

Multiphase model for thermal activity in a multistory residential home

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Abstract

This paper discusses the indoor climate in a full-scale three-story house using the MICS model, which is a multiphase model that is able to predict the velocity and temperature profiles in a 3D domain, as well as the interaction of temperature between air and different solid materials. The paper first compares the numerical results with existing experimental results done for similar multistory structures. Further more, numerical experiments are conducted with different heating methods: floor heaters and panel heaters, in order to find the optimum conditions required to heat the building efficiently. As a result, the suitable heating method is successfully suggested in the multistory building by the multiphase model.

Keywords: Indoor climate, multiphase model, CFD, multi-story house

Introduction

It is an important engineering subject to keep the comfortable indoor climate of multi-story houses located in cold districts with efficient heating system to save energy. For this purpose, many experimental investigations have been conducted within experimental rooms and in actual outside fields. On the other hand, the numerical studies to predict indoor climate have relatively few in particular for the actual multi-story houses due to the difficulty in dealing with the complicated-shaped and multiple materials of houses, which have different thermal conductivities.

Thus, the numerical predictions were carried out for a full-scale three-story house [1] with a multiphase model, MICS proposed by Ushijima [2]. The MICS model is useful to deal with thermal interactions between air and the solid materials having different thermal conductivities. As a result of computations, it was shown that the temperatures on the walls between the experiment and simulation are in good agreement in first and second floors. In addition, numerical experiments were conducted for the house with different heating elements: floor heaters and wall attached panel heaters. It was shown that the floor heaters provide a better heating in the house compared with the panel heaters.

Computational method

The governing equations of the multiphase model MICS model [2] are shown as follows:

$$\frac{\partial u_i}{\partial x_i} = 0 \quad (1)$$

$$\frac{\partial u_i}{\partial t} + \frac{\partial u_i u_j}{\partial x_j} = -\frac{1}{\rho} \frac{\partial p}{\partial x_i} + \frac{1}{\rho} \frac{\partial \tau_{ij}}{\partial x_j} + g_i \quad (2)$$

where τ_{ij} is given by Equation (4)

$$\tau_{ij} = \mu \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \quad (3)$$

$$\frac{\partial T}{\partial t} + \frac{\partial (T u_i)}{\partial x_i} = \frac{1}{\rho S_p} \frac{\partial}{\partial x_i} \left(\lambda \frac{\partial T}{\partial x_i} \right) + S_c \quad (4)$$

In the above equations, t is time, x_i is the orthogonal coordinate, S_c is the heat source term, g_i is acceleration due to gravity and u_i is the mass-averaged velocity between gas and solid phases defined by the following equation:

$$u_i = \frac{\sum_k \rho_k V_k U_{ki}}{\sum_k \rho_k V_k} \quad (5)$$

In Equations (2) to (4), temperature T , density ρ , specific heat S_p , Pressure p and viscosity coefficient μ are volume-averaged variables defined by

$$\Psi = \frac{\sum_k V_k \Psi_k}{\sum_k V_k} \quad (6)$$

In Equations (5) and (6), V_k represents volume of the phase- k . In this study, the non-isotropic characteristics for thermal conductivity λ are taken into account [3].

The governing equations are discretized with FVM. The numerical algorithm for solving the set of equations is divided into three separate stages: prediction stage, pressure calculation stage and correction stage. In the prediction stage, in which convection and diffusion equations are solved, the implicit method is used on a collocated grid system, which is called C-ISMAL method [4]. In the C-ISMAL method, tentative velocity u_i^* is calculated from Equation (2) as follows:

$$\frac{u_i^* - u_i^n}{\Delta t} = g_i - \frac{1}{\rho} \frac{\partial p^n}{\partial x_i} - \gamma_1 \frac{\partial}{\partial x_j} (u_i^* u_j^n) - (1 - \gamma_1) \frac{\partial}{\partial x_j} (u_i^n u_j^n) + \frac{\gamma_2}{\rho} \frac{\partial \tau_{1,ij}}{\partial x_j} + \frac{1 - \gamma_2}{\rho} \frac{\partial \tau_{2,ij}}{\partial x_j} \quad (7)$$

with

$$\tau_{1,ij} = \frac{\partial}{\partial x_j} (\mu u_i^*) + \frac{\partial}{\partial x_i} (\mu u_j^*) \quad (8)$$

and

$$\tau_{2,ij} = \frac{\partial}{\partial x_j} (\mu u_i^n) + \frac{\partial}{\partial x_i} (\mu u_j^n) \quad (9)$$

where $0 \leq \gamma_1, \gamma_2 \leq 1$. Fifth-order TVD scheme [5] is used to solve the convection terms included on the right hand side of Equation (7).

In the pressure calculation stage, C-HSMAC method [6] is used. It satisfies the incompressible conditions accurately.

The relationship between density and temperature is given by the following equation:

$$\rho = \frac{\rho_0}{1 + \beta(T - T_0)} \quad (10)$$

where β is the coefficient of thermal expansion, ρ_0 and T_0 are the reference density and temperature respectively.

In order to improve computational efficiency, the numerical procedures are parallelized using Message Passing Interface (MPI). Due to this parallelization, computational times are largely reduced in particular to solve the implicit equations as well as the pressure computation stage.

Application

The multiphase model was applied to the full-scale three-story house, for which experimental study had been conducted by Usami[1] in the Sendai prefecture in Japan. Figure 1 shows the house that was used for the experimental study.



Figure:1 Experimental house [1]

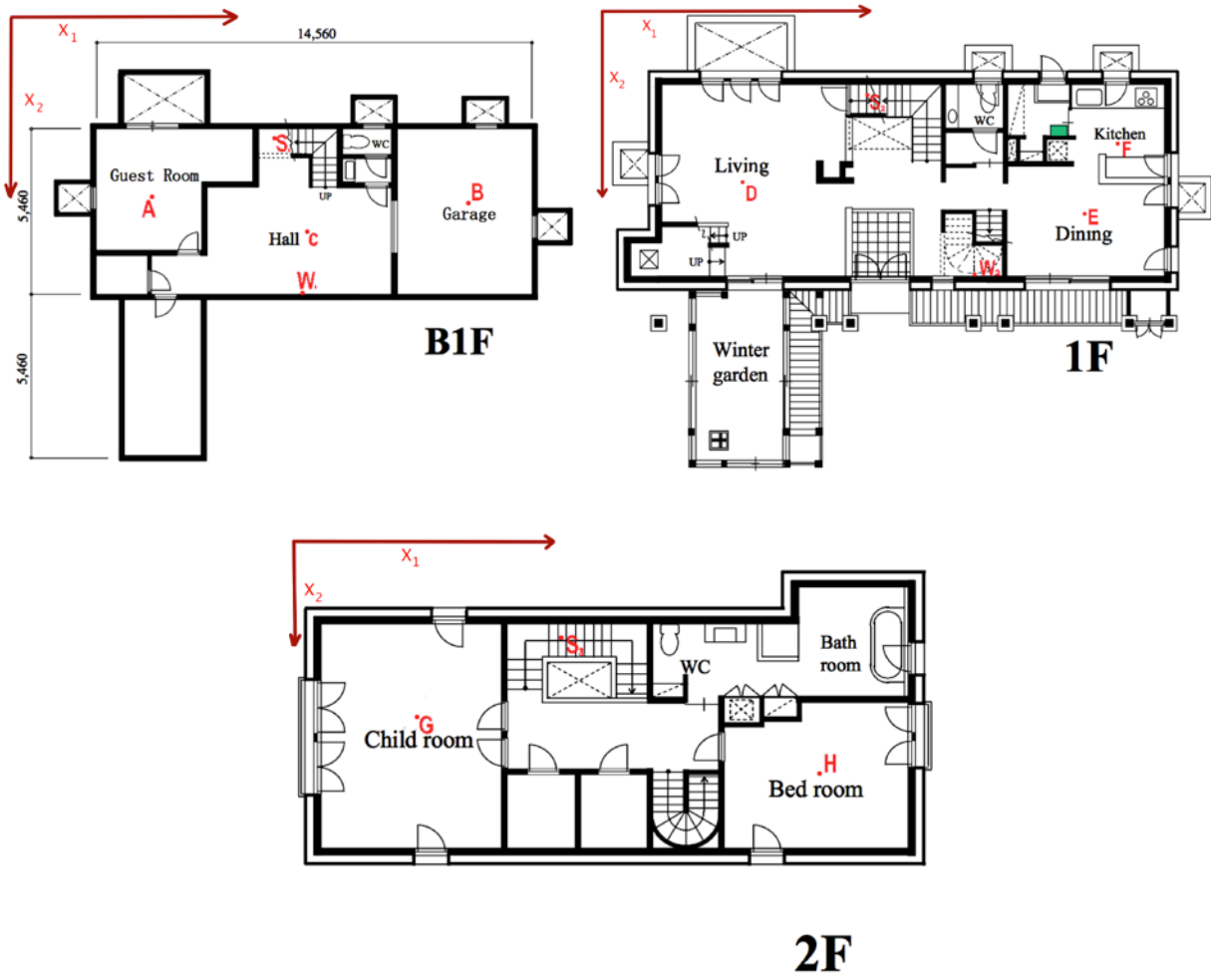


Figure: 2 Blue prints of the house with the locations of measured points [1]

Table 1: Locations of measuring points.

Location for measurement (x_1 [m] * x_2 [m])

A	2 x 2.3	G	2.4 x 2.5
B	12.9 x 2.6	H	11.9 x 3.5
C	7.3 x 3.5	S1	6.1 x 0.5
D	2.6 x 2.7	S2	6.1 x 0.5
E	11.9 x 2.7	S3	6.1 x 0.5
F	12.9 x 1.8	W1	7.3 x 5.5
		W2	8.9 x 5.5

The house used in the experiment is a three-story house complete with minimal furniture. Figure 2 shows the blueprints of each level as well as the measured locations of temperature. The exact locations are given in Table 1. The height of the measured locations is 1.5m above the floor level. The locations were chosen for the center point of major human activity.

In the experiments, the effect of the floor heaters was examined. The thermal conductivity for each material in the house is shown in Table 2. The heat supplied by the floor heater is 7.8 kW.

Table 2: Thermal conductivity for materials in the house

Materials	Thermal conductivity (W/(m.K))
1st floor walls	0.45
2nd floor	0.45
2nd floor walls	0.13
3rd floor walls	0.13
furniture	0.13
2nd floor windows	0.96
3rd floor windows	0.96

In the present numerical study, the solid materials of the house were represented by tetrahedron elements to respond to the complicated-shaped structures as shown in Figures 3 and 4.

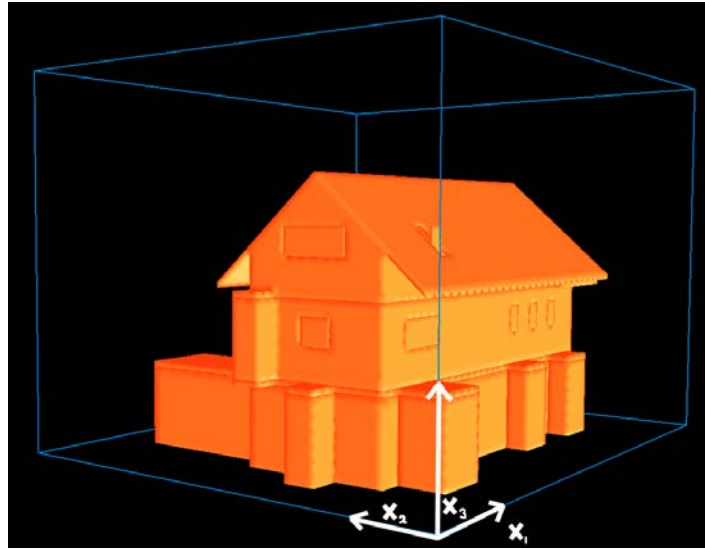


Figure 3: Visualization of the house in 3D and co-ordinate system

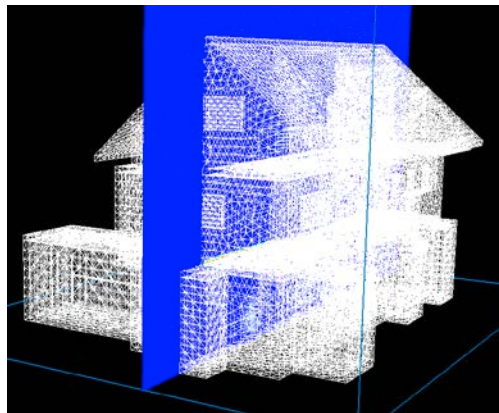


Figure 4: Tetrahedron mesh created for the solid parts of the house

The number of computational cells is $240 \times 240 \times 120$. The simulation required 26 hours of computational time for 10 actual hours. The computation used 128 processors. The simulations were run in Cray XE6 in Kyoto University.

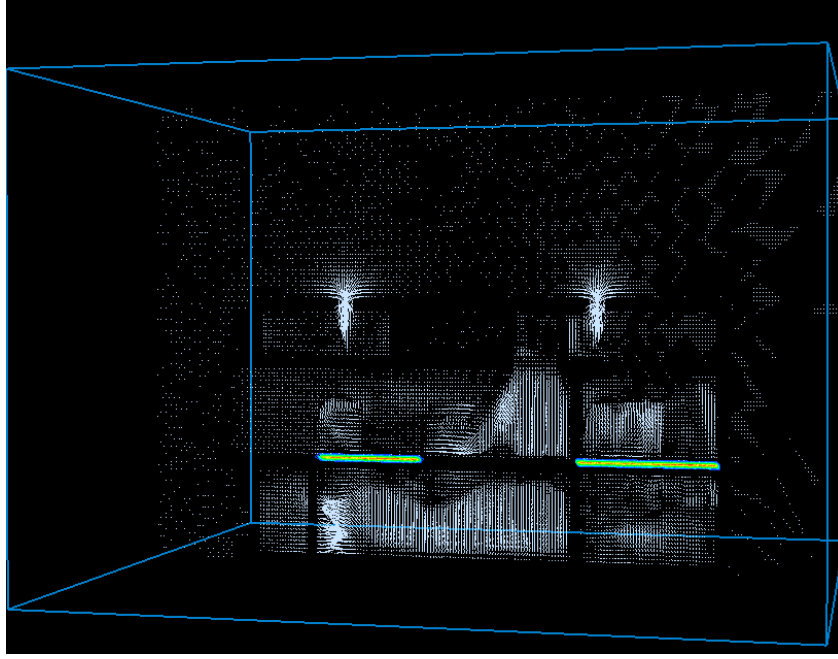


Figure 5: Cross section on $x_1 - x_3$ plane at $x_2 = 4.5$ [m]

Figure 5 shows the $x_1 - x_3$ plane view of the velocity profile inside the middle of the house. The green and yellow area indicates the location of the floor heaters. The outside boundary condition is set at 0°C with the no wind, while the adiabatic condition is used for the floor. As shown in Figure 5, the bottom left and bottom right rooms have little disturbance.

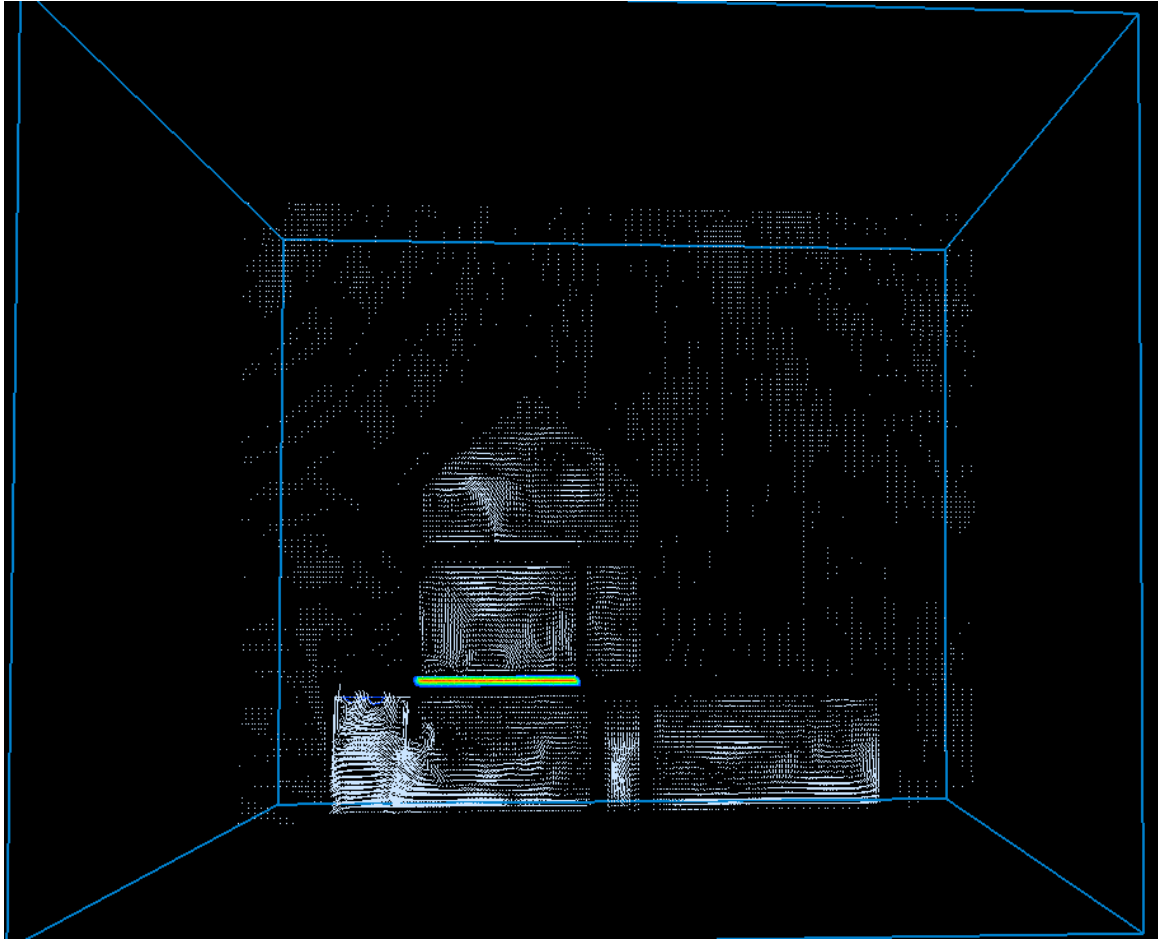


Figure 6: Cross section on $x_2 - x_3$ plane at $x_1 = 4.5$ [m]

The $x_2 - x_3$ plane view of the velocity profile is shown in Figure 6. It is noted that the location of the stairs that is on the right side of the Figure 6 plays an important role in drawing out air in the bottom floors, as shown in Figure 7. In Figure 7, the air flows upwards due to buoyancy effects, thus reducing the heat at the first floor.

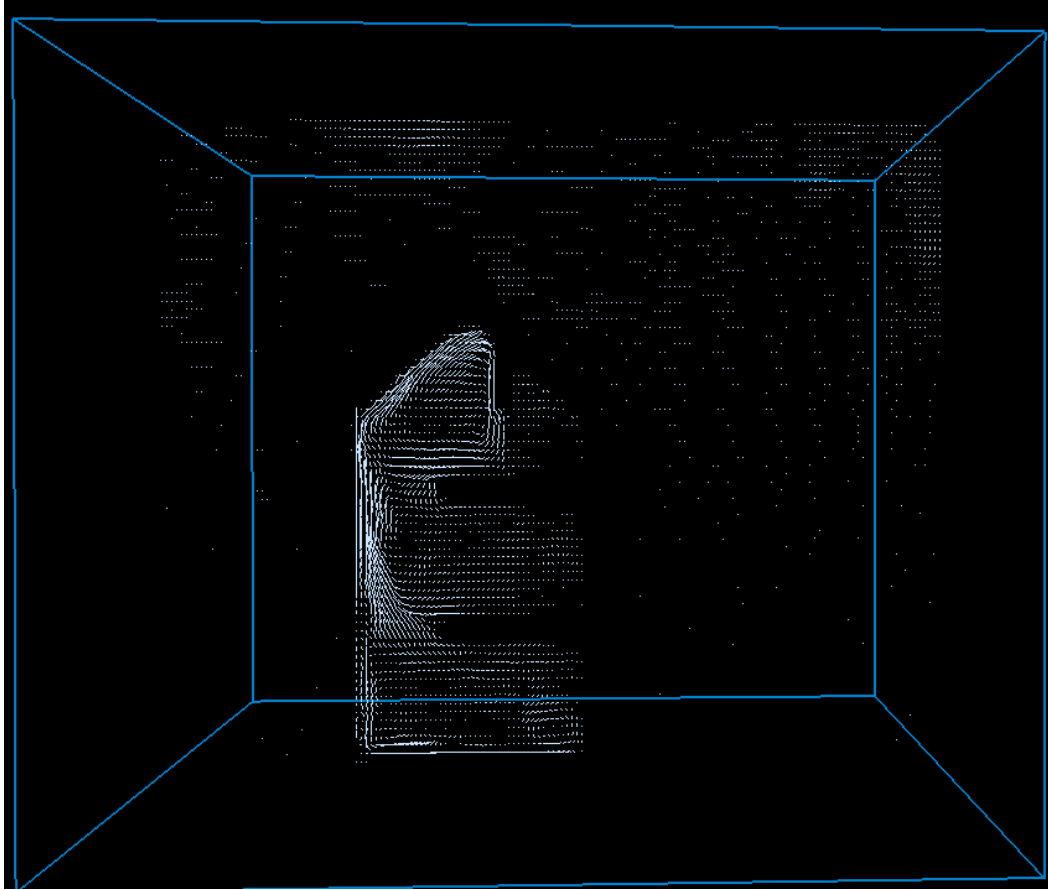


Figure 7: Velocity profile in the stairs on $x_2 - x_3$ plane
at $x_1 = 8.5$ [m]

Comparisons with experimental results

The calculated temperatures on the walls in first floor, W1, and second floor, W2, are shown in Figure 8. Compared with experimental results in Figure 8, it can be seen that they are in good agreement.

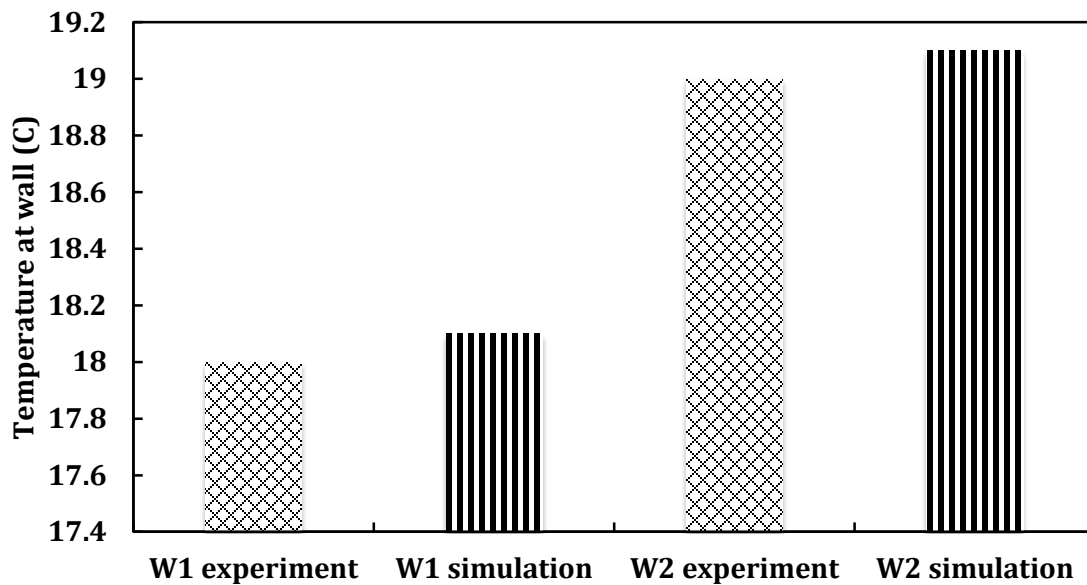


Figure 8 : Temperature at the walls in experiment and current simulation

Figure 9 shows the comparison of the temperatures at the measuring points, A, D and G, in the rooms shown in Figure 2. In general, the calculated results agree with the experimental data. The differences of temperature between the experimental data and the calculated results are less than 0.1 °C.

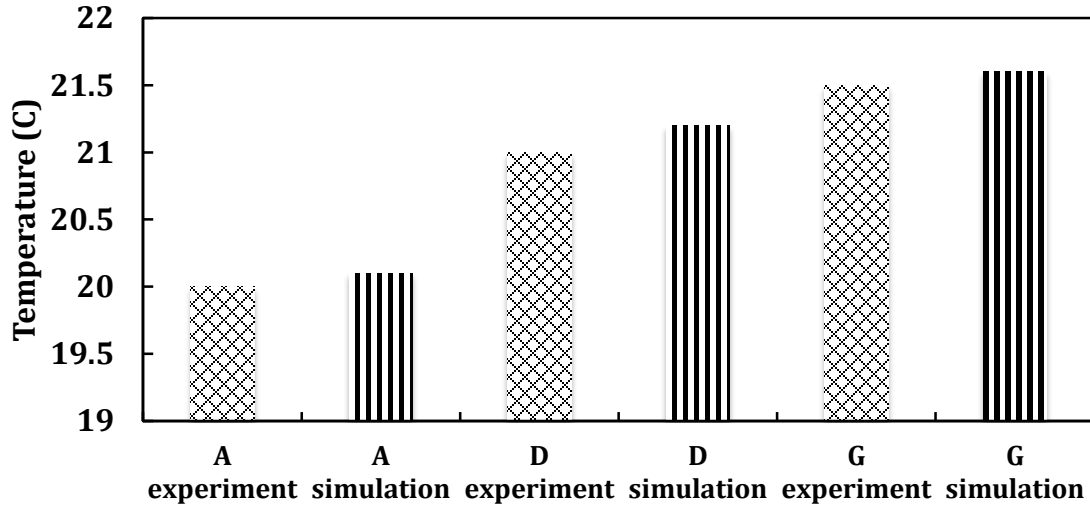


Figure 9: Temperature in the rooms in experiment and simulation

Numerical experiments

In addition to the comparisons with experimental results, numerical experiments were conducted to find the effective heating method. Using the same three-story house and boundary conditions, two heating methods were compared: floor heaters and heat panels with same heat source at 7.8 kW. The floor heater configuration is the same as the simulation above. The panel heaters were installed near the floor on the second floor walls of the house. Figure 10 shows the locations of three panel heaters, in blue, as well as the resulting velocity profile. Figure 11 shows the resulting temperature distributions in the house. The measured points are taken from the center of the room at 1.5m in height. The locations of points A to S3 are shown in Figure 2.

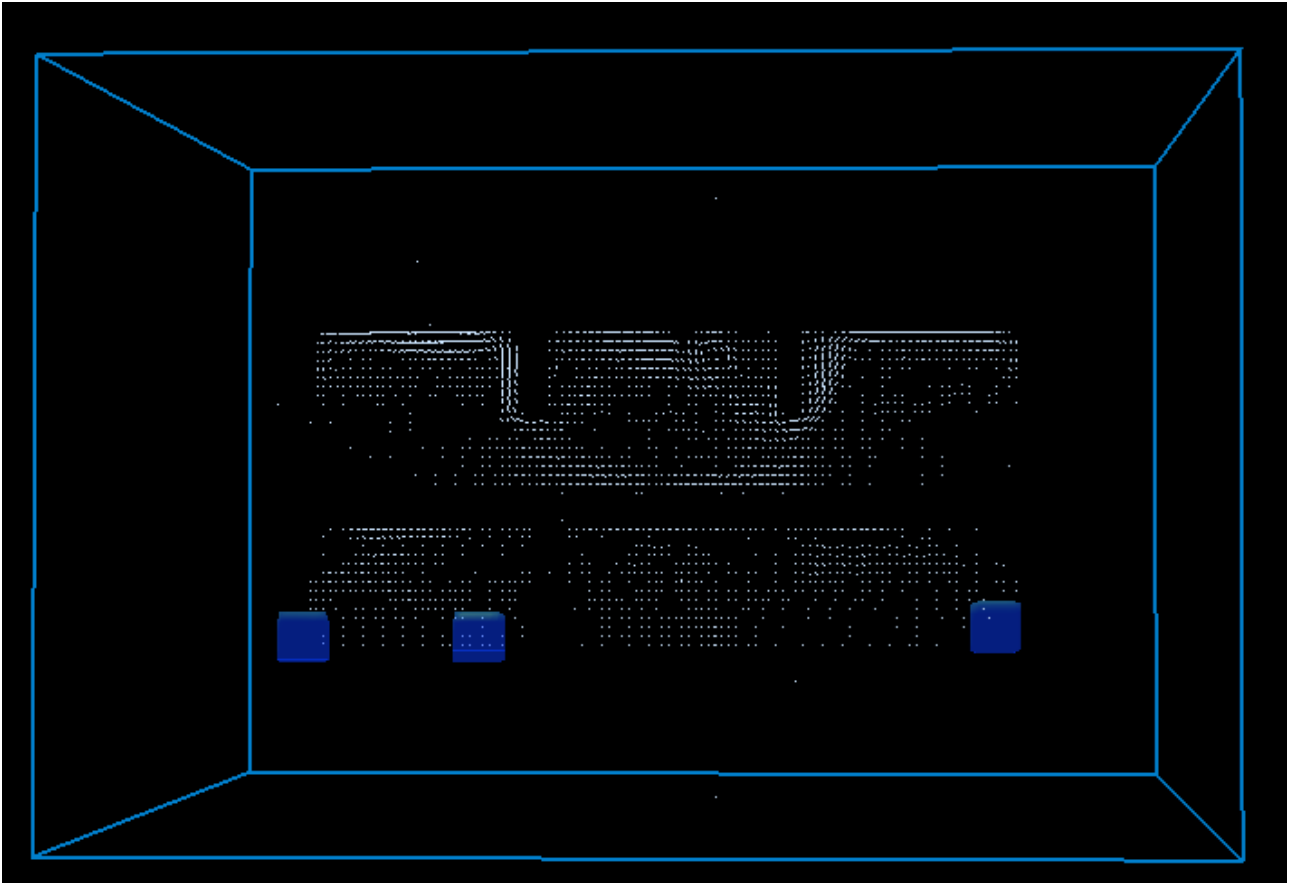


Figure 10: Cross section of the house on $x_1 - x_3$ plane at $x_2 = 5$ [m]

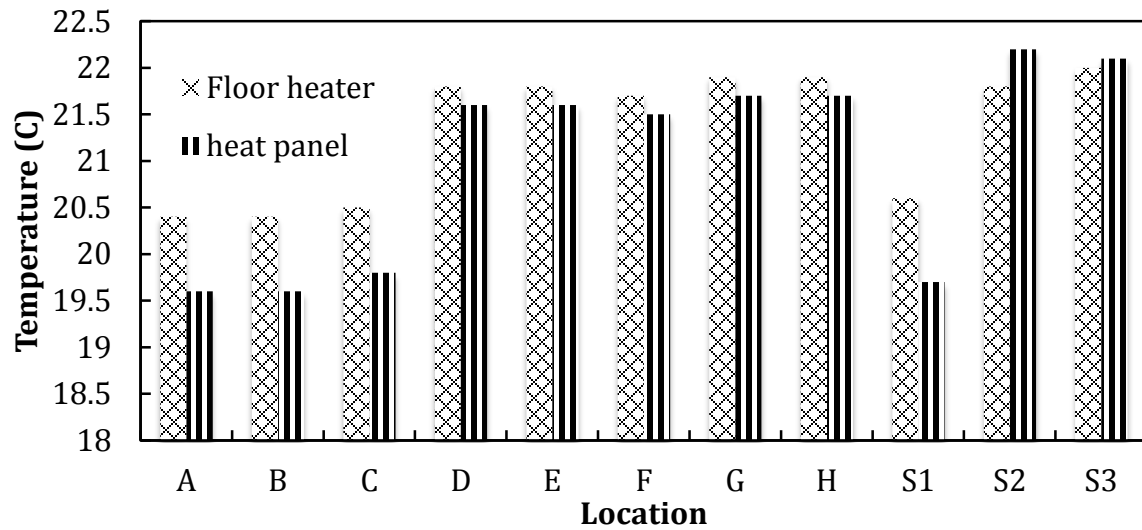


Figure 11: Temperature distribution in house comparing floor heater and heat panel

As shown in Figure 11, it is clear that the floor heater is able to increase temperature in all of rooms, A to H, except the stair regions, S2 and S3. The top two floors, locations D, E, F, G and H, have a less significant difference in the temperature at only less than 0.5 C different results.

Conclusively, it was suggested that the present multiphase model enables us to find optimum heating method with minimum energy. The computational method is a useful tool since the heating method can be easily changed compared with the full-scale experiments.

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