Development of Residence with Solar Heating, Earth Cooling, and Air Circulation

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ABSTRACT

A new type of residence (the SEA house) has been proposed. In winter, the house is heated by solar energy. Thermal insulation, heat storage, and air circulation are used to maintain the room temperature at a comfortable level and to reduce the temperature difference between the south side and the north side of the house. In summer, earth tubes are used for the purpose of cooling the proposed house. The thermal performance of the house was simulated by a computer program called PSSP, which can predict room temperature in a multiroom system. It is estimated that in Tokyo, the room temperature can be maintained at less than 28°C (82.4°F) in summer and more than 18°C (64.4°F) during most hours in winter without air-conditioning equipment.

INTRODUCTION

There have been many studies of thermal comfort and energy savings in solar houses. One of the problems for solar houses is the temperature difference between the southern and northern rooms in winter. If there is too much direct heat gain in the rooms on the south side of a solar house, these rooms will tend to overheat on sunny days while the room temperature on the north side remains too low. During winter nights, the inner surface temperature of the north wall easily drops to the dew point so that water condenses on the wall surface and sometimes inside the wall. To reduce the temperature difference between the southern and northern sides, solar houses with air circulation loops have been proposed (e.g., Wright [1978]), most of which were equipped with a greenhouse or a sunroom on the south side. A thermal envelope house was developed (Akridge and Benton 1980) to reduce the temperature difference between the southern and northern sides using air circulation loops. These houses performed well due to their high level of insulation, but usually a greenhouse or a sunroom on the south side cannot supply enough driving force.

To obtain enough driving force for the circulation, it is important to raise the temperature of the solar collect part to a high enough level. Another important point is to cool the air with heat storage parts on the north side of the house. The solar collection parts should be on the south side instead of on top of the house. In the same way, the heat storage parts should be on the north side instead of at the bottom. Without heating the air on the south side and cooling the air on the north side of the house, the air circulation will not work effectively.

In this study, a new type of residence with solar heating, earth cooling, and air circulation (it is abbreviated as SEA house hereafter) is proposed in which both passive heating and cooling are considered. In winter, the house is heated by solar energy, and the temperature fluctuation is evened out by heat storage. The difference between the southern and northern rooms is reduced by means of air circulation caused by buoyancy. The solar collection parts on the south side are divided into the solar collection wall and the solar collection storage wall. Another characteristic of the SEA house is that there is a mass heat storage wall on the north side of the house. In summer, the house is cooled by the earth through earth tubes.

THE SEA HOUSE MODEL

Winter Performance Pattern

The design and operation of the SEA house in winter are shown in Figure 1. The names and materials of each part of the house can be found in Table 1. During the day, solar radiation reaches the solar collection storage wall (3) and the solar collection wall (7) through double-glass covers (1 and 2), and most of the radiation is absorbed at the black surface. The air temperature in the south ventilating layer (4) is raised, and the air rises through a damper (5). The thermal energy carried by the air is transferred to the heat storage wall (6); therefore, the air temperature in the north ventilating layer (8) drops and its density increases. There will be air circulation in the direction

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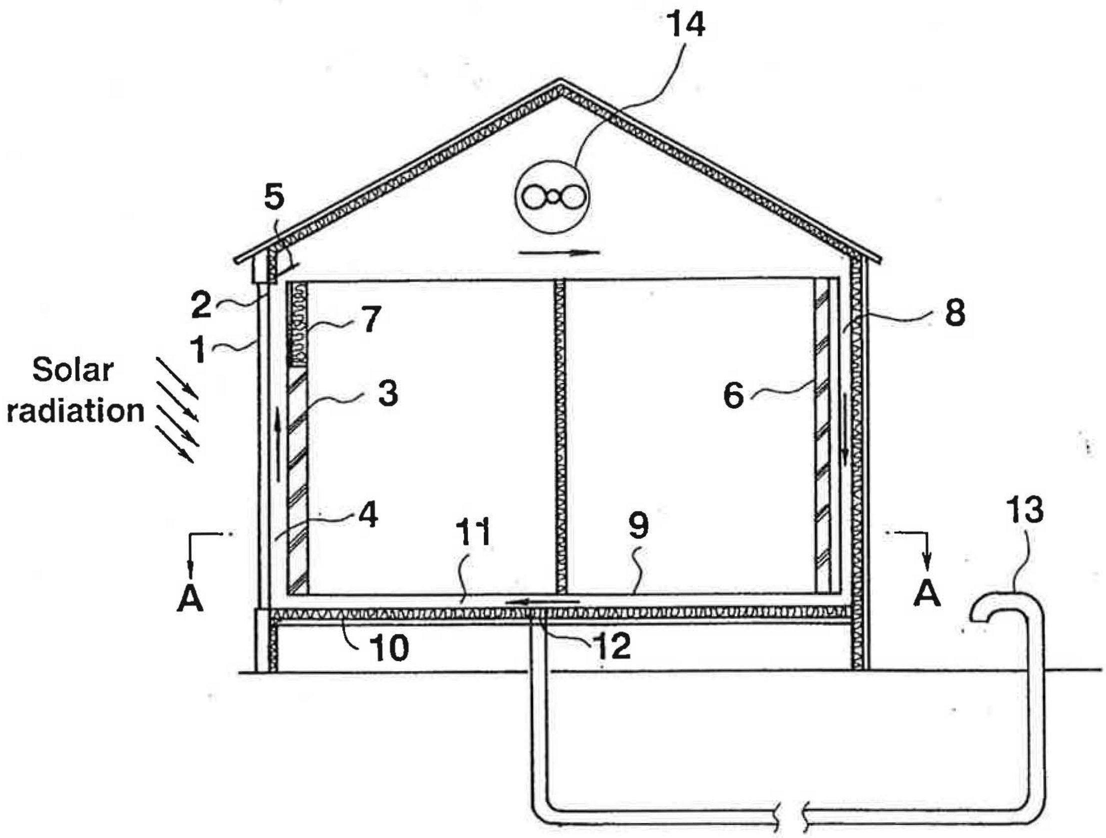

Figure 1 *The SEA house and its performance in winter.*

TABLE 1 Names and Materials of Each Part of the SEA House

No.	Name	Material	Thermal Resistance		Thermal Capacity	
			(K·m²/W)	(h·ft²·°F/Btu)	(kJ/(m²·K)	(Btu/(ft²·°F))
1	Glass with low-E inside coating	5-mm-thick glass	0.006	0.03	13	0.64
2	Glass	5-mm-thick glass	0.006	0.03	13	0.64
3	Solar collection storage wall	300-mm-thick concrete with black surface	0.18	1.02	603	29.55
4	South ventilating layer					
5	Damper	Cellular polyethylene	0.3	1.70	0.85	0.04
6	Heat storage wall	250-mm-thick concrete with fins 100 mm long	0.18	1.02	603	29.55
7	Solar collection wall	1-mm-thick copper with black surface	—	—	3	0.15
		300-mm-thick cellular polyurethane	12.0	68.16	9	0.44
8	North ventilating layer					
9	Upper floor	10-mm-thick TATAMI	0.1	0.57	4	0.20
		10-mm-thick plywood	0.08	0.45	11	0.54
10	Lower floor	100-mm-thick cellular polyurethane	4.0	22.72	3	0.15
		10-mm-thick plywood	0.08	0.45	11	0.54
11	Floor ventilating layer					
12	Cap of the earth tube	100-mm-thick cellular polyurethane	4.0	22.72	3	0.15
13	Earth tube	Polyethylene pipe	0.03	0.17	16	0.78
14	Fan					

of the south ventilating layer (4) to the attic to the north ventilating layer (8)to the floor ventilating layer (11) to the south ventilating layer (4). The solar energy collected by the solar collection storage wall (3) and the solar collection wall (7) is not only stored on the south side of the house but also on the north side by the heat storage wall (6). The north surface of the heat storage wall is finned to promote heat transfer between the heat storage wall and the air in the north ventilating layer. The difference between the function of the solar collection storage wall (3) and the solar collection wall (7) is that the latter does not store thermal energy but transfers all the absorbed heat to the air. Therefore, the solar collection wall (7) can also be considered a heat source for the heat storage wall (6) on the north side of the house. The temperatures in the southern and northern rooms can be balanced by changing the area of the solar collection wall. All the exterior walls except the solar collection parts on the south side of the house are thermally insulated with 100 mm (3.9 in.) thick cellular polyurethane.

During the night, the air temperature in the south ventilating layer drops due to heat loss to the outdoors, so the air becomes heavier. The damper (5) shuts automatically due to the weight of the damper to prevent airflow in the direction opposite that of the daytime. The heat stored in the solar collection storage wall and the heat storage wall during the day will be transferred to the air in the south room and north room, respectively, so the room temperature will not drop significantly.

Summer Operation

In summer, the solar collection parts are covered by a white shutter for the purpose of solar shading (see Figure 8); however, the window facing south remains uncovered for daylighting. The opening in the lower floor (12) is opened so that the air can be led to the ventilating layers of the house though the earth tubes. After cooling the solar collection storage wall on the south side and the heat storage wall on the north side of the house, the air is exhausted to the outdoors by the electric fan (14) installed in the attic. The southern and northern rooms are cooled by the solar collection storage wall and heat storage wall, respectively.

In normal earth tube systems that lead the air directly from the tubes to the rooms, the air pressure in the rooms is kept either higher or lower than the outdoor air pressure to create a driving force for air circulation. In these earth tube systems, natural ventilation of the house is impossible without sacrificing the function of the earth tubes. In the SEA house, however, the air pressure within the rooms is not influenced; therefore, natural ventilation can be performed at the same time. Another advantage of the SEA house over other earth tube systems is that an air conditioner can be jointly used with the earth cooling if the room temperature is not considered low enough.

SIMULATION OF THE SEA HOUSE

The thermal characteristics of the SEA house can be examined by two methods: field experiments and computer simulations. For this paper, the latter was adopted so that the thermal environment in a SEA house could be predicted before the house was built.

House Characteristics Used for Simulations

A hypothetical house was assumed for the simulation study. Elevation and plan views are shown in Figure 2. It is a one-story house with a floor area of 80 m^2 (861 ft^2). The plan is divided into the south room, the north room, and the corridor. There are insulating walls between the rooms and the corridor. Ten earth tubes were embedded in the earth beneath the house at a depth of 2 m (6.6 ft). The tubes, each 20 m (65.6 ft) long, are made of polyethylene, and the diameter of the tubes is 0.2 m (7.9 in.). There are two windows in the house, and the area of each is 3 m^2 (32.3 ft^2). Heat and vapor gains by occupants are not considered in the simulations.

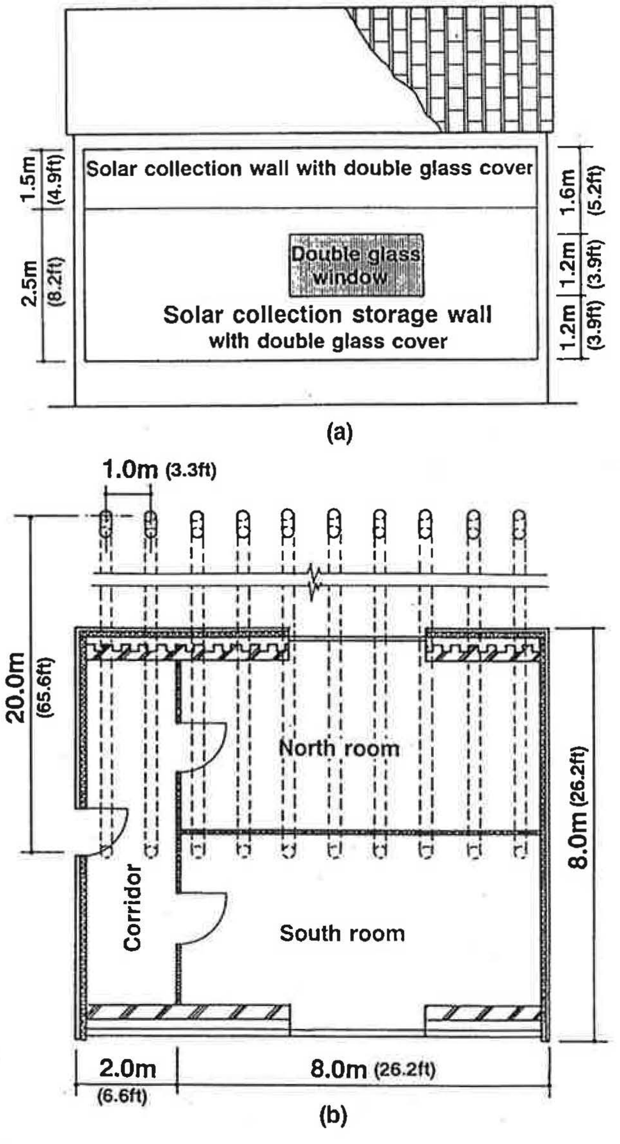

Figure 2 Elevation and plan of the house for simulation.

The Computer Simulation

A computer simulation model called PSSP has been developed by Hayashi et al. (1987). The thermal behavior of a multiroom system can be predicted, including the calculation of ventilation among the rooms. The heat conduction through the walls and roof is calculated with successive state transition equations. The accuracy of the model has been verified by comparing the simulation results with experimental data provided in other papers (e.g., Zhang et al. [1987]). In this study, the model was used to predict the room temperature of the SEA house.

The simulations were conducted with PSSP using the Standard Weather Data of Tokyo. To investigate the thermal characteristics of the house in winter and summer, the data of January and August were selected because these two months represent the Tokyo extremes.

The earth temperature at a depth of 0.3 m (0.98 ft) was assumed to be equal to the monthly mean ambient temperature and was the boundary condition of the calculation. Because the house was thermally insulated by 100 mm (3.9 in.) thick cellular polyurethane, this rough assumption is not considered to significantly affect the results.

The thermal behavior of the earth tubes in summer is simulated by another computer model called CT1, which was developed by Ishihara and Zhang (1992). Three-dimensional heat transfer in the earth and water condensation on the inner surface of the tubes are considered in this model. According to simulations by the CT1, dehumidification by earth tubes is almost impossible in Tokyo because the earth temperature is higher than the dew point of the outdoor air during most hours in summer. Therefore, the main purpose of the earth tubes in the SEA house is to make use of the sensible cooling of the earth. The calculation for summer can be divided into two steps. First, the exit temperature of the earth tubes is calculated by the CT1 model, then the room temperature is calculated by the PSSP.

SIMULATION RESULTS

Results for Winter

Figure 3 shows the temperature distribution in the model SEA house in a winter afternoon. The temperature at the surface of the solar collection wall reaches 85.2°C (185.4°F). The wall is well insulated on the room side to reduce heat transfer to the room; therefore, the absorbed solar energy can only be delivered to the air in the south ventilating layer through convection and to the double-glass cover through radiation. The surface temperature of the solar collection storage wall is 57.7°C (135.9°F), about 27 degrees lower than the solar collection wall because of the heat conduction to the inside of the wall. The air temperature rises about 10 degrees, from 30.2°C (86.4°F) at the inlet to 40.0°C (104°F) at the exit while flowing through the south ventilating layer. The heat contained in the air is transferred to the heat storage wall because of a significant

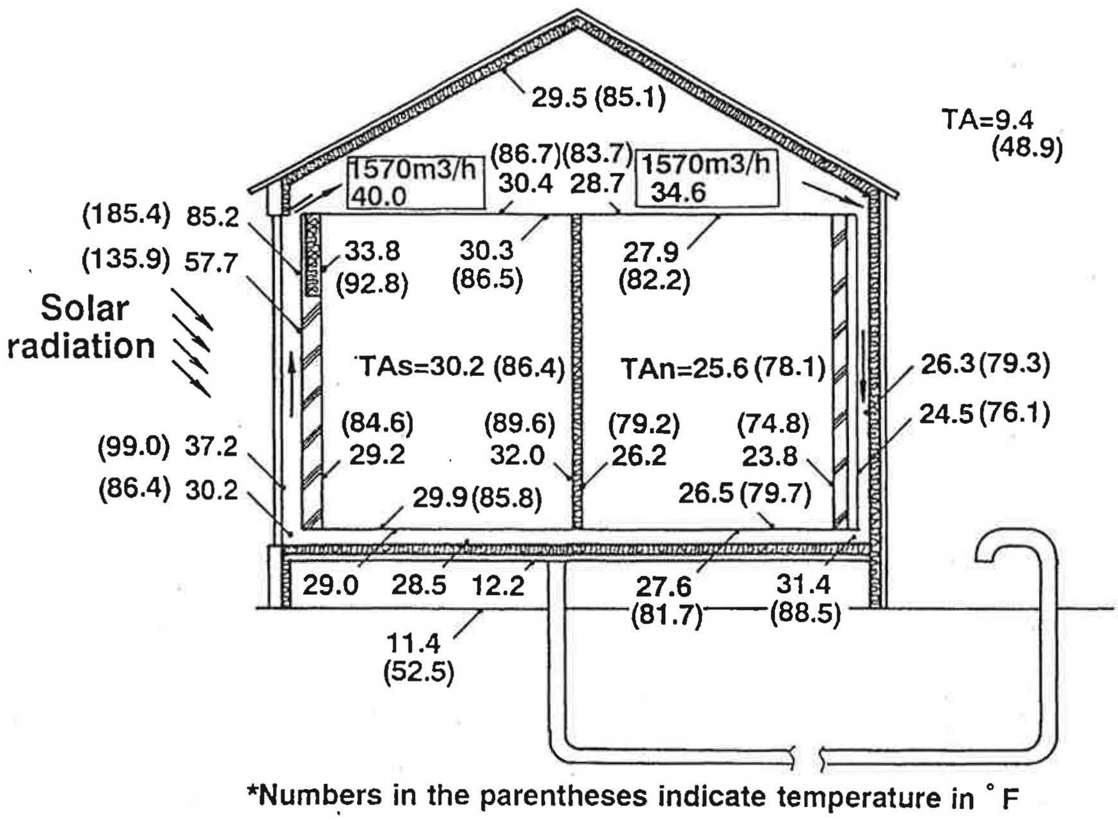

Figure 3 *Daytime temperature distribution winter (1:00 p.m., Jan. 11).*

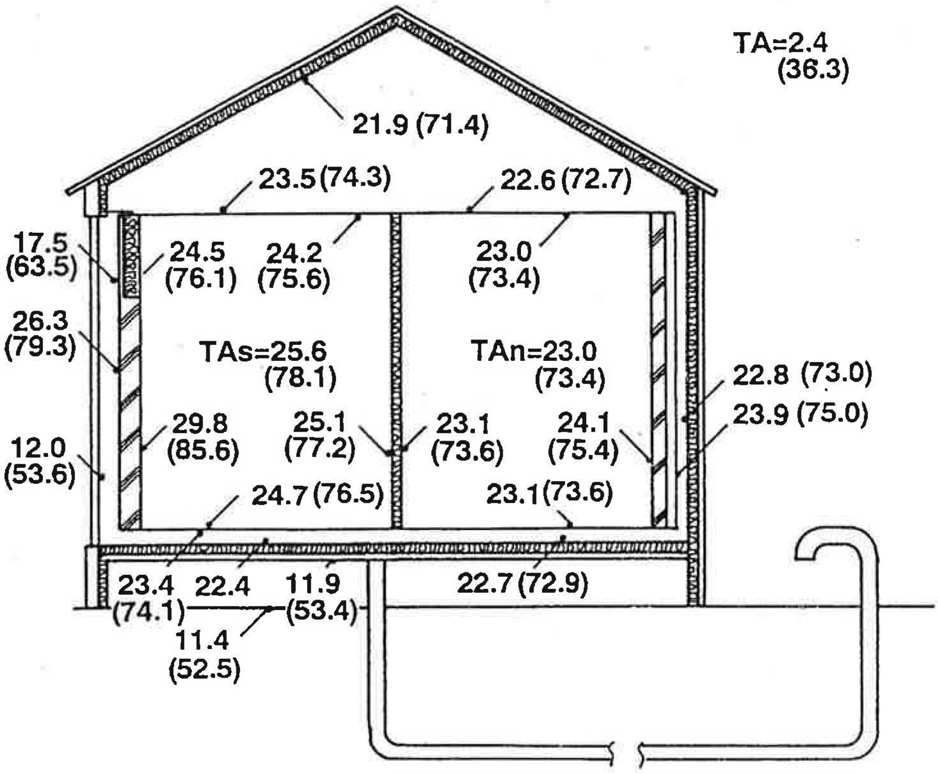

Figure 4 *Temperature distribution at dawn in winter (6:00 a.m., Jan. 12).*

temperature difference between the air and the surface of the wall. The airflow rate in the direction of the south ventilating layer to the attic to the north ventilating layer to the floor ventilating layer to the south ventilating layer is about 1,570 m^3/h at 1 p.m. The air temperature in the south room (TAs) is 30.2°C (86.4°F), a little warmer than what is considered to be comfortable. The air temperature in the north room TAn is 25.6°C (78.1°F), which is about 16 degrees higher than the outdoor temperature (TA).

During the winter night, the air temperature in the south ventilating layer drops due to the heat loss though the glass. The damper shuts automatically due to its weight; therefore, the air circulation stops. The temperature distribution at winter dawn is shown in Figure 4. The temperature of the inside surface of the solar collection storage wall is 29.8°C (85.6°F), 4.2 degrees higher than the south room temperature (TAs). The inside surface temperature of the heat storage wall is 24.1°C (75.4°F), the highest among the walls in the north room. Because the temperature of the inside surface of the north wall is higher than the room temperature, water condensation (which is always a care in a normal house) will not occur. The room temperature is maintained above 23°C (73.4°F) even when the outdoor temperature drops to 2.4°C (36.3°F), which is almost the minimum temperature of the day.

The fluctuation of air temperature in the south and north rooms and the weather conditions are shown in Figure 5. When sunny days continue, the room temperature will be kept above 20°C (68°F), which is considered to be comfortable, without heating equipment. The temperature difference between the south and north rooms is between two and five degrees. This difference can still be reduced by increasing the area of the solar collection wall and/or by solar shading at the south window.

The relation between the air temperature of the south room and the outdoor temperature can be seen in Figure 6. The room temperature is kept in the range of 18°C (64.4°F) to 30°C (86.0°F) during most hours, with a minimum temperature of 13°C (55.4°F). The minimum temperature occurs when the cloudy days continue because solar energy is the only heat source of the SEA house. To prevent the room temperature from decreasing, it is important to locate the SEA house in a place where the weather is sunny in winter. The maximum temperature is more than 30°C (86.0°F), which is warmer than what is considered to be comfortable. However, the problem of overheat can be easily solved by opening the window or by increasing the thermal capacity in the south room. Compared with the temperature in the south room, the air temperature in the north room (shown in Figure 7) is less variable. The maximum is 28°C (82.4°F) and the minimum is about 14°C (57.2°F). The percentage of hours when the room temperature is below 18°C (64.4°F) is less than 10%.

Results for Summer

The thermal performance of the SEA house and the temperature distribution in the summer afternoon are shown in Figure 8. The airflow rate of each tube is 100 m^3/h; therefore,

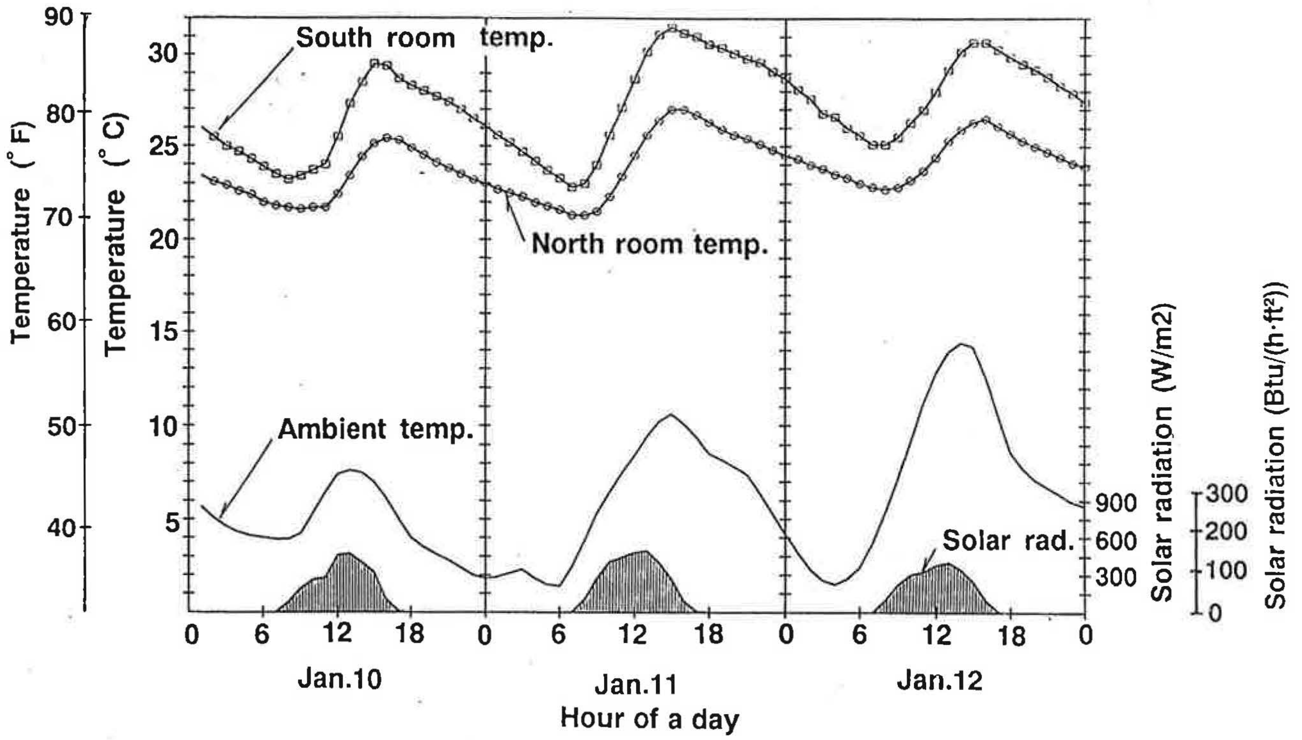

Figure 5 Fluctuation of the room temperature in winter.

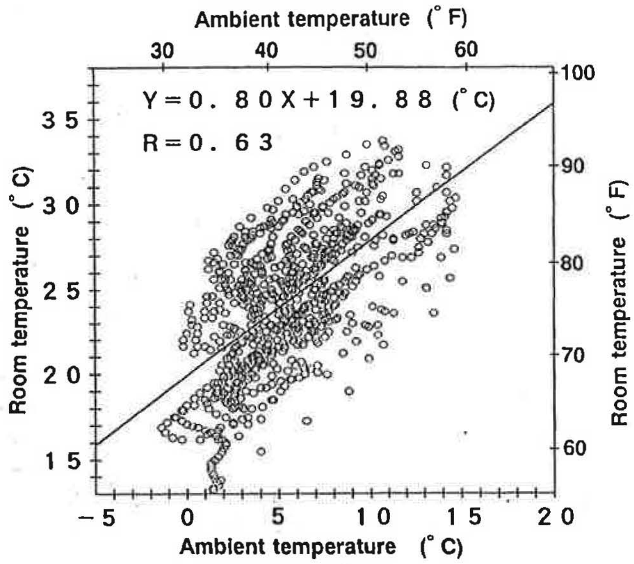

Figure 6 Correlation between the south room temperature and ambient temperature.

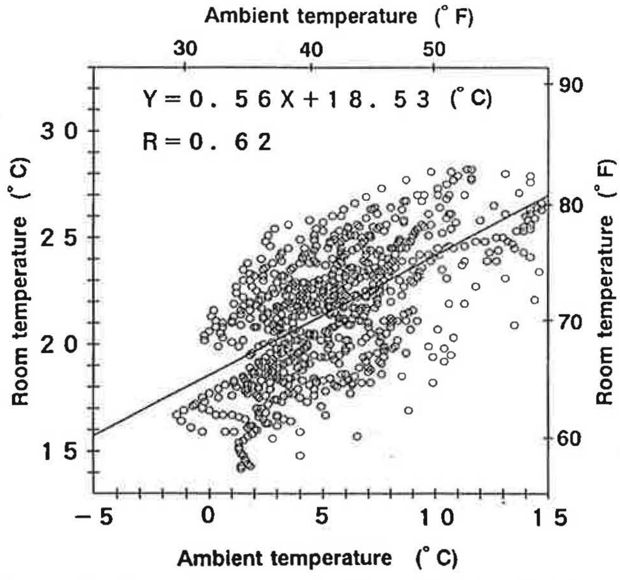

Figure 7 Correlation between the north room temperature and ambient temperature.

the total airflow through all the tubes is 1,000 m^3/h. The outdoor temperature is 35.2°C (95.4°F), which drops to 25.8°C (78.4°F) at the exit of the tubes. After cooling the solar collection storage wall on the south side and the heat storage wall on the north side of the house, the air with the temperature of 27.4°C (81.3°F) is exhausted to the outdoors by the fan installed in the attic. The air temperature in the south room (TAs) is 27.5°C (81.5°F) and the north room temperature is 25.4°C (77.7°F), while the outdoor temperature is 35.2°C (95.4°F). The solar collection storage wall stores cooling energy but does not collect solar energy because the solar radiation is reflected by the shutter. Condensation does not occur in the house because the temperature of any part of the house is higher than the temperature at the exit of the earth tubes. Therefore, even if the air at the exit of the tubes is saturated, condensation will not occur.

The fluctuation of room temperature in summer is shown in Figure 9. Even though the outdoor temperature is higher than

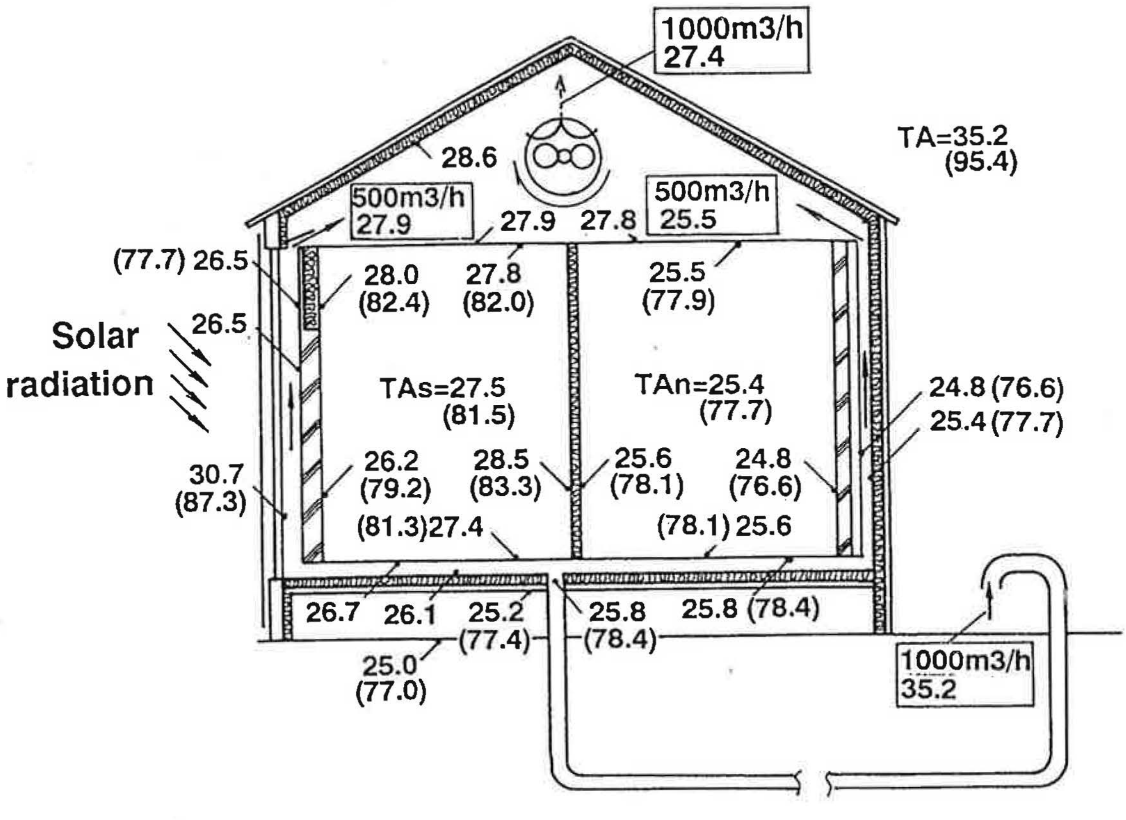

Figure 8 *Daytime temperature distribution in summer (1:00 p.m., Aug. 8).*

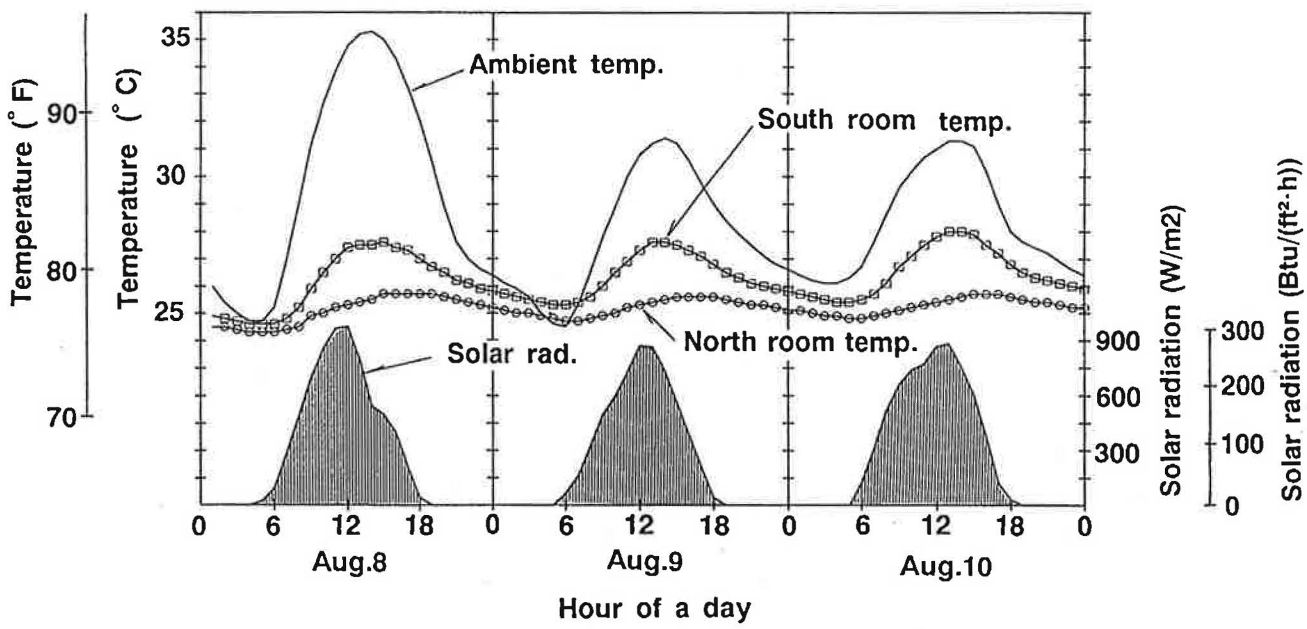

Figure 9 *Fluctuation of the room temperature in summer.*

30°C (86.0°F) during the day and the solar radiation is strong, the south room temperature is kept below 28°C (82.4°F), a tolerable level for the human body. The air temperature in the north room is low and steady.

The correlation between air temperature in the south room and the outdoor temperature in summer is shown in Figure 10. The correlation coefficient is 0.89, much higher than for winter. The reason for this is that in winter, the room temperature is

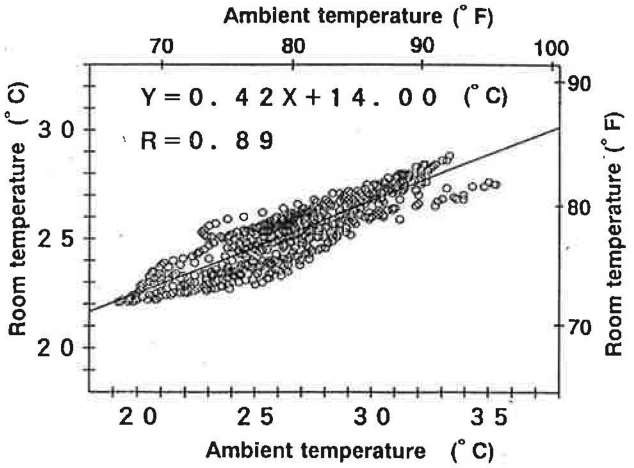

Figure 10 *Correlation between the south room temperature and ambient temperature in summer.*

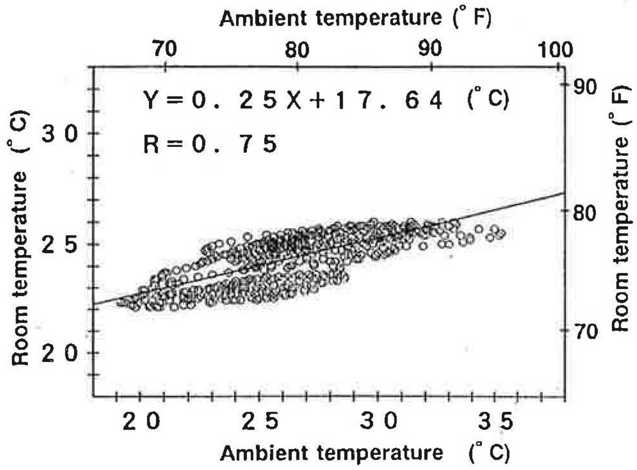

Figure 11 *Correlation between the north room temperature and ambient temperature in summer.*

influenced by both the outdoor temperature and the solar radiation, while in summer, the solar radiation is reflected by the shutter outside the solar collection storage wall and the solar collection wall; therefore, the solar radiation has little effect on the room temperature. The air temperature in the north room (Figure 11) changes within the range of 23°C (73.4°F) to 26°C (78.8°F).

DISCUSSION

The results mentioned above are based on the model house shown in Figures 1 and 2. The distance between the solar gain side and the back side of the house is 8.0 m (26.2 ft). It is obvious that air circulation changes with the size of the house because both driving pressure and pressure loss depend on the size of the house. The balance of the driving pressure and the pressure loss in the circulation loop of the SEA house is given by

$$\int_0^{h_w} (\gamma_n - \gamma_s) dh = \left(\Sigma C_j \frac{\gamma_j}{2g}\left(\frac{1}{A_j}\right)^2 + \Sigma f_k \frac{L_k}{D_k}\frac{\gamma_k}{2g}\left(\frac{1}{A_k}\right)^2\right) Q^2 \quad (1)$$

where

A_j, A_k = cross-sectional area of parts j and k,
C_j = local loss coefficient of part j,
D_k = hydraulic diameter of part k,
f_k = friction factor of part k,
g = acceleration due to gravity,
h_w = height of the vertical ventilating layer,
L_k = length of part k,
Q = volume circulation rate,
γ_j, γ_k = specific weight of air in parts j and k,
γ_n = specific weight of air in the north ventilating layer at the height of h,
γ_s = specific weight of air in the south ventilating layer at the height of h.

Therefore, air circulation, Q, is calculated by

$$Q = \sqrt{\frac{\int_0^{h_w} (\gamma_n - \gamma_s) dh}{\Sigma C_j \frac{\gamma_j}{2g}\left(\frac{1}{A_j}\right)^2 + \Sigma f_k \frac{L_k}{D_k}\frac{\gamma_k}{2g}\left(\frac{1}{A_k}\right)^2}} \quad (2)$$

It is clear from Equation 2 that the distance between the solar side and the back side in a large house may cause the reduction in air circulation. This reduction is from two parts: the attic and the double floor. The pressure drop in the attic can be neglected because the cross-sectional area is large enough. Therefore, the circulation problem in a large house is only the pressure drop in the double floor. This problem can be solved by increasing the cross-sectional area of the double floor, by increasing the height of the solar collection wall, or by increasing both. In designing an SEA house, it is important to consider carefully the balance of the distance between sides and the height of the house to make the circulation rate large enough to reduce the temperature difference between the solar side and the back side. Another important method to reduce the temperature difference between the two sides is to adjust the areas of the solar collection storage wall and the solar collection wall, as stated previously.

CONCLUSIONS

A new type of residence with solar heating, earth cooling, and air circulation (the SEA house) has been proposed and the thermal characteristics examined with computer simulations. The SEA house is a "fully" passive house and almost free of commercial energy for cooling and heating in mild regions. In Tokyo, room temperature may be maintained above 18°C (64.4°F) during most hours in winter and below 28°C (82.4°F) in summer without air-conditioning equipment.

The temperature difference between the southern and the northern rooms is small due to air circulation in the direction of the south ventilating layer to the attic to the north ventilating layer to the floor ventilating layer to the south ventilating layer. The room temperature fluctuation is evened out by heat storage, not only with the solar collection storage wall on the south side, but also with the heat storage wall on the north side of the house.

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