MEASUREMENT AND SIMULATION OF THE THERMAL ENVIRONMENT OF A LOW ENERGY HOUSE WITH AIR-CIRCULATION IN BRICK WALLS

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ABSTRACT

Brick houses are high-grade in terms of life cycle assessment, life span and maintenance costs after construction. However, earthquakes made brick infamous as a fragile material in Japan. Now quakeproof brick houses have been developed and they will be authorized in the near future in Japan. We can control the indoor thermal environment and reduce cooling and heating loads using a passive system and the large thermal capacity of bricks. This paper reports the development of Passive Brick Houses with Air-circulation Systems. We have made predictions about the indoor thermal environment and cooling and heating loads using the simulation software "Triple P" (TrP = Program for Passive System Simulation with Personal Computers). The prediction using TrP is useful because currently there are no brick houses in Japan.

INTRODUCTION

There are no brick houses in Japan for two reasons. One is their fragility in earthquakes. Masonry structures are regulated by the building code in Japan. The other reason is condensation. The Japanese hot and humid climate in summer further reduced the popularity of brick houses because of mold. The structural difficulty in making large openings interfered with ventilation and the large temperature caused dew on walls and was a sanitary disaster.

Now quakeproof brick houses with large openings have been developed (the "Distributed Unbond Pre-stress Method" by Matsufuji 1992). If we can control the indoor thermal environment and reduce cooling and heating loads using a passive system and the large thermal capacity of bricks, brick houses will become popular in Japan. We have measured the indoor thermal environment and cooling and heating loads of a test brick room that was constructed, and made predictions about the environment and the loads of a test brick house that is under construction using the simulation software TrP (Program for Passive System Simulation with Personal Computers).

DESCRIPTION OF THE TEST ROOM

A test room was constructed and its thermal performance was measured to evaluate a newly proposed air-circulation system. Then the test room was simulated using the software TrP and we compared the results of measurement and simulation. Furthermore we changed it to many types of model and made predictions about each of them.

The test room was built in 1998 in Kumamoto prefecture, in the southern part of Japan (Figure 1 to 4). The test room has three main passive systems. One is a Trombe wall on the south side. The other is a solar collector, 16.2 m^2, about 1m above the ground. Another is two 20 m lengths of cool tubes at 3 m depth below the ground. The north, east and west walls have air cavities between brick walls.

In winter, outdoor air is drawn into the solar collector and warmed up. The warmed air is sent to the air cavity of the north wall through the space under the floor. And then the air comes into the room from the north air cavity. The air in the room goes through the lower slits in the east and west walls, goes up to the attic space through the air cavity of the east and west walls and is exhausted to the outside. On the other side, the room air goes through the lower slits in the south wall, goes up in the cavity of the Trombe wall and comes back to the room through the upper slits. (See Figure 4(a))In summer, the outdoor air cooled by two 20 m lengths of cool tubes goes into the room directly. The air in the room goes up to the attic space through the upper slits in the east and west walls. The air in the attic space is exhausted to the outside using the forced ventilation. The Trombe wall and windows are solar-shaded by the shutter all day long. (See Figure 4(b))

Figure 1 Outside View of the South Facing Face of the Test Room

(a) South Aspect (Trombe Wall)

(b) North Aspect (Cavity Brick Wall)

Figure 2 Inside View of the Test Room

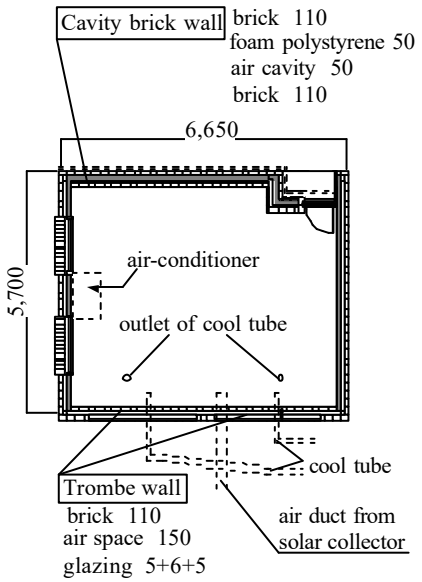


Figure 3 Floor Plan of the Test Room [unit : mm]

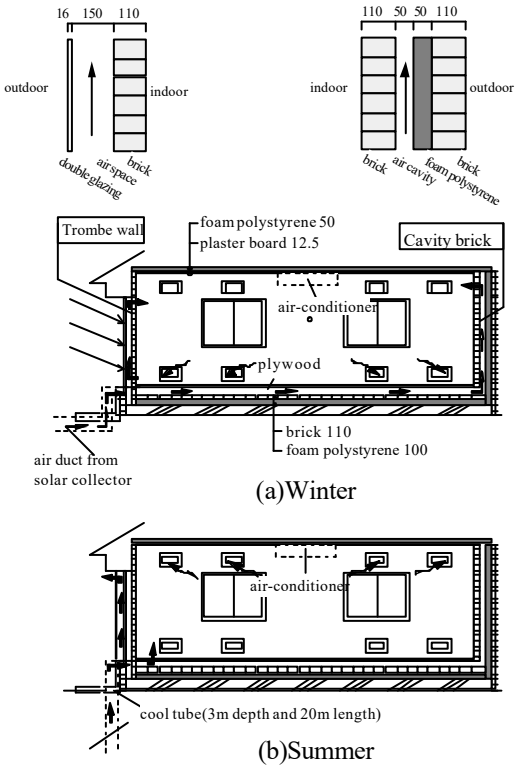


Figure 4 Sections and Details of the Test Room [unit : mm]

COMPARISON OF MEASURED AND SIMULATED RESULTS FOR THE TEST ROOM

We made predictions using the simulation software TrP (Program for Passive System Simulation with Personal Computers). We input outside air temperature, outside absolute humidity mixing ratio, solar irradiance, wind direction, wind velocity and cloud cover from the standard weather data for Kumamoto. We were able to get room air temperature, PMV and heating/cooling loads for each hour as output. Assumptions for the simulation are shown in Table 1. TrP has some suppositions as premises. (See Table 2)

Table 1 Conditions for the Simulation

- weather data :
  standard weather data (Kumamoto in Japan)
- simulation interval time : 1 hour
- date : December 7 (winter)
  August 14 (summer)

Table 2 Suppositions for TrP

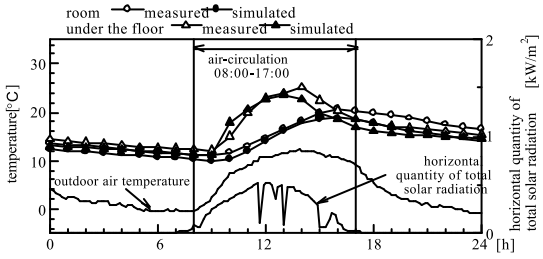
- Rooms are rectangular parallelepiped
- Rooms have 6 faces
  (east, west, south, north, floor, ceiling)
- Walls are divided into some parts
- Heat conducts one-dimensionally in every part
- Parts have no temperature distribution
- Room temperature is the same in each rooms
- Heat diffuses all over the room immediately

Figure 5(a) shows air temperature in the room and under the floor in winter. The results of measurement and simulation are almost the same.

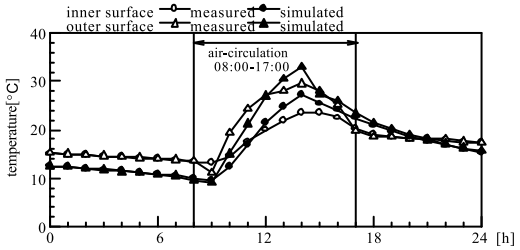
Figure 5(b) shows the temperature of the surface of the south brick wall in winter. Temperatures in simulation rose a little bit higher than in reality. This is because the air tightness of the double glazing on the south Trombe wall in the simulation was better than in actual measurements. The maximum difference was about 3 K.

Figure 6(a) shows the room air temperature in summer. In the morning, actual temperatures were about 2 K higher than in the simulation. This is because the outdoor air cooled by the cool tubes is re-warmed just before it goes into the room.

Figure 6(b) shows inside air temperature of the cool tube in summer. The results were very similar and the maximum difference was less than 1 K.

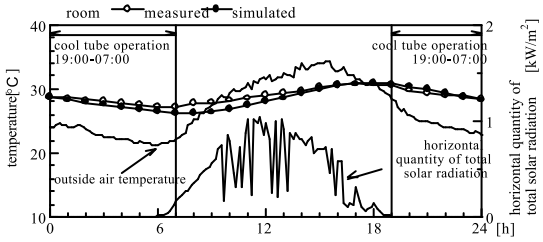


(a) Room and Under Floor Air Temperature

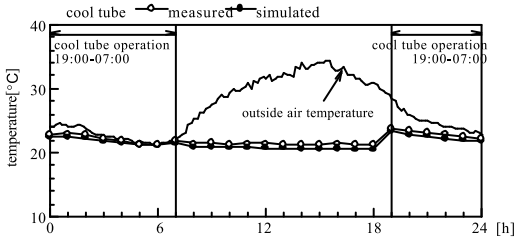


(b) Temperature of the Surface of the South Brick Wall

Figure 5 Room and Surface Temperature in Winter (December 7, 1999)



(a) Room Air Temperature



(b) Cool Tube Air Temperature

Figure 6 Air Temperature in Summer (August 14, 1999)

SIMULATION OF THE TEST ROOM

We made predictions about the indoor thermal environment and cooling and heating loads using the simulation software TrP while changing some parameters.

SIMULATION IN WINTER

In winter we changed the surface area of the solar collector. Figure 7 shows the room air temperature. When the surface area of the solar collector was large, the room air temperature was high, but the rate of temperature increase was small. We also changed the mass flow rate of the solar collector. A mass flow rate of 100m^3/h resulted in better temperatures than a rate of 200 m^3/h. Too much mass flow rate prevents the air drawn into the solar collector from becoming warm enough.

We also changed the thickness of the brick layer of the Trombe wall. Figure 8 shows the room air temperature and Figure 9 shows the inner surface temperature of the brick wall. A thickness of 50 mm resulted in the best room air temperatures in the daytime but all types resulted in almost the same temperatures at night. The inner surface temperature showed a similar tendency in the daytime but a wall thickness of 200 mm resulted in the highest temperatures at night.

Figure 10 shows the comparison of seasonal heating loads. The target temperature was 22 °C and the heating time was from 17:00 to 08:00. When the surface area of the solar collector was 5.4m^2, the mass flow rate of the solar collector was 100m^3/h and the thickness of the south brick layer of the Trombe was 100mm, the seasonal heating load was lowest. It was 6.6 GJ which was 2.8 GJ (30%) lower than the load of the house without passive systems.

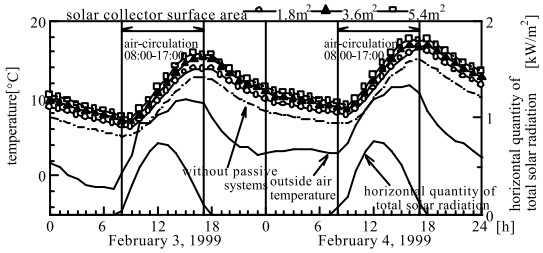


Figure 7 Room Air Temperature

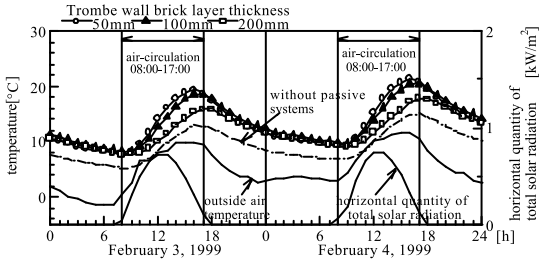


Figure 8 Room Air Temperature

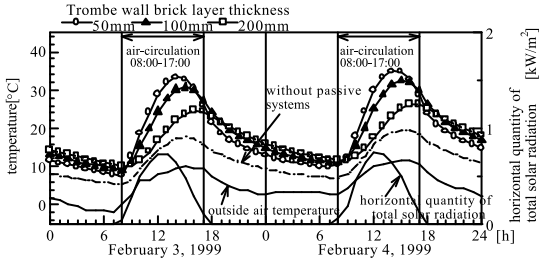


Figure 9 Inner Surface Temperature of the Brick Wall

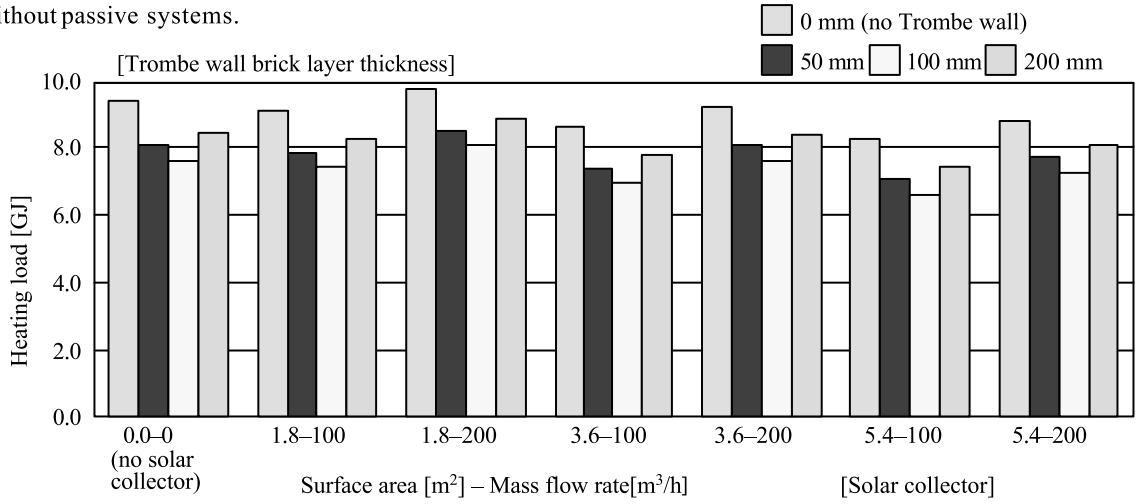


Figure 10 Comparison of Heating Load

SIMULATION IN SUMMER

In summer we changed the length of the cool tubes. Figure 11 shows the room air temperature. In the daytime, the longer the cool tube, the lower the room air temperature. But there was little variation at night.

In summer we also changed the mass flow rate of the cool tube. Figure 12 shows the room air temperature. The larger the mass flow rate, the lower the room temperature. When the mass flow rate became large, the room air temperature became low, but the rate of decrease became small.

Figure 13 shows the comparison of seasonal cooling loads. The target temperature was 26 °C and cooling time was from 07:00 to 19:00. When the length of the cool tubes was 30m and the mass flow rate of the cool tubes was 300m^3/h, the seasonal cooling load was lowest. It was 2.7 GJ which was 0.9 GJ (25%) lower than the load of the house without passive systems.

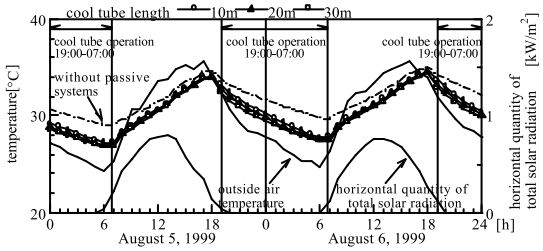


Figure 11 Room Air Temperature

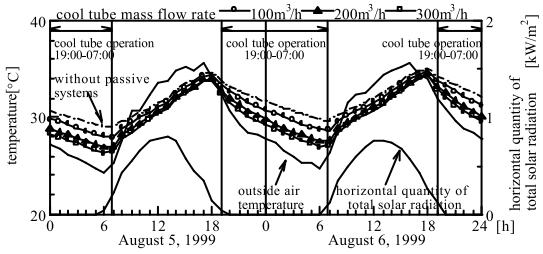


Figure 12 Room Air Temperature

DESCRIPTION OF THE TEST HOUSE

We have explained about the test room that was constructed and measured. For the next stage, we propose a test house as large as an actual residence. The test house is under construction next to the test room and so currently we have only a computer model. We have made predictions about the indoor thermal environment and cooling and heating loads using the simulation software TrP.

Figure 15 is the plan of the proposed house and Figure 16 shows the sectional diagram of the passive system. The brick house with air-circulation is a two-story house and the total floor area is 194m^2. The exterior walls are cavity brick structure.

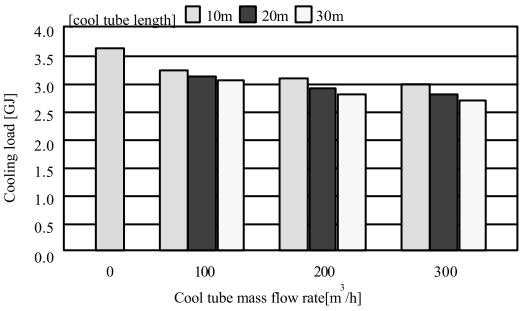
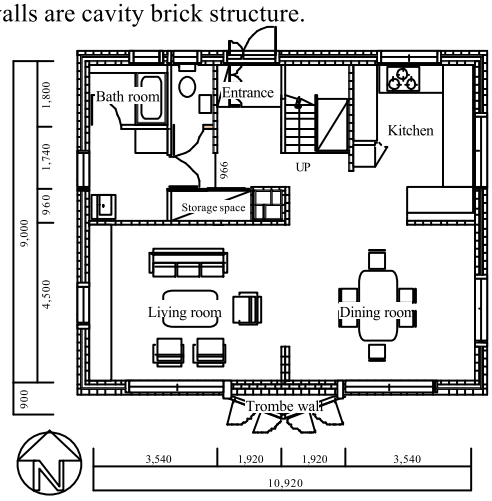
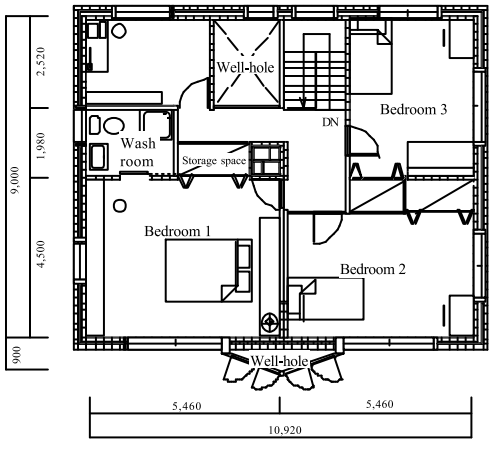


Figure 13 Comparison of Cooling Load



(a) First Floor Plan



(b) Second Floor Plan

Figure 14 Plans of Passive Solar House [unit: mm]

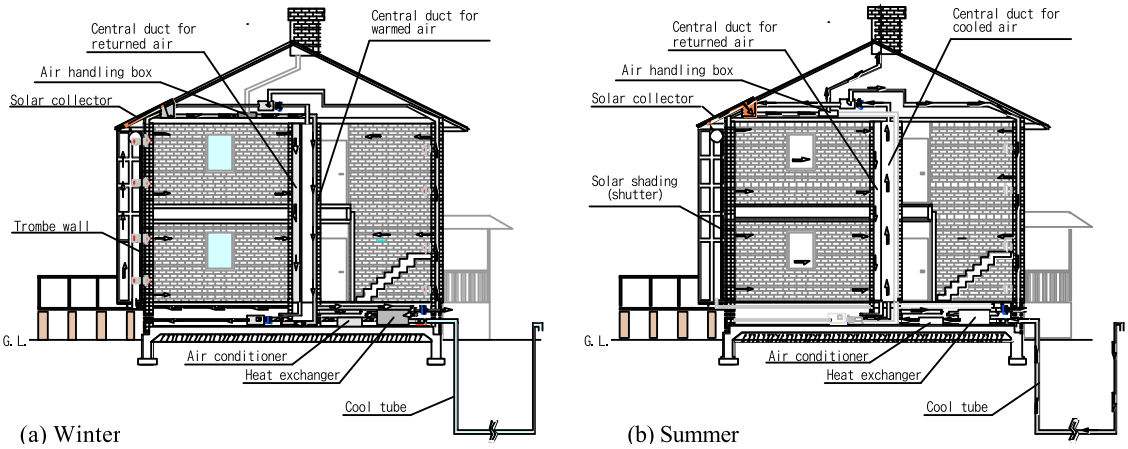


Figure 15 Sectional Diagram of Passive Devices [unit: mm]

In winter, the room air goes into the heat exchanger under the floor through the central duct. The air from the solar collector is pre-heated in the air space in the Trombe walls facing to the south and drawn into the solar collector by the electric fan in the air-handling box. The air from the solar collector and the return air from the rooms exchange sensible heat at the heat exchanger. The warmed air is sent to the rooms through the air cavities in the cavity brick walls, and returned to the heat-exchanger. In the night, heat radiation into the room from the Trombe walls and the cavity brick walls keeps the room comfortable and the pulled-down shutter on the Trombe walls prevents heat loss. (See Fig. 15 (a))

In summer, the room air goes into the heat exchanger under the floor through the central duct. The air from the cool tube and the return air from the rooms exchange sensible heat at the heat exchanger to prevent mold caused by the moist air in the cool tubes. The cooled air is sent to the rooms through the air cavities in the cavity brick walls, and returned to the heat-exchanger under the floor through the central duct. The Trombe walls and the windows are solar-shaded by the shutter, the outdoor air is drawn in to the air space in the Trombe walls, led to the attic space and exhausted to the outside by an electric fan to prevent the temperature from rising. (See Fig.15 (b))

SIMULATION OF THE TEST HOUSE

We made predictions using the simulation software TrP. The presumptions for the simulation are shown in Tables 3 to 5. Table 3 shows the components of the wall structures of the proposed solar house. However, five types of wall structure were examined to compare their thermal performance. The first type was a passive

Table 3 Components of Wall Structures

Roof	plywood	10mm
	clay tile	40mm
1F ceiling	plaster board	10mm
2F ceiling	plaster board	10mm
	thermal insulating board	50mm
Floor	plywood	10mm
Ground	concrete	200mm
	crushed stone	50mm
	soil	50mm
Foundation	brick	110mm
	thermal insulating board	50mm
	brick	110mm
Exterior wall Ⅰ	brick	110mm
	air cavity	50mm
	thermal insulation board	50mm
	brick	110mm
Exterior wall Ⅱ	plywood	10mm
	mortar	10mm
	air cavity	50mm
	urethane foam	30mm
	plaster board	10mm
Trombe wall Ⅰ	brick	330mm
	air space	100mm
	double glazing	5+10+5mm
Trombe wall Ⅱ	concrete	330mm
	air space	100mm
	double glazing	5+10+5mm
Interior wall Ⅰ	brick	110mm
Interior wall Ⅱ	plaster board	10mm
	air cavity	50mm
	plaster board	10mm

brick house with an air-circulation system, the same as the test house that is under construction. The second type was termed brick house A and had the same wall structure but no air-circulation. The third type was termed brick house B and had an exterior wall with inside insulation. The fourth type was a wooden house with air-circulation with the exterior brick walls replaced by plywood panels. The fifth type was a wooden house, the same as the fourth one but without an air-circulation system or a Trombe wall.

The thermal performances of the five types of house shown in Table 4 were compared to confirm the validity of the proposed system. In winter, the surface area of the solar collector was 28.7 m^2 and the mass flow rate was 500 m^3/h. The electric fan was operated when the air temperature in the air-handling box exceeded 25°C. The shutter on the Trombe wall was pulled up from 08:00 to 17:00. In summer, the cool tube was 3 m deep, 50 m long and had a mass flow rate of 500 m^3/h. The electric fan was operated from 19:00 to 07:00.

SIMULATION IN WINTER

Figure 16 shows air temperatures in bedroom 1 and outside on February 10 and 11. The room air temperature of all three brick houses was stabler than that of the two wooden houses because of the large thermal capacity of the indoor brick walls. In the daytime, the room air temperature of the brick house with air-circulation was lower than that of the wooden house with air-circulation. However, the former was about 5 K higher than the latter at night.

Figure 17 shows a comparison of the seasonal heating loads in winter among the five types of house. The target temperatures and air-conditioning time shown in Table 5 were applied to these simulations. The thermal capacity of the brick walls reduced the temperature decrease at night. Therefore, the seasonal heating load of the passive brick house with air-circulation was lowest. Compared with the seasonal heating load of the wooden house, that of the brick house with air-circulation was 38% lower.

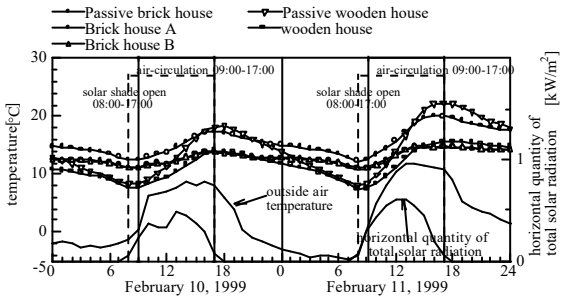


Figure 16 Comparison of Air Temperatures in Winter (Bedroom1)

Table 4 Specification of Simulation Models

<<Passive brick house>> (air-circulation, over-all heat loss coefficient: 1.69) Standard type (wall type I)
<<Brick house A>> (no air-circulation, over-all heat loss coefficient: 1.69) Change Trombe wall I to exterior wall I
<<Brick house B>> (no air circulation, over-all heat loss coefficient: 1.69) Change Trombe wall I to exterior wall I Change outside insulation to inside insulation
<<Passive wooden house>> (air-circulation, over-all heat loss coefficient: 2.19) Change wall type I to II
<<Wooden house>> (no air-circulation, over-all heat loss coefficient: 2.51) Change wall type I to II Change Trombe wall II to exterior wall II

Table 5 The Conditions for Simulation Data

Weather data: Expanded AMeDAS Weather Data (Kahoku)
Simulation interval: 1 hour
Active heating
Period: December – March
Time: 17:00-08:00
Target temperature: 22 °C
Active cooling
Period: June – September
Time: 07:00-19:00
Target temperature: 26 °C

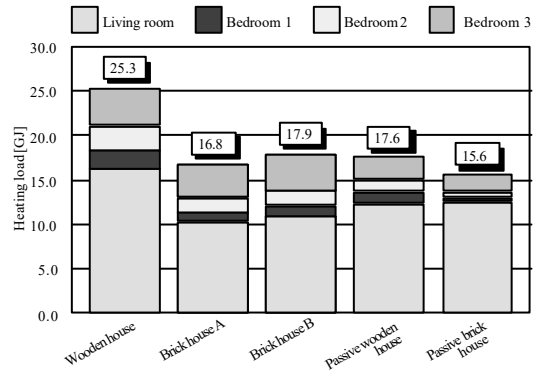


Figure 17 Comparison of Air Heating Load (Winter)

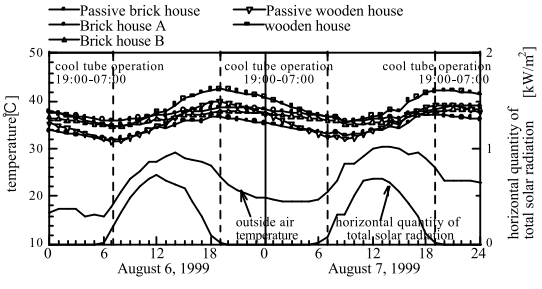


Figure 18 Comparison of Air Temperatures in Summer (Bedroom1)

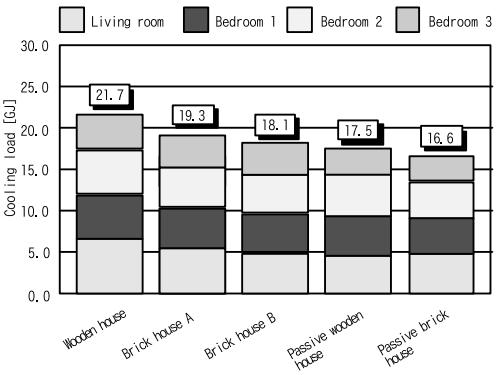


Figure 19 Comparison of Air Cooling Load (Summer)

Figure 18 shows the air temperature in bedroom 1 and outside on August 6 and 7. The room air temperature of the brick house with air-circulation was higher than that of the wooden house with air-circulation at night. However, the former was about 3K lower in the afternoon.

Figure 19 shows a comparison of the seasonal cooling loads in summer among the five types of house. The target temperatures and air-conditioning time shown in Table 5 were applied to these simulations. The seasonal cooling load of the passive brick house with air-circulation was lowest. Compared with the seasonal cooling load of the wooden house, that of the brick house with air-circulation was 24% lower.

CONCLUSIONS

In the first stage of this research, a test room was constructed and its thermal performance was measured. Then the test room was simulated using the simulation software TrP and a comparison was made of the results of measurement and simulation. The results were very similar and so the simulation software TrP was considered to be suitable for making predictions about the environment and the heating and cooling loads of houses.

In the second stage, predictions were made about the environment and the loads of several types of test houses using TrP. Comparisons were made for different solar collector surface areas and mass flow rates, different thicknesses of brick in the Trombe wall and different cool tube lengths and mass flow rates. In winter, the lowest heating load was 6.6 GJ which was 2.8 GJ (30%) lower than the load of the house without passive systems. In summer, the lowest cooling load was 2.7 GJ which was 0.9 GJ (25%) lower than the load of the house without passive systems .

In the third stage, a passive system utilizing the thermal capacity of brick walls and earthen floors was proposed and its thermal performance was simulated. The passive system was combined with a solar air-heater, Trombe walls and air-circulation. As for the seasonal heating load, the passive brick house with air-circulation was 38% less than a normal wooden structure house. In summer, the proposed passive system combined with earth cool tubes decreased by 24% the seasonal cooling load in comparison with a normal wooden structure house.

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Hayashi, T. (1992). Development of Thermal Performance Simulation Program for Multi-Space Dwellings Using Personal Computers, *Annual Report Housing Research Foundation*, No.19, pp. 337-346, (in Japanese)