Development of Heat Recovery Radiant Heating System using Dynamic Insulation

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Abstract. From various studies, it is said that floor heating is a more hygienic and comfortable heating system than air-conditioning heating. However, floor radiant heating does not use all of the energy used for indoor heating, and some of it causes heat loss to the underfloor space. This research proposes a heat recovery type radiant heating system that can recover heat radiation under the floor by applying dynamic insulation to the underfloor space. The purpose of this study is to examine the heat recovery effect and the risk for condensation by using the actual measurement and CFD simulation of the experiment module. To achieve this goal, using 2 m × 5 m × 2.5 m experiment module measurement with and without dynamic insulation during the heating period, the heat load, ventilation rate, and thermal environment were measured. Previously, according to the results of model measurements on a 1/3 scale of the experiment module, when the temperature difference between indoors and outdoors was 20 °C, a dynamic insulated floor radiant heating system was used to reduce the heat load by 23.8%.
And, as the real-scale CFD simulation results, the heat load was reduced by up to 49% using the heat recovery radiant heating system. In order to confirm the risk of condensation during the cooling period, the relative humidity of the underfloor space was measured. When air is taken into the room from under the floor, there is a high possibility that condensation will occur during the cooling period. To reduce the risk of condensation, it is necessary to take air out of the room from under floor during the cooling period.

Keywords. Floor Heating, Dynamic Insulation, CFD simulation
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1. Introduction

From various studies, floor radiant heating is said to be a more hygienic and comfortable heating system than convection heating. When floor radiant heating is performed, the vertical temperature in the room is constant. Floor radiant heating produces less noise, draft, and dust than convection heating.1) However, floor radiant heating does not use all of the energy used for indoor heating, and some of it causes heat loss to the underfloor space. Shimizu2) reported that up to 47.9% of the heat from floor heating emits below the floor. The reason is that the floor surface is heated at a temperature higher than that of the outside air and the ground surface, so that heat is transferred under the floor. According to ASHRAE Standard 553), a floor temperature range of 19˚C to 29˚C is recommended range in the occupied zone for rooms with sedentary or standing occupants wearing normal shoes. In the japan standard, 25 ˚C to 29˚C is recommended range in the occupied zone for rooms. Therefore, when considering energy saving, it is necessary to reduce the heat loss to the floor.

This study is to propose a heat recovery type radiant heating system that can recover heat radiation under the floor by applying dynamic insulation4) to the underfloor space, and to measurement the heat recovery effect. This system recovers the heat that escapes from the ground and takes heat into the room to improve the insulation performance of the floor (Fig.1). Since the heat recovery system provides a ventilation path in the underfloor space, it is possible to secure a ventilation rate of 0.5 times/h or more as stipulated by Japanese law. At the same time, it recovers the heat loss that escapes to the ground and sends it indoors, so it can be expected as an efficient energy-saving system. It is also expected to be effective in preventing dew condensation in the underfloor space by changing the ventilation direction depending on the season. Therefore, in this study, the heat recovery effect of the heat recovery type radiant heating system will be quantitatively examined by measurement and CFD simulation.

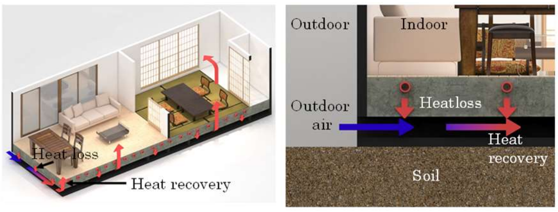
2. Examination of heat recovery effect by model measurement

2.1 Measurement methods

In order to examine the heat loss reduction effect of the proposed heat recovery system, we will actually measure the model. The model is a conventional dirt floor heating system model (Fig. 2 (a)). Heat recovery is a model that introduces outside air by providing a ventilation layer in the space under the dirt floor. (Fig. 2 (b)). The model is shown in Fig.3. The dimensions of the model are 910 x 910 mm for the concrete floor. The indoor space is 910 x 910 x 800 mm for the soil floor model and 1,000 x 910 x 800 mm for the heat recovery floor model. The wall of the model is 100 mm styrofoam. The dirt floor is a 100 mm concrete block, and the heat recovery model is provided with a ventilation layer of 30 mm. Ventilation uses a small sirocco fan and a variable resistance of 15.7 m^3/h. However, with a ventilation volume of 0.24 m^3/h, it is difficult to maintain a uniform flow velocity in the ventilation layer. Therefore, it is uniform in the ventilation layer. A large air volume is given to confirm the flow velocity. For heating, a PTC (positive temperature coefficient) heat ray is embedded between two aluminum plates in a sandwich manner and installed on the concrete in order to uniformly apply heat to the model. The output of the PTC heat ray is 20 W/m. A maximum of 600 W of heat can be applied by using 30 m per model. A thermostat (temperature controller) is installed at the indoor ventilation and exhaust port to keep the temperature inside the model constant. On-off control is performed at the set temperature of 20.0 °C (± 0.1 °C). In addition, in order to clarify the heat recovery effect of the proposed system, the change in underground temperature and the amount of energy used for PTC are measured in the actual measurement of this model. Table.1 shows the actual measurement conditions.

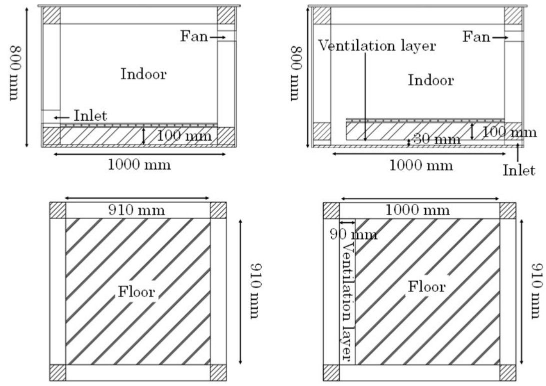
2.2 Measurement Result

Figure 4 shows the cumulative values of the internal temperature, outside temperature, and power consumption of the model. The room temperature of the Dirt floor model could be maintained from 19.0 °C to 20.3 °C. The room temperature of the Heat recovery model fluctuated from 20.8 °C to 21.0 °C, both of which were found to be stable near 20 °C. During the actual measurement period, the power consumption of the PTC heat ray was 122 kWh for the Dirt floor model and 65 kWh for the Heat recovery model. The Heat recovery model reduces power consumption by 42% compared to the Dirt floor model. From this actual measurement, it was found that the heating load can be reduced by applying this system. However, in this measurement, the ventilation volume is large, so it cannot be said that the heat recovery effect is accurate. Therefore, the heat recovery effect of this system will be quantitatively examined using CFD simulation.



(a) Concept (b) Detail view

Fig.1 - Heat recovery radiation system



(a) Dirt floor model (b) Heat recovery model

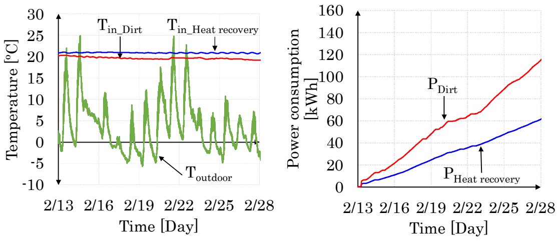
Fig.2 - Model sectional view

(a) Model in production (b) measurement model

Fig.3 - Model photo

Tab.1 - measurement conditions

Item	contents
Period	2020.02.13~02.28 (16 Day)
Model scale	Heat recovery: 1.00 (x) × 0.91 (y) × 0.8 (z) [m] Dirt floor: 0.91 (x) × 0.91 (y) × 0.8 (z) [m]
Model indoor temperature	20.0 °C (±0.1 °C), On-off control
Heating capability	600 W
Measurement location	4-17-1 Wakasato, Nagano City, Nagano, Japan
Ventilation rate	15.7 [m3/h]



(a) T_{in} and T_{out} (b) P_{Dirt} and $P_{Heat\ recovery}$

Fig.4 - Measurement result

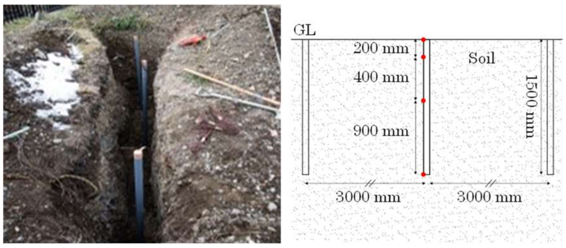
3. Examination of consistency of CFD simulation model

3.1 Simulation methods

To quantify the energy saving effect of this system, it is necessary to clarify the heat loss toward the ground. The underground temperature distribution constantly changes depending on the solar radiation, wind speed, temperature, and the presence or absence of a building. Therefore, in this study, we will create an underground CFD simulation model and compare it with the measurement in time series to examine the consistency. The temperature distribution in the ground is measured by the method shown in Fig.5. Figure 6 (a) shows the outline of the simulation model. The simulation area is 4.0 (x) x 4.0 (y) x 3.0 (z) m, and the soil part is 4.0 (x) x 4.0 (y) x 1.5 (z) m. A model with an atmospheric region of 4.0 (x) x 4.0 (y) x 1.5 (z) m was assumed. For the external wind speed, the speed change in the height direction of the model is taken into consideration by using the wind speed profile by Hargreaves et al.$^{5)}$. The wind speed data is from Nagano Meteorological Observatory, every 10 minutes on March 17, 2021 (Fig. 7 (b)). The standard height in the wind speed profile is 19.0 m for the anemometer of the Nagano Meteorological Agency. Shows the wind speed profile used in Fig. 6 (b). The total amount of solar radiation obtained by actual measurement is used for the simulation (Fig. 7 (a)). Therefore, the total amount of solar radiation is separated into direct solar radiation and scattered solar radiation. For direct insolation, the direct insolation method by Udagawa et al.$^{6)}$ is used in consideration of the convenience of being able to estimate the amount of direct and scattered insolation only from the horizontal total amount of solar radiation.

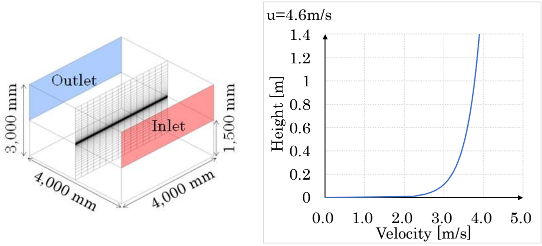
3.2 Simulation result

Figure 8 shows a comparison between the measured values of the underground temperature and the simulation results. On the ground surface (0 mm) affected by convection, the simulation value was higher than the measured value after 18:00, and the result was about 3 °C higher at 0 o'clock. It is considered that this is because the wind speed higher than the data of the AMeDAS was generated due to the influence of obstacles (trees, buildings, etc.) around the measured site, or the uneven state of the ground surface caused the turbulence of the air flow and increased the convection transmission rate. On the other hand, at depths of 200 mm and 600 mm other than the ground surface, the measured and analyzed values were similar, so it is considered that the consistency of the CFD simulation model was ensured. Table.2 shows the simulation conditions. In order to analyze the heat transfer coefficient near the ground with high accuracy, the Abe-Kondo-Nagano low Reynolds k-ε model is applied as the turbulence model in this simulation.



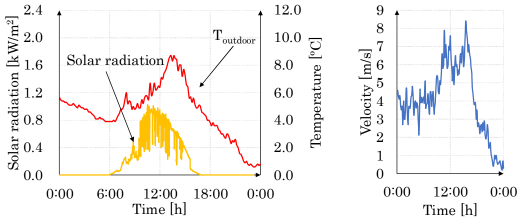
(a) Picture (b) Detail view

Fig.5 - Measurement summary



(a) Mesh (b) Wind profile

Fig.6 - Simulation summary



(a) Solar radiation and temperature (b) Wind velocity

Fig.7 - Observed values

Tab.2 - Simulation condition

Item	contents
Number of mesh	100,000 ea
Simulation area	Soil: 4.0 (x)×4.0 (y)×1.5 (z) [m] Air: 4.0 (x)×4.0 (y)×1.5 (z) [m]
Turbulent model	Abe-Kondo-Nagano low Re number k-ε model
Radiation model	Surface to surface
Temperature conditions	Observed values , Fig. 7
Wind velocity and direction	AMeDAS (automated meteorological data acquiaition system, Japan), Fig. 7
Solar radiation	Observed values , Fig. 7
Physical property (Soil)	Density : 1,350 [kg/m³] Specific heat : 500 [J/(kg·K)]

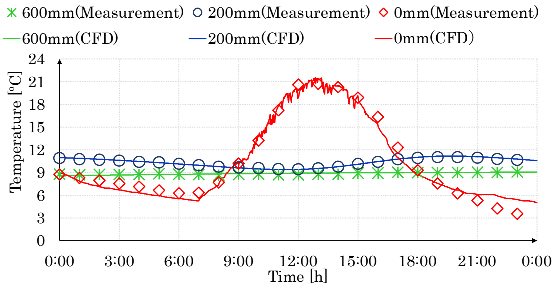


Fig.8 - Simulation result

4. Examination of heat recovery effect on a full-scale scale by CFD simulation

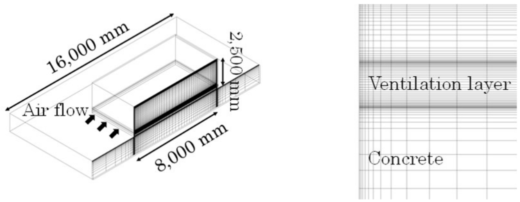
4.1 Simulation methods

A full-scale heat and air transfer simulation is performed using a CFD simulation model to evaluate the heat recovery effect of the proposed system. Figure 9 shows the simulation model. The interior space will be 8.0 (x) x 8.0 (y) x 2.5 (z) m by simplifying the one-story house. Figure 10 shows a cross-sectional view of the study case. (a) In the Dirt floor, the concrete floor is 180 mm, the insulation is 30 mm, and the foundation height is 210 mm. (b) Heat recovery (Dirt floor) is a case where a heat recovery type system is applied to the soil. A 65 mm ventilation layer is provided between the concrete soil and the heat insulating material to introduce the outside air from the outside to the room. In addition, a heat reduction sheet is attached to the concrete surface in contact with the ventilation layer in order to reduce the radiant heat generated from the concrete. (c) The double floor consists of concrete 150 mm, heat insulation 30 mm, air layer 65 mm, mortar 70 mm, particle board 20 mm, and foundation height 335 mm. (d) Heat recovery (Double floor) is a structure that introduces outside air into the room by using an air supply port in the air layer of the buried double floor.

Table.3 show the CFD conditions and the physical property values of the materials. A 24-hour unsteady calculation is performed to take into account changes in the heating load due to the heat storage effect of concrete and soil. In order to simplify the calculation, the simulation is performed assuming that the heating method is floor heating by directly applying 100 W/m^2 to concrete and mortar. In addition, in this calculation, except for the solar radiation calculation of the indoor space, the temperature change of the soil gave the measured temperature to the ground. The emissivity is 0.1 on the surface to which the heat reduction sheet is attached. Where it is not attached is set to 0.8.

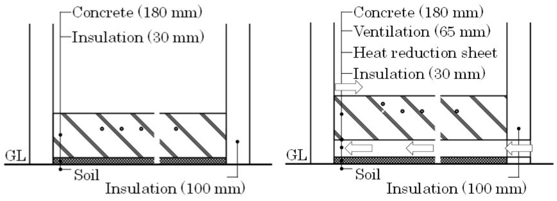
4.1 Simulation result

Figure 11 shows the simulation results. The amount of energy required to maintain the room at 20 °C is 242 MJ for the dirt floor, 184.2 MJ for the heat recovery floor (dirt), 192.1 MJ for the buried double floor, and 151.9 MJ for the heat recovery floor (double). The heat loss that escaped under the floor was 54.7 MJ for the dirt floor, 19.3 MJ for the heat recovery floor (dirt), 2.9 MJ for the buried double floor, and -4.7 MJ for the heat recovery type floor (double floor). Figure 12 shows the heat balance of each case. (a) Of the 242 MJ on the dirt floor, 54.7 MJ was transferred into the ground, 112.8 MJ was transferred indoors, and 3.6 MJ was transferred to the outside, and 70.7 MJ was stored in the soil. (b) In

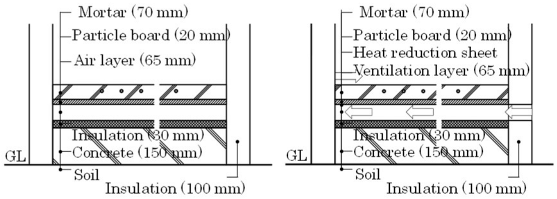


(a) Calculation model (b) Meshes

Fig.9 - Calculation model and meshes



(a) Dirt floor (b) Heat recovery (Drit)

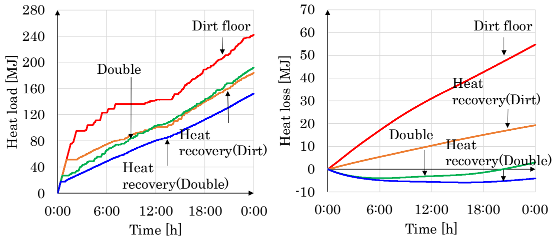


(c) Double floor (d) Heat recovery (Double)

Fig.10 - Simulation model

Tab.3 - Simulation condition

Item	contents
Number of mesh	1,100,000 ea
Simulation area	Soil: 16.0(x) × 16.0(y) × 1.5(z) m Indoor: 8.0(x) × 8.0(y) × 2.5(z) m
Turbulent model	Abe-Kondo-Nagano low Re number k-ε model
Radiation model	Surface to surface
Scheme	SIMPLE
Indoor temperature	20 °C
Heating capacity	100 W/m^2
Simulation time	24 h
Ventilation rate	80 m^3/h
Physical property (Air)	Density: 1.20 kg/m^3 (20 °C, Boussinesq approximation)
Physical property (Thermal conductivity)	Concrete: 1.6 W/(m·K) Insulation: 0.04 W/(m·K) Particle board: 0.12 W/(m·K) Mortar: 1.5 W/(m·K)
Physical property (Emissivity)	Heat reduction sheet: 0.1 Without heat reduction sheet: 0.8



(a) Heat load (b) Heat loss

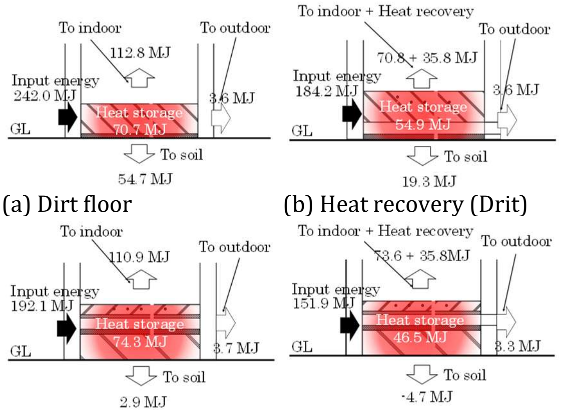
Fig.11 - Simulation result (Cumulative value)

the heat recovery floor (dirt), of the energy of 184.2 MJ, 19.3 MJ in the ground, 70.8 MJ indoors, 35.8 MJ heat recovery, 3.6 MJ energy moves to the outside, and 54.9 MJ stores heat in the soil. Heat recovery is the energy recovered by this system and goes indoors. By applying this system, it was possible to reduce the heat escaping to the ground by 64% and the amount of energy by 23.8% on the dirt floor. (c) In the buried double floor, energy of 2.9 MJ in the ground, 110.9 MJ indoors, and 3.7 MJ outside was transferred in 192.1 MJ, and 74.3 MJ was stored. (d) In the heat recovery floor (double floor), out of 151.9 MJ of energy, -4.7 MJ in the ground, 73.6 MJ in the room, 35.8 MJ in heat recovery, 3.3 MJ of energy moves to the outside, and 46.5 MJ. The heat was stored. By applying this system, the amount of energy in the buried double floor was reduced by 20.9%. In the (c) and (d), there is foundation concrete under the floor, and it is considered that the heat loss is small because the foundation concrete stores heat toward the underfloor. In particular, (d) recovers the heat stored in the foundation concrete indoors by this system, so the temperature of the foundation becomes lower than the temperature of the ground, and the heat that takes heat from the ground and escapes to the ground. Shows a negative value.

5. Examination of heat recovery effect on a full-scale scale by CFD simulation

5.1 Simulation method

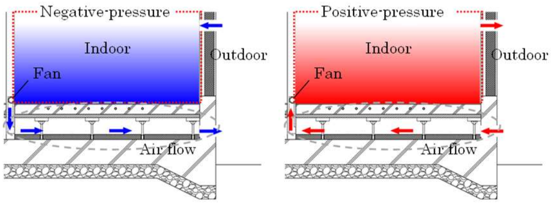
This system can reduce heat loss in winter. On the other hand, there is a high risk of dew condensation in the underfloor space in summer. In summer, the hot and humid outside air is taken into the room from under the floor, so the underfloor surface cooled by cooling contact with the outside air, causing reverse dew condensation. In this study, we propose an operation system that changes the ventilation direction depending on the season (Fig.13). In this chapter, the presence or absence of dew condensation under the floor depending on the ventilation direction will be examined by CFD simulation. The simulation model targets the interior space of a detached house-shaped living room proposed by the Building Environment and Energy Conservation Organization (IBEC). The outline of the model is shown in Fig.15. A variable fan for introducing and discharging air into the room is placed in the center with a size of 200 x 120 mm. The structure and physical properties of the underfloor space are shown in Fig. 15 and Table.4. The case is for taking in air, and the room temperature is 26 °C (case 1-1), 24 °C (case 1-2), and the humidity is 60%. When taking out indoor air, the room temperature is 26 °C (case 2) and the humidity is 60%. The data for the weather on August 11, 2020 (sunny) in Tokyo (Fig. 16) will be used for the simulation. The ventilation volume shall be 29.06 m^3/h, which is 0.5 times ventilation of the target space. The simulation interval is calculated every 10 minutes for 24 hours.



(a) Dirt floor (b) Heat recovery (Drit)

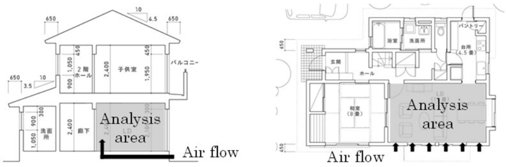
(c) Double floor (d) Heat recovery (Double)

Fig.12 - Energy balance



(a) In winter (b) In summer

Fig.13 - Variable ventilation system

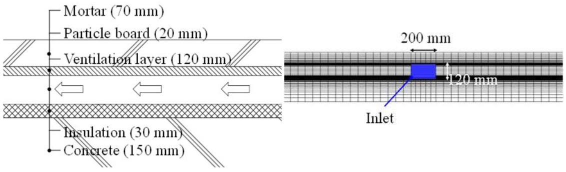


(a) Cross view (b) Plan view

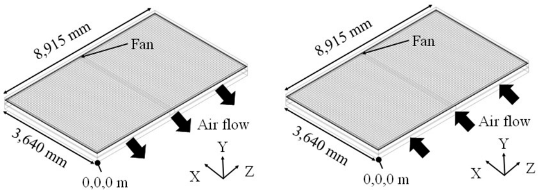
Fig.14 - Simulation area

Tab.4 - Simulation condition

Item	contents
Number of mesh	500,000 ea
Simulation area	3.640(x) × 8.915(y) × 0.330(z) m
Radiation model	Surface to surface
Simulation time	24 h
physical property (Thermal conductivity)	Concrete：1.60 [W/(m·K)] Insulation：0.04 [W/(m·K)] Particle board：0.12 [W/(m·K)] Mortar：1.50 [W/(m·K)]



(a) Detail veiw (b) Meshes



(c) Case 1-1,2 (d) Case 2

Fig.15 - Simulation model

5.2 Simulation result

Fig. 17 shows the maximum and average relative humidity of the floor surface at 24:00, and (c) shows the humidity contour of the floor surface at 12 o'clock. In Case 1-1, the relative humidity exceeded 90% for 24 hours, and in Case 1-2, dew condensation occurred for 24 hours. In Case 2, the relative humidity of 60% was maintained and the occurrence of dew condensation could be suppressed.

6. Conclusions

In this research, we propose a heat recovery type radiant heating system that uses ventilation driving force to recover heat loss generated in the ground by utilizing the underfloor space of floor heating as a ventilation path and examine it by model measurement and CFD simulation. The following findings were obtained from the examination results.

(1) Heat Recovery Radiant Heating System using a model, we examined the power consumption of electric floor heating by this system. The Dirt floor model generated 122 kWh in 2 weeks, and the Heat recovery model consumed 65 kWh, which was a 42% reduction in power consumption compared to the Dirt floor mode.

(2) In the CFD simulation on a full-scale scale, the input energy for maintaining the room at 20 °C for 24 hours is 242 MJ for the dirt floor, 184.2 MJ for the heat recovery floor (dirt floor), 192.1 MJ for the buried double floor, and heat recovery floor (double floor) generated 151.9 MJ, and by applying this system, it was possible to reduce energy by 23.8% in the full-scale model of dirt floor and 20.9% in the buried double floor model. This clearly confirmed the heat recovery effect of this system.

(3) The structure of this system was embodied, and the reverse dew condensation in the summer was examined by CFD simulation. When the outside air was taken into the room on a representative day of summer, when the room was cooled at a room temperature of 26 °C, dew condensation occurred 6 times in 24 hours, and the relative humidity was maintained at 90% or higher throughout the day. Then, when the cooling temperature was set to 24 °C. under the same conditions, almost dew condensation occurred. On the other hand, when the air in the room was taken out, the underfloor space was the same environment as the room because no backflow occurred, and there was no risk of dew condensation.

(4) In the future, we will study the heat insulation performance and heat recovery effect of this system by measuring it on a full-scale scale by designing it for actual housing and using the experimental building. We also plan to study the energy-saving effect of applying this optimized system to actual houses.

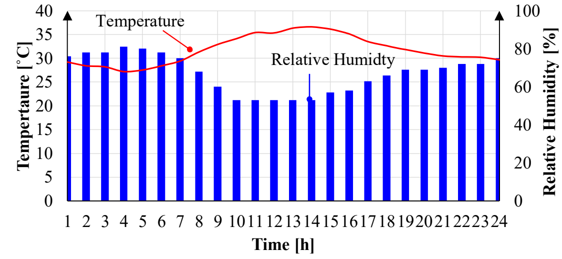
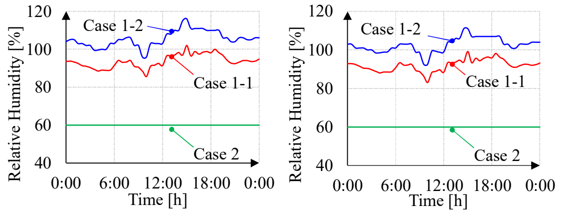
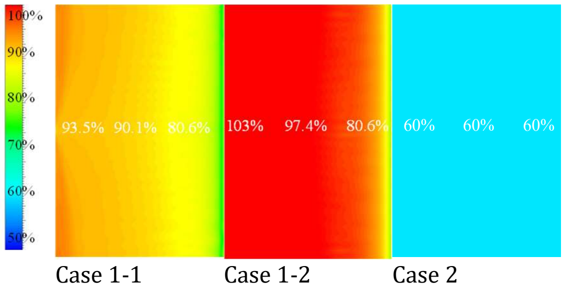


Fig.16 - Outdoor air conditions



(a) In 24h max RH (b) In 24h average RH



(c) At 12:00 RH contour

Fig.17 - Simulation result

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