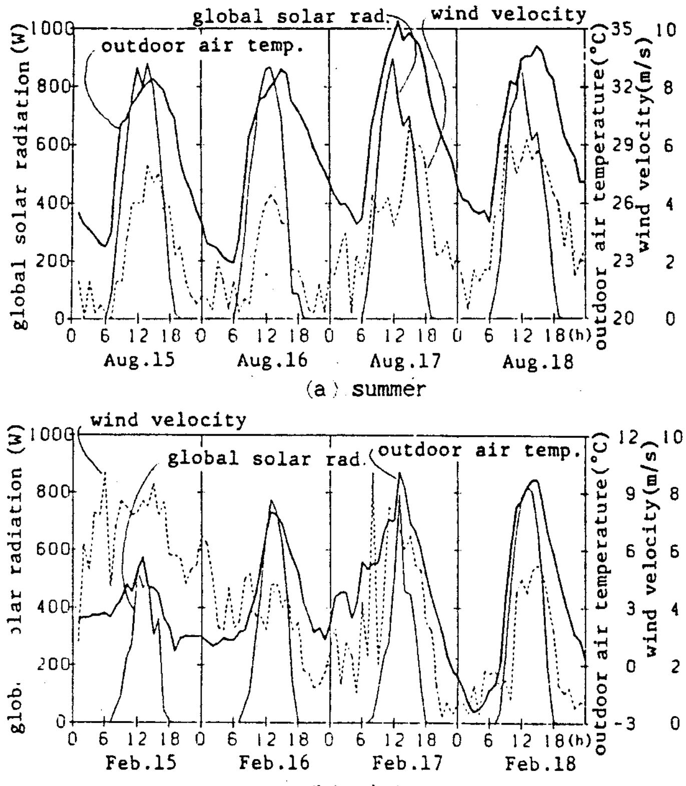



Fig.7 Diagram of equipment.

## Active devices of the Clean House

The Clean House has a heat pump unit which is driven only in midnight and stores hot water in winter and cool water in summer for air conditioning. In addition, it provides hot water ··hich is pre-heated for cooking and bathing by solar llector.

Floor heating and cooling is adopted as a main air-conditioning system of the Clean House. But, fan coil unit system is installed too, as for comparison.




(a) summer

(b) winter

Fig.8 Meteorological data.

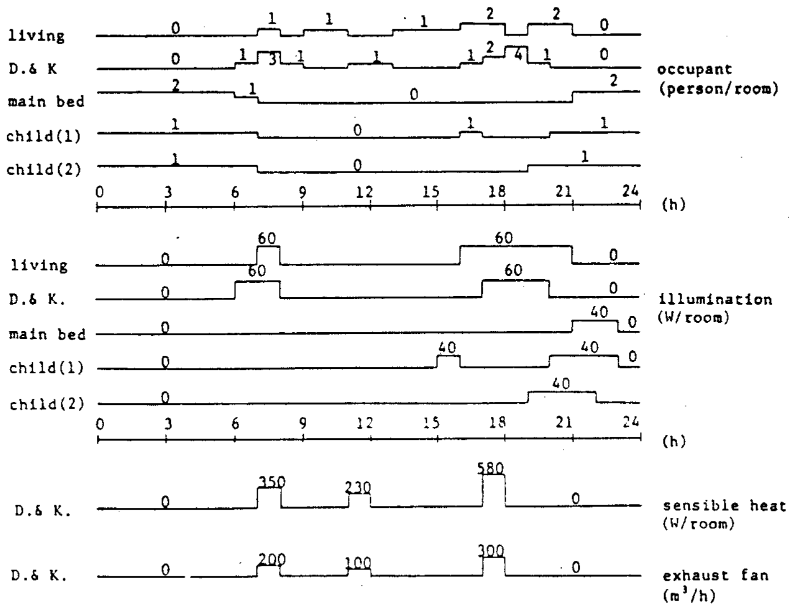



Fig.9 Room schedules.

A small heat pump air-conditioner is installed in the attic. In winter, it recovers the surplus heat from living room air to save energy and to prevent overheating. In summer, it reduces the indoor moisture for remedy of dewing at the floor surface.

## Simulation results and discussion

We introduce the simulation results of the Clean House. Figure 8 shows meteorological data of Fukuoka in summer and in winter which is presumed by the Standard Weather Data [7]. Figure 9 shows the schedules of the Clean House.

The simulation results in summer are shown from Fig.10 to Fig.12. In these, wall and fenestration on south side are shaded by sliding overhangs and pergolas against solar radiation, and outside movable blinds on fenestration of west side and east

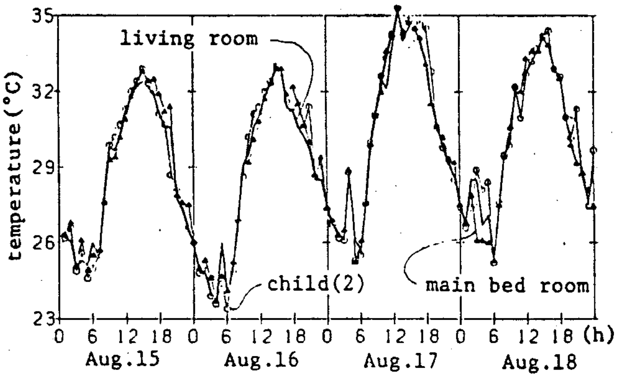



Fig.10 Room air temperatures under natural ventilation.

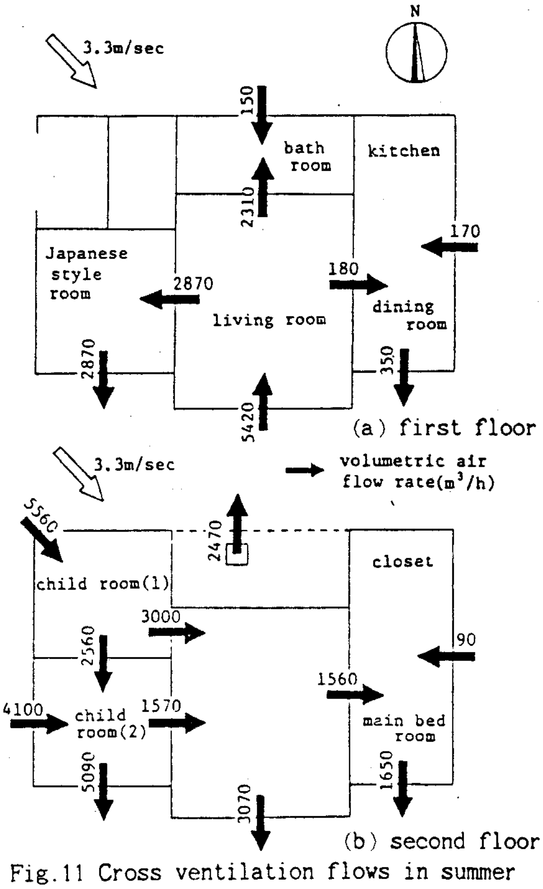



Fig.11 Cross ventilation flows in summer (15:00, Aug.16).

side are drawing. We estimate these effects by using shading factors, $SCDN_{j,n}=SCRS_{j,n}=0.25$. The soil temperature at 1m depth is assumed as 22°C(72°F).

Figure 10 shows hourly fluctuation of room air temperatures under the natural ventilated condition, where the windows of second floor are opened all day long, and those of first floor are opened only during daytime. The typical air flow distributions at daytime is shown in Fig.11, outdoor air comes into the Clean House from north-west direction and goes out to southward. As the outdoor air temperature in this period is too high, we can not get thermal comfort only by natural ventilation.

In Fig.12, we show the result of floor cooling. Floor cooling is carried out during night (from 0 to 6 o'clock) at first floor, and during daytime (from 8 to 18 o'clock) at second floor. The inlet temperature of cool water is 15°C(59°F) and its flow rate is 40$l$/m²h (0.37gal/ft²h). The room air are cooled enough by floor cooling, but it is necessary to ensure the extraction of moisture to prevent floor surface from dewing.

The simulation results in winter are shown from Fig.13 to Fig.15. In these case, we assume that the plant on the pergola withers, sliding overhangs and outside movable blinds are fully opened, and the soil temperature at 1m depth is 17°C(63°F).

With Fig.13, we compare living room's mean radiative temperatures in the case of earth-contact floor and elevated floor. The outside of elevated floor is insulated with a 30mm thick form polystiren board. The temperature in soil is higher than that of outdoor air in winter. Because of conductive heat from soil and its large heat capacity, the mean radiative temperature of earth-contact floor room is higher than that of the elevated floor room.

Figure 14 and Fig.15 show the room air temperatures and heat extraction rate when the heat recovery system is carried out. If the living room air temperature exceeds 20°C(66°F), the heat pump unit in the attic is driven. Though it is fine and cold on the 18th in February, we can recover more than 5000W of surplus heat from living room air.

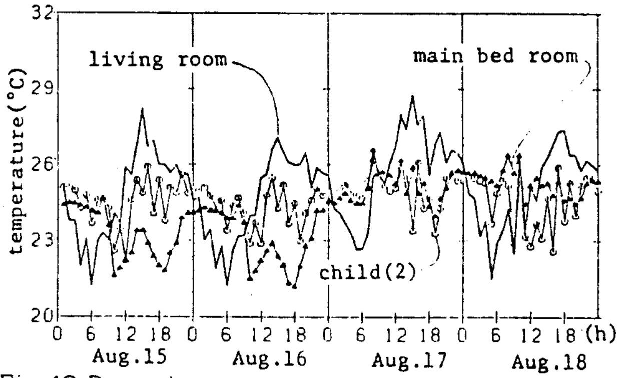


Fig.12 Room air temperatures with floor cooling.

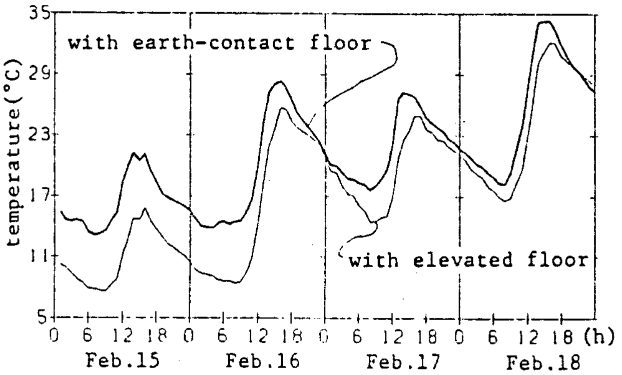


Fig.13 Mean radiative temperatures of living room.

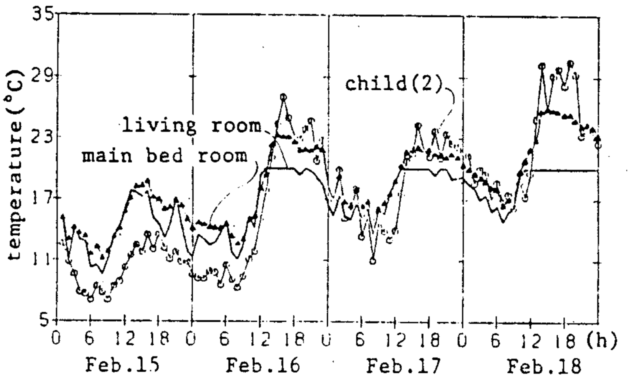


Fig.14 Room air temperatures with heat recovery.

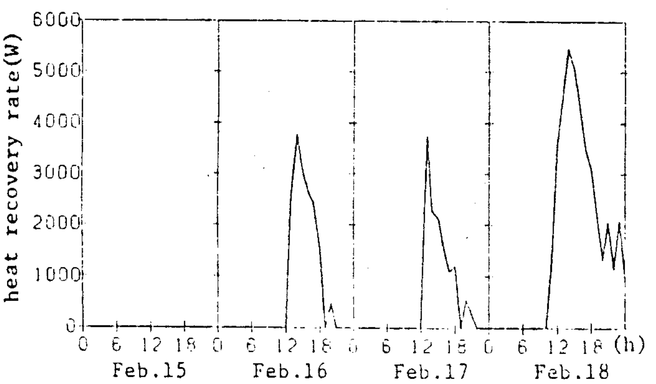


Fig.15 Heat recovery rate.

## CONCLUSIONS

We introduce the theories, algorithms and procedures of the PSSP, and its application example to a hybrid solar house. The conclusions of this paper is following.

(1) The theoretical backbone of the PSSP is a transient room temperature model, in which surface temperature and room air temperature are expressed as successive state transition equations.

(2) Solving these equations, we can get surface temperatures, room air temperatures or heat extraction rate at every time step. As we can get easily mean radiative temperatures or operative temperatures, they will be good help to estimate thermal comfort of rooms and buildings.

(3) The PSSP aims exact investigation of solar house's thermal performance. To realize this purpose, it includes minute calculating procedures of radiative heat exchange and natural ventilation for multi-room.

(4) The PSSP program is written by FORTRAN and executed by large-sized computer such as FACOM-M series. The hourly simulation of the Clean House during one month period, which must solve about 300 dimensional simultaneous linear equations by each time step, needs about 8 minutes' CPU time with FACOM-M382.

(5) Simulation results using the PSSP are fed back to the construction of the Clean House, and its accuracy will be confirmed and presented in near future opportunity.

## NOMENCLATURE

$A$ = each term's coefficient of wall indicial response, $W/m^2K$
or area of opening, $m^2$

$ADE$ = $TDN$ absorbed at inside surface, $W/m^2$

= atmospheric radiation incident upon horizontal surface, $W/m^2$

$ARE$ = $TRS$ absorbed at inside surface, $W/m^2$

$ASL$ = $SL$ absorbed at inside surface, $W/m^2$

$a$ = solar absorptance

$C$ = outdoor wind pressure coefficient

$CD$ = conductive heat flux, $W/m^2$

$CL$ = convective heat by lights, human bodies, etc., W

$CV$ = convective heat flux, $W/m^2$

$DN$ = direct solar radiation incident upon a normal surface, $W/m^2$

$F_{\bar{j}s}$ = shape factor by which surface $\bar{j}$ views the sky

$F_{lj}$ = shape factor by which surface $l$ views surface $j$

$G$ = air specific gravity, $kg/m^3$

$H$ = heat supplied to room air, W

$h$ = height of leakage from standard level, m

L = length of crack, m

$LR$ = long-wave radiation incident upon surface, $W/m^2$

$NLR$ = net long-wave radiation, $W/m^2$

$NSR$ = net short-wave radiation, $W/m^2$

$P$ = static pressure of room air, $kg/m^2$

$Q$ = heat absorbed immediately on wall indicial response, $J/m^2K$

$QR$ = room heat capacity, J/K

$RS$ = diffuse solar radiation incident upon outside surface, $W/m^2$

$S$ = area of surface, $m^2$

$SH$ = sky diffuse solar radiation incident upon horizontal surface, $W/m^2$

$SL$ = short-wave radiation emitted from lights, $W/m^2$

$SCDN$ = shading factor against $DN$

$SCRS$ = shading factor against $RS$

$T$ = temperature of surface or room air, K

$TDN$ = $DN$ transmitted through fenestration, $W/m^2$

$TH$ = global solar radiation, $W/m^2$

$TRS$ = $RS$ transmitted through fenestration, $W/m^2$

$V$ = volumetric air flow rate, $m^3/h$

$VI$ = incoming air flow rate, $m^3/h$

$v$ = outdoor wind velocity near surface, m/s

$WV$ = outdoor wind velocity, m/s

$\alpha$ = root of characteristic equation of wall heat conduction system, 1/h

$\alpha_c$ = convective heat transfer coefficient, $W/m^2K$

$\alpha_r$ = radiative heat transfer coefficient between outside surface and outdoor air, $W/m^2K$

$\alpha_{r,lj}$ = radiative heat transfer coefficient between surface $l$ and surface $j$, $W/m^2K$

$\beta_{lj}$ = long-wave absorption factor between surface $l$ and surface $j$

$\gamma_{lj}$ = short-wave absorption factor between surface $l$ and surface $j$

$\Delta$ = calculating time interval, h

$\delta(t)$ = Dirac's delta function, 1/h

$\varepsilon$ = long-wave emittance or absorptance

$\theta$ = incident angle of direct solar radiation, degree

$\Lambda$ = volumetric air specific heat, $J/m^3K$

$\mu$ = air flow coefficient

$\nu$ = crack coefficient

$\xi$ = sunlit area ratio of surface

$\pi$ = pressure difference, $kg/m^2$

$\rho$ = solar reflectance or albedo

$\sigma$ = Stefan-Boltzmann constant, $5.67 \times 10^{-8} W/m^2K^4$

$\phi$ = wall indicial response of surface heat flux against surface temperature excitation, $W/m^2K$

## SUBSCRIPTS

$f$ = fenestration surface
$g$ = ground surface
$i$ = room or room air
$j$ = inside surface of wall $j$
$\bar{j}$ = outside surface of wall $j$
$k$ = inside surface
$l$ = inside sunlit surface
$m$ = sort of wall indicial response or room air
$n$ = time
$s$ = sky

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