VALIDATION OF ENERGY SIMULATION PROGRAM FOR PASSIVE SOLAR HOUSE

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ABSTRACT - Development and validation of a dynamic energy simulation program, ESPAR/M[1] for predicting thermal performances of residential building equipped with passive solar systems are reported. The program consisting of 9000 steps in FORTRAN is formulated around a finite differential heat conductive model for analyzing multi-room air temperatures, HVAC loads and other related thermal parameters. Analytical models include passive solar submodels such as inter-room conductive heat transfer and air circulation, PCM latent heat storage wall/floor, Trombe wall, attached sun-room, solar air collector, cool-tube, heat pipe, movable insulating shield and-the other passive solar features. Several validation steps including comparison between calculated and measured room temperatures of life-sized experimental houses have been applied to establish an analytical reliability. The result of this validation study indicates that the program can be effectively utilized for thermal performance optimization of the passive solar house in the development and/or designing stages.

INTRODUCTION

In the development and constructive design of the passive solar house, pre-evaluation of the thermal performance is essential to determine and optimize its physical specifications. Because the passive solar systems generally present weather sensitive and/or internal environment sensitive properties, their thermal performances are the result of complicated functions of various parameters associated with the site of construction, weather, system configulations, building specifications and operating conditions.

The computer simulation is a useful and effective tool for analyzing thermal performance of the systems, in view of its flexibility and reproducibility to compare the difference between system specifications or operating conditions. The purpose of this work is to confirm the validity of the computer simulation program, ESPAR/M, which has been developed to evaluate thermal performances of passive solar systems installed in a multi-room residential unit.

FUNCTION AND FLOW OF THE PROGRAM

An analytical model of ESPAR/M is formulated around the hour-by-hour implicit finite differential wall/floor heat conductive algorithm[2] associated with room temperature formations through inter-room heat transfer processes related to the passive solar systems installed in the multi-room residential unit. Inter-room heat transfer by air-circulation is calculated by the crack method formulated by linearized equations[3] considering thermal convection as well as the effect of outdoor wind and ventilating fans. The 9000 step FORTRAN based ESPAR/M analytically calculates thermal performance parameters of the passive solar systems along with room temperatures, humidities and HVAC loads for each space of the residential unit. The passive solar system submodels of ESPAR/M include (1)Direct gain system, (2)Sensible and/or PCM latent heat storage wall/floor, (3)Air circulation system, (4)Movable insulating shield, (5)Solar-air collector, (6)Cool tube system, (7) Heat pipe heat transport system, (8)Trombe wall system including the PCM latent heat storage wall, (9)Attached greenhouse, (10)Selective light reflective glazing, (11)Louver with thermal storage and (12)Movable eaves.

The program flow of ESPAR/M is shown in Fig.1.

As shown in the figure, after reading the input data followed by initialization process, the main program starts to execute hour-by hour calculation by controling 78 subprograms. The hour-by-hour standard weather data consisting of ambient air temperatures and humidities, normal beam and horizontal diffused insolations, cloud coefficients and wind directions and velocities are read in at each day loop as a data set for the period of a day. The weather data format to be used for ESPAR/M is compatible to the standard HASP weather

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**Energy Simulation system for Passive-solar Assisted Residence Multi-room version data[4], which covers major 25 cities throughout Japan. In addition to the primary output data on room temperatures/humidities and HVAC loads, intermediate parameters such as surface/inner wall temperatures, glass temperatures, passive system parameters and the reference weather ta can also be obtained by ESPAR/M.

DIFFERENTIATION ERROR

The analytical model of ESPAR/M to solve Fourier's heat conductive equation includes finite differentiations for both time and spacial coordinates, which could introduce differential errors. Time slice is fixed to one hour in the program and spacial division can be set by the user as input data.

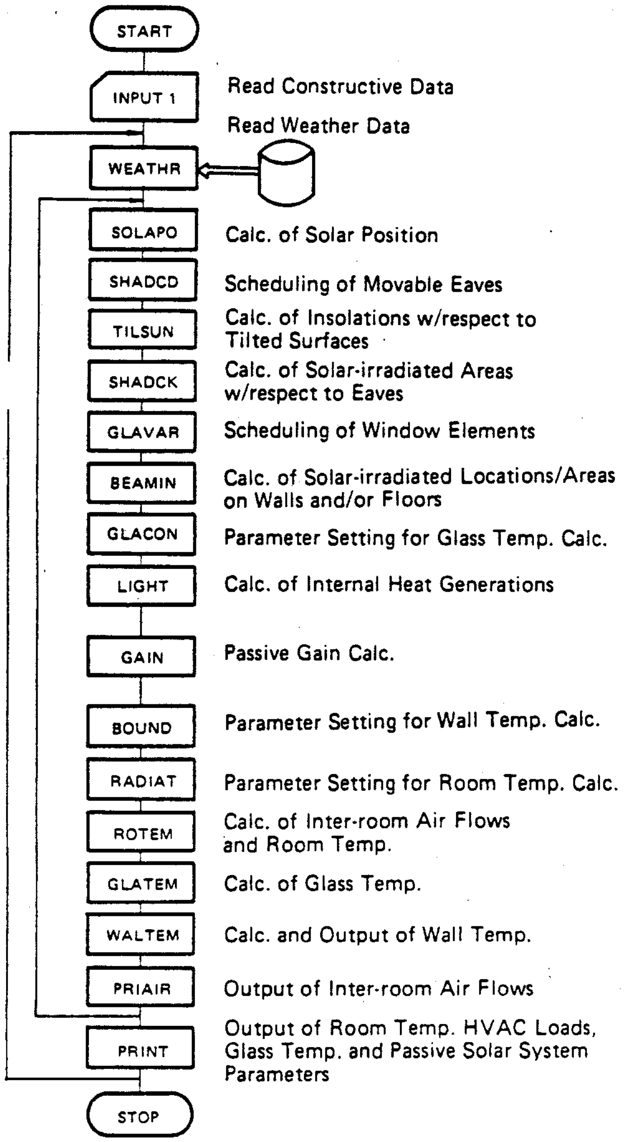


Fig.1 Flowchart of ESPAR/M

Conditions for Evaluation

To evaluate the degree of calculative errors related to the time slice and spacial divisions, thermally insulated wall (50mm thick glasswool) and thermal storage wall (100mm thick concrete) are selected. Thermal response of the wall for a change of unit degree in outside air temperature as an external stimulation has been calculated in both heat flow through the wall and temperature of inside air. Fig.2 shows conceptual model for this study. Heating load to keep inside air at unit degree is also calculated for evaluating the influence of the time slice variations.

Influence of Spacial Differentiation

For evaluating the influence of the spacial differentiation, walls divided in 9 layers and in single layer are compared for the standard one hour time slice. Fig.3(a) and Fig.3(b) respectively show calculative results of heat flow and temperature for thermally insulated wall. There can be seen slight differences in first time step in both graphs, however, the amount is negligible.

Fig.4(a) and Fig.4(b) show the results for thermal storage wall. Difference between a wall divided in 9 layers and a single layer is 8% in first time step in maximum. The difference can be observed for the period of 8 or 9 hours with the tendency of gradual decrease. While, for the wall divided in three layers, difference between 9-layered wall is within 1% even at the first time step. It can be concluded that the errors related to the spacial division could be neglected if the wall is divided in less than 30mm thick layer even for heavy thermal storage wall such as concrete.

Influence of Time Differentiation

To evaluate an influence of time differentiation, time slice of 0.1 hour and the standard one hour time slice are

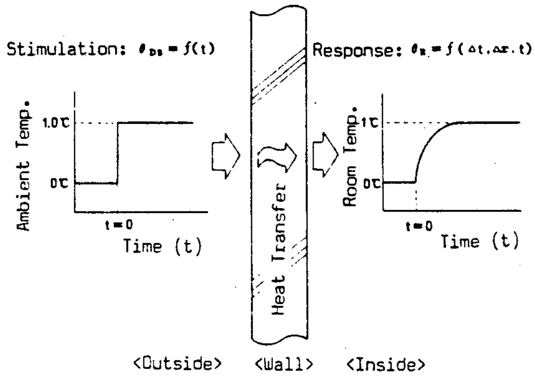


Fig.2 Model for Differntial Error analysis (Responce of Inside Air Temerature)

compared for the 9-layered wall. Accuracy and convergence of the solution for the time slice of 0.1 hour are confirmed by comparing the solutions by the implicit and the explicit finite differential methods for 0.01 hour time slice as shown in Fig.5. Fig.6(a), 6(b) and 6(c) respectively show heat flow, temperature and heating load for the insulated wall. Differences are observed for the first time step, but the amount is less than 5% and can be considered to be within practically allowable range.

Fig.7(a) shows comparison of heat flow for thermal storage wall. The case of standard time slice (one hour) shows quick response in comparison with the case of 0.1 hour time slice in the initial stage. After the third standard time step, the difference between both cases is less than 3% and the value gradually converge to the theoretical solution thereafter. The values of cumulative heat flow for 24 hours for both cases are exactly coincide to each other within the range of calculative error.

Fig.7(b) shows a result for temperature. The characteristics of difference between both cases is similar to the previous case and the maximum amount of difference is less than 0.05°C (which is 5% with respect to the external stimulation).

Fig.7(c) shows heating load to keep inside space at unit degree of air temperature. Difference between both cases is within 2% even in the fist standard time step and the maximum difference of cumulative heating load is 1.1% at the second time step.

Consequently, it can be concluded that in the case of thermal storage wall of 100mm thick concrete, the analysis using one hour time slice is practically acceptable for the room temperature and the heating load calculations. But when the amount of changing rate of outside air condition (i.e. Sol-Air Temperature) is relatively large, the calculative error for the heat flow through the wall might not be ignored. To evaluate practical effect of this factor, heat flow through the walls for a cube consisting of six concrete walls (1 square meter x 100mm thick) has been simulated under real weather condition. The weather data used for simulation is the HASP standard weather data-TOKYO for the period of 23rd to 25th of January, and the daily weather pattern is fine-cloudy-fine. The result is shown in Fig.7(d). It can be seen in the figure that the case of the standard time slice shows slightly quick response for the change of the external weather parameters. However, the differences in the daily total amount of heat flow during the three days are less than 1%.

It can be concluded for the effect of time slice that the standard one-hour time slice gives practically acceptable calculative result for the real weather condition.

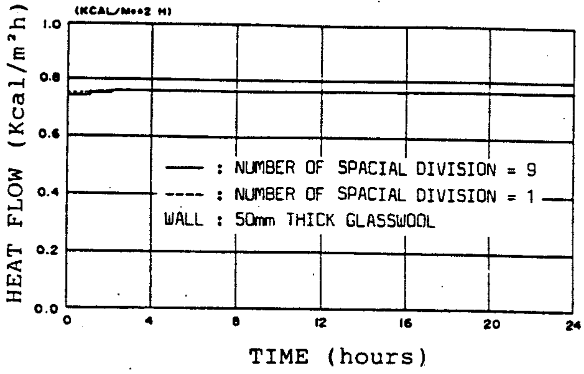


Fig.3(a) Influence of Spacial Division Error
for Heat Flow Through Insulation Wall

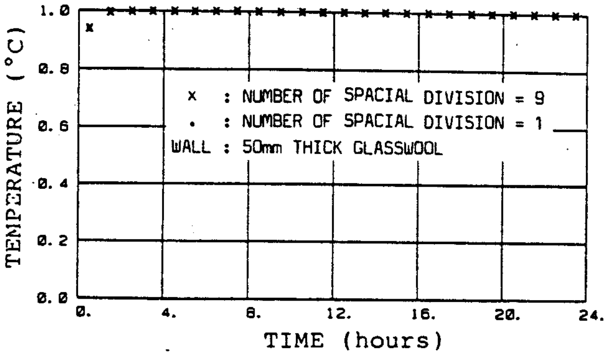


Fig.3(b) Influence of Spacial Division Error
for Inside Air Temp. of Insulation Wall

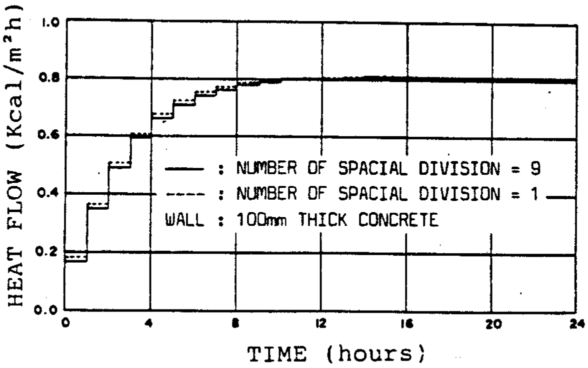


Fig.4(a) Influence of Spacial Division Error
for Heat Flow Through Heat Storage Wall

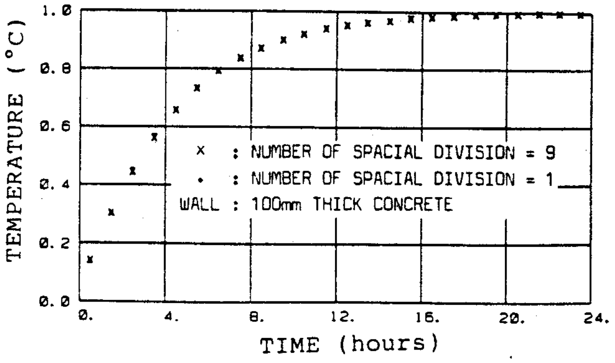


Fig.4(b) Influence of Spacial Division Error
for Inside Air Temp. of Heat Storage Wall

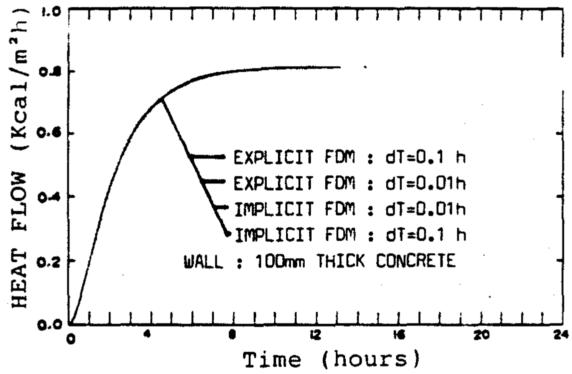


Fig.5 Convergence of Solution for Heat Storage Wall

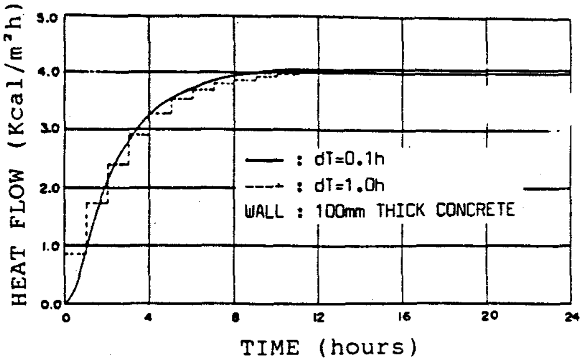


Fig.7(a) Influence of Time Division Error for Heat Flow Through Heat Storage Wall

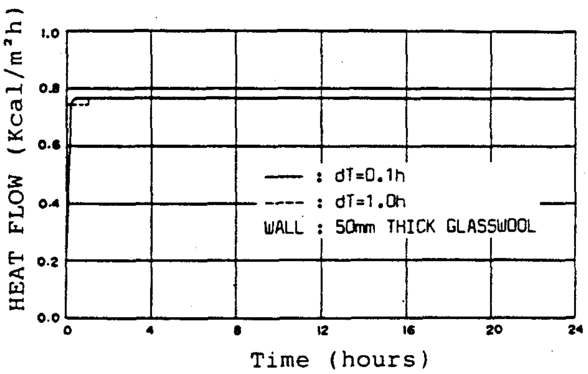


Fig.6(a) Influence of Time Division Error for Heat Flow Through Insulation Wall

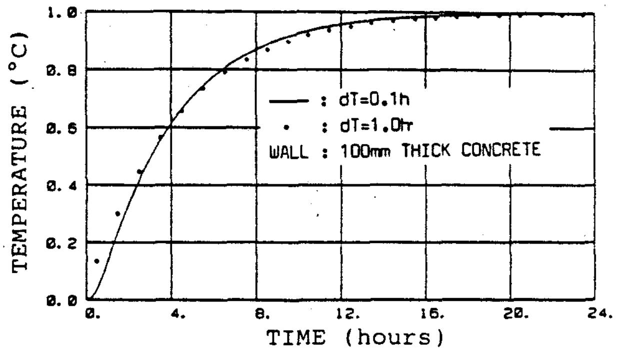


Fig.7(b) Influence of Time Division Error for Inside Air Temp. of Heat Storage Wall

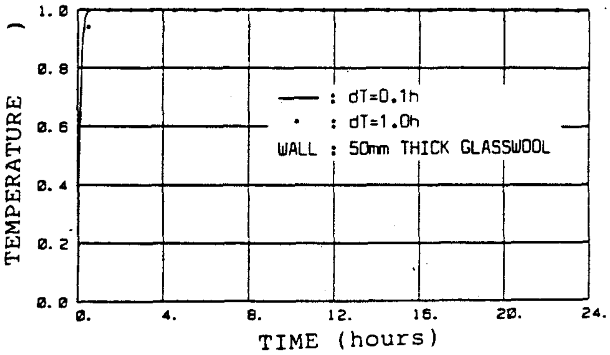


Fig.6(b) Influence of Time Division Error for Inside Air Temp. of Insulation Wall

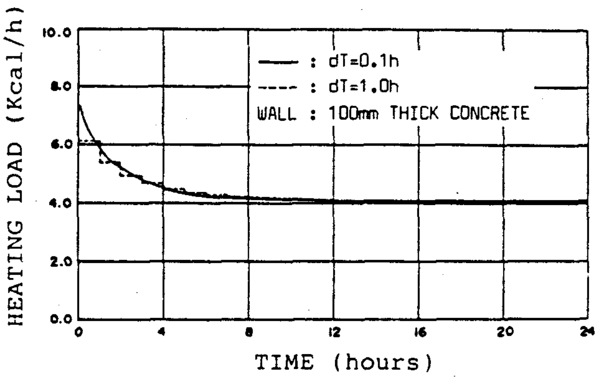


Fig.7(c) Influence of Time Division Error for Heating Load of Heat Storage Wall

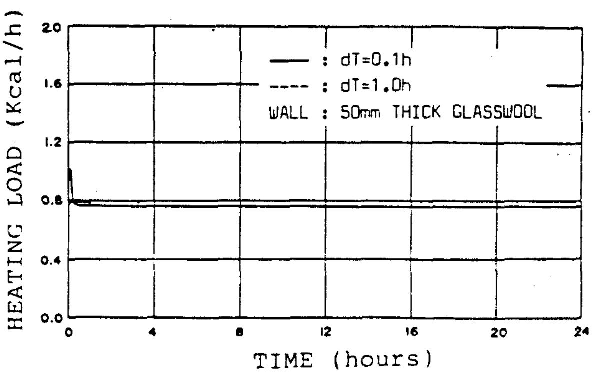


Fig.6(c) Influence of Time Division Error for Heating Load of Insulation Wall

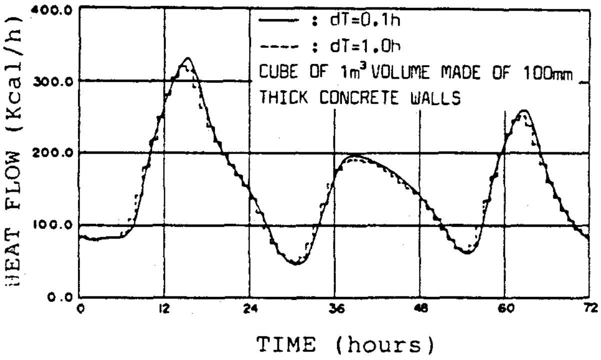


Fig.7(d) Responce of Through-the-Wall Heat Flow for Concrete Cube to Standard Weather Data

ANALYTICAL SIMULATION ON RESIDENTIAL BOX MODELS

Experimental results of simplified solar houses of single room with single passive solar system have been compared to the corresponding simulated results to validate the basic calculative performance of ESPAR/M

Analytical/Experimental Conditions

The residential box model have been constructed in Komono, Mie, Japan (Lat. 35.0N, Long.136.5E) to evaluate elementary thermal performance of passive solar systems[5].
A basic physical plan and structural specifications are shown in Fig.8(a). Experiments on the different types of the passive solar systems have been performed by constructively modifying or alternating the basic plan, with subsequent simulations under the same conditions to allow direct comparison with the experimental results. Case examples are listed below and the configurations of corresponding cases are shown in Fig.8.

Case(a):Basic Plan(reference):
The basic plan is basically a model of single room residential unit with well-insulated walls having relatively large south opening.

Case(b):Direct gain system with thermal storage floor:
The case is intended to evaluate thermal storage effect of sensible storage material placed on the floor to receive insolation from the south opening. The plan is the same as the basic plan except for the presence of 150mm thick concrete blocks place on the floor.

Case(c):Direct gain system with PCM latent heat storage floor:
The case is to evaluate thermal storage effect of latent heat storage material. The plan is the same as the Case(b) with replacing 25mm thick $CaCl_2.6H_2O$ phase change material filed in PBC casing instead of the concrete blocks.

Case(d):Indirect gain system (Trombe wall):
The case is to evaluate thermal effect of Trombe wall to adjacent residential space. Trombe wall is composed of 150mm thick concrete having a pair of vents with 100mm diameter at the upper and lower part of the wall respectively. Solar receiving surface is laminated with selective absorber film and covered by glass plate allowing 100mm distance between the glazing to the wall surface.

Input weather data for the simulation are sampled from the measured data on the days of 15th to 17th of February, 1982, and converted to the computer readable HASP

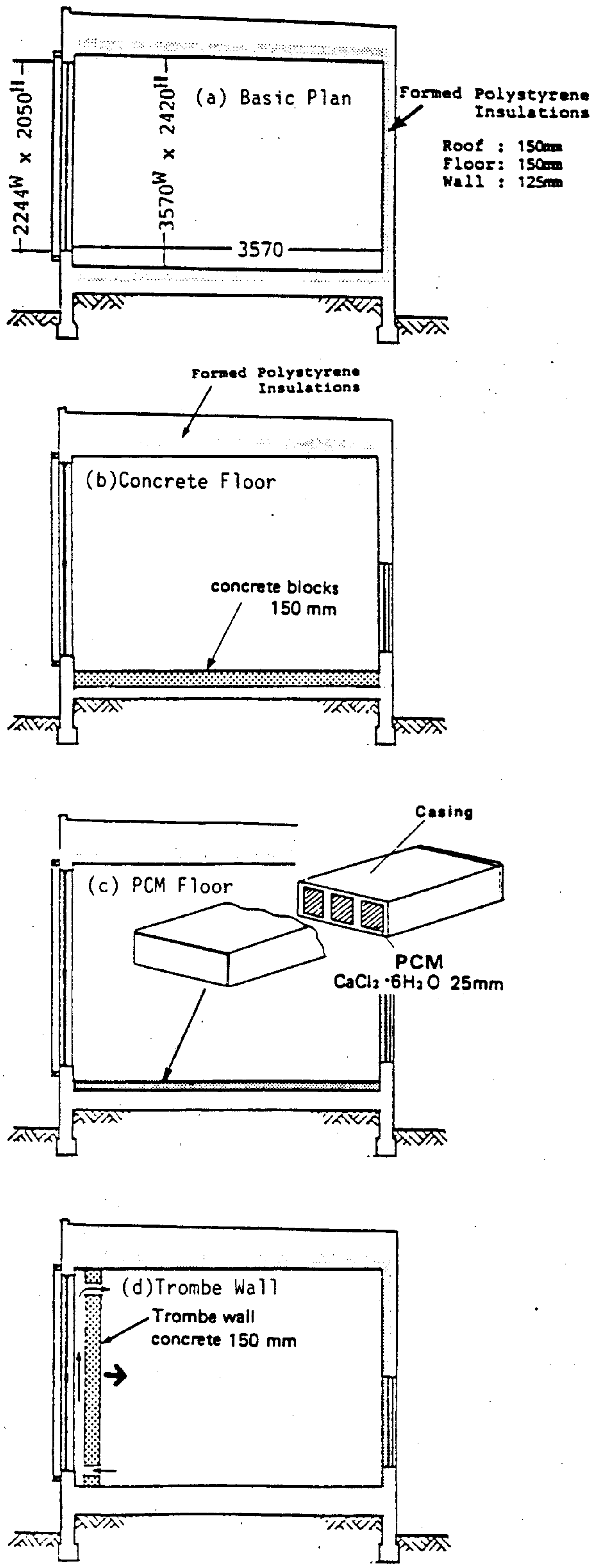


Fig.8 Plan of Residential Box Model

weather data format.

Analytical/Experimental Results

Analytical results on room temperature for above cases are shown respectively in Fig.9, with corresponding measured results. The uppermost graph shows the measured al horizontal insolations for the three consecutive days associated with the graphs (a) to (d) which correspond to the above four cases. A trend of the measured ambient air temperature is also shown in each graph.
Graph(a) in the figure shows a typical thermal characteristic for insulated south room, i.e. steep rise and fall of room temperatures associated with insolations. It is seen from the figure that the room temperatures decrease close to the ambient temperatures toward the end of the first day.
Graph(b) shows the case of concrete floored room. A rate of increase of the room temperature rise in day time is suppressed as compared to the previous case due to the thermal storage effect of the solar irradiated concrete floor. Thermal effect of the storage lasts for the first day toward the next day.
Graph(c) shows the thermal storage effect of PCM latent heat storage floor which exhibits slightly different characteristic as compared to the previous case. The room temperatures at the end of the first day are higher in this case, however, a rate of decrease of the room temperature thereafter is larger than the case of the concrete floor.
ph(d) shows the room temperature trend for the room with Trombe wall. A gradual change of the temperature due to the thermal storage wall can be seen.
It is seen from the figure that the room temperature trends shown in the each graph for three consecutive days of fine-cloudy-fine days characteristically reflect the difference between the systems, and the analytical calculations agree with the experimental results.
As a result, it can be concluded that the validity for the elemental heat transfer calculation algorithm and thermal models of each passive solar system in ESPAR/M is well established.

ANALYTICAL SIMULATION ON MULTI-ROOM RESIDENTIAL ENGINEERING MODEL

Several multi-room simulations have been carried out under the same conditions with measured results in the field experiment based on life-sized multi-room residential models [6],[7] to establish the validity of the calculation by ESPAR/M.

Analytical/Experimental Conditions

The resdidential engineering models M) have been constructed in Gotemba, Shizuoka, Japan (Lat. 35.3N, Long.138.9E) to evaluate composite thermal performances for the passive solar systems and living environment.
The present simulations are focused on the validation of the algorithms related to inter-room, through-the-wall/floor heat transfer and air flow processes. Fig.10 shows floor plan for 1st and 2nd floors of REM. As seen in the figure, REM consists of

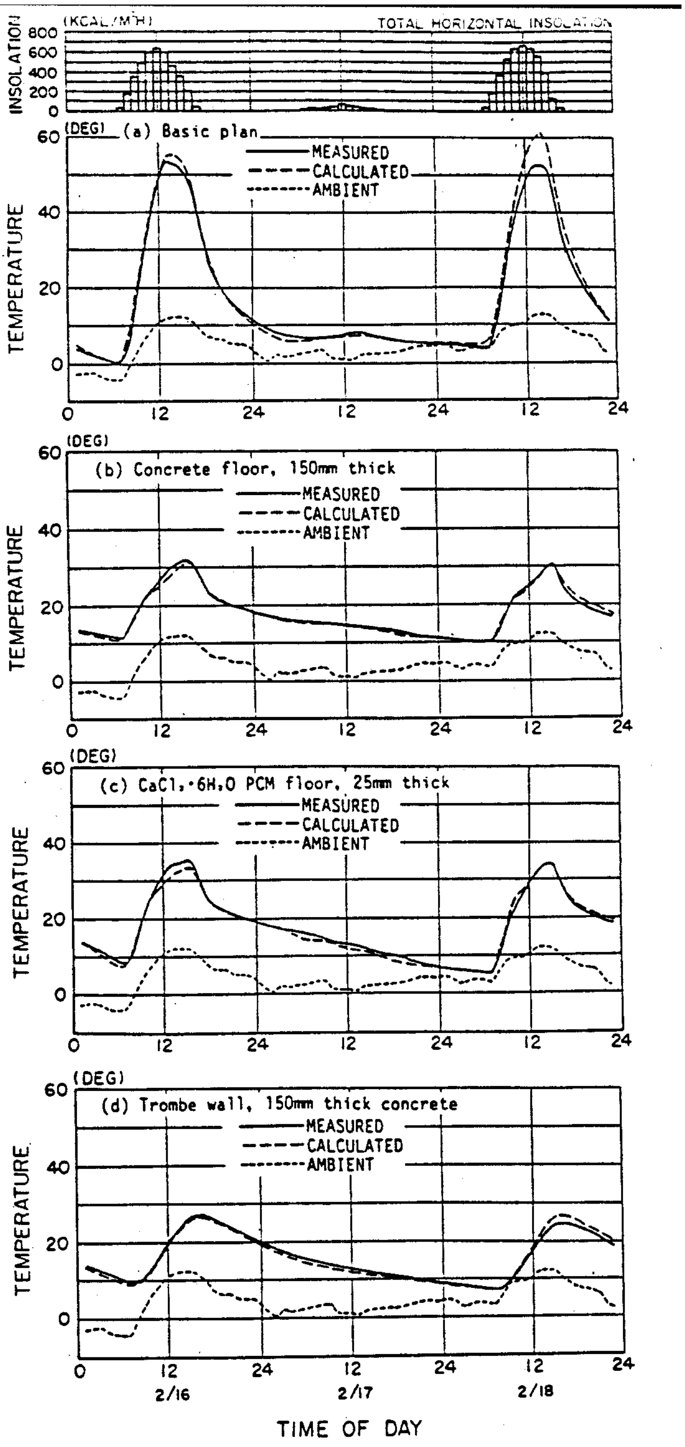


Fig.9 Measured and Calculated Room Temperatures of Residential Box Model

the east zone and the west zone which are thermally isolated mutually by intermediate center rooms and heavily insulated center wall with 200mm thick formed polystyrene insulator. The west and east walls facing outside are also heavily insulated with 200 mm thick insulator covering wall in order to eliminate the effect of insolations on the walls and to equalize thermal properties of the west and the east zones. Double glazing of 3mm thick glass with 6mm spacing are used for south and north openings with movable insulators.

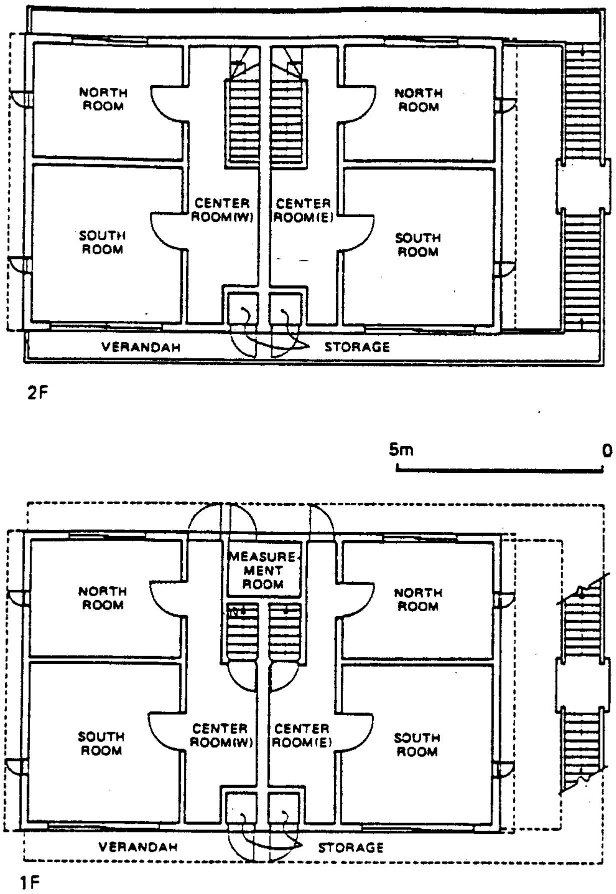
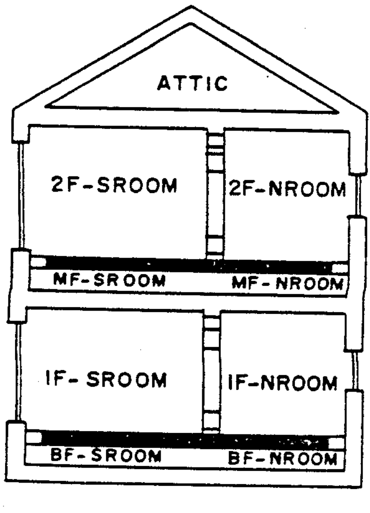


Fig.10 Floor Plan of Residentia Engineering Model



Formed Polystyrene Insulations
2F Ceiling:200mm
Outer wall:100mm
Partition :50mm

Heat Storage Floors
Concrete:65mm

Fig.11 Cross-sectional View of Reidential Engineering Model

Fig.11 shows cross-sectional view of REM and its elementary structural specifications used for the measurements and the subsequent simulations. The plan represents a basic configuration of REM which emphasizes the inter-room heat transfer. As can be seen in the figure, the unit has under-floor air flow channels which are also defined as room space in the input procedure of the simulation. As a result, 14 room spaces including the attic and the under-floor air flow channels are defined as the input data for the simulations.

Input weather data for the simulation are sampled from the data measured at the location on the days of 16th to 18th of February, 1984, and converted to the computer readable HASP weather data format.

Analytical/Experimental Results

Analytical results by ESPAR/M by room temperatures for south and north rooms of the first and the second floor are shown in Fig.12, with corresponding measured results by the field experiment. The uppermost graph in the figure represents the measured total horizontal insolations for the three consecutive days and middle and lower graphs show the analytical and experimental results of each floor respectively. The trend of the measured ambient temperature

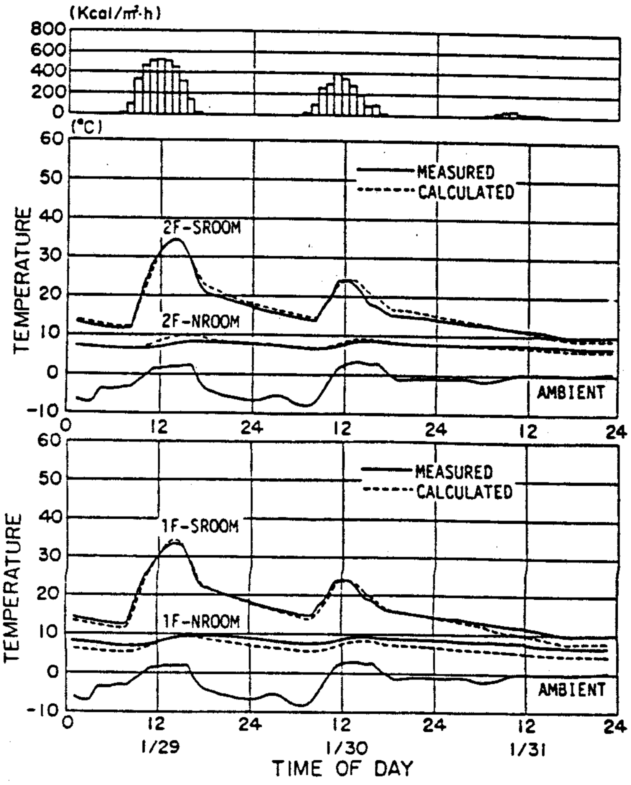


Fig.12 Room Temperature Trend of REM

is also shown in the figure.

It is seen in the figure that the south rooms exhibit relatively mild room climate due to the thermal storage effect of the concrete floors. The room temperatures in the south rooms maintain at 14°C to 15°C even in the dawn of the second day when the bient temperature becomes -8°C. The north ms, on the other hands, exhibit a steady cold room climate. It is seen in the figure that the comparison of the experimental result and corresponding calculative result generally agree to each other, which indicates that the inter-room heat transfer model of ESPAR/M is appropriately formulated.

DISCUSSIONS

The validity of the simulation program ESPAR/M is confirmed through the evaluation of the time and spacial differentiation errors and comparisons of calculated and measured room temperatures in multi-room passive solar house as well as the single room simplified experimental box models. In the study for evaluating the differential errors, it is found that the amounts of the errors are negligible for thermally insulated wall. For the thermal storage wall, errors related to spacial division could be neglected when the wall is divided in less than 30mm thick during the input data definition.

The time differentiation errors which are observed under the standard one hour time slice could not be neglected for the case of heat flow through the wall in its tial stage of transient process. ever, the cumulative influence under the real weather condition is smaller as compared to the idealized step variation of external weather parameters as shown in Fig.7(d) and the calculative errors in daily total heat flow are less than 1% for each day. This fact suggests that the calculated heating load for each hour may include some errors, especially at the transient period of the change of external sol-air temperatures. However, those errors compensate to each other during prolonged airconditioning period of time. Therefore, the differential error can be neglected unless the airconditioning is scheduled in short period of time, i.e. one to two hours.

The comparative simulations by ESPAR/M with experimental results showed reasonable agreement in this study. Further challenge of actual data measured in the other types of passive solar house will make the level of calculative reliability of ESPAR/M higher for thermal performance evaluation. Beside the above mentioned calculative errors, some means to avoid human errors which are possively caused during the data input stage should be considered. Computer assisted data entry and display system will be one of the solutions to avoid such human rors.

CONCLUSIONS

The simulation program, ESPAR/M for passive solar house has been validated through the comprehensive thermal performance analysis for various steps related to the mathematical formulation, submodel and output parameter levels including the comparison between the detailed field experimental data. In the thermal performance evaluation of the passive solar system installed in the actual houses, inter-system and/or inter-room heat transfer process play an essential role. The necessity of the simulation tool which can treat such behaviors has been widely recognized. The state-of-the-art program, ESPAR/M can be a promising candidate as such a development or constructive design tool for evaluating thermal performances of the passive solar house as well as the component passive solar systems at various conditions associated with location, weather, system and building specifications, operating conditions and living patterns.

ESPAR/M has been originally developed on IBM model 4331 and currently installed on several main-frame computers for the passive solar house simulations. It is also installable on 16bit microcomputer environment with 1MB memory and metal disc drive. It is hoped that the microcomputer based simulation stimulates the wider use of the program in the housing and constructive component industries for design optimization of their passive solar system installations.

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