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A STUDY ON THE THERMAL RESPONSE CHARACTERISTICS OF THE FLOOR OF HYDRONIC FLOOR HEATING SYSTEMS

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ABSTRACT

Many studies have been performed on floor heating systems. However, there is almost no data on the response characteristics immediately after the start of the operation. In Japan, floor heating systems are often intermittently operated, so these response characteristics are important. In this research, the heat transmission response, the heat absorption response, and other response characteristics are simulated just after the start of the operation using a two-dimensional heat conduction calculation. This calculation was performed using the finite element method. Moreover, the characteristics of the two-dimensional floor model were compared with the commonly used one-dimensional floor model.

INTRODUCTION

Hydronic floor heating systems have been widely adopted in Japan, and many are operated only intermittently. Hydronic floor heating systems, whose pipe is embedded in concrete floor, have a great thermal storage capacity. So when the floor heating systems are intermittently operated, the thermal response of the floor is considerably delayed just after the start of the operation. In simulation of space thermal comfort and energy consumption for buildings with intermittent operation of hydronic floor heating systems, the heat transfer rate from the floor to the space has been calculated using fin efficiency that was first proposed by Kollmar and Liese (1967) for steady state calculation and was extended to use for unsteady state calculation by Udagawa (1986) and by Inoue et al. (1995). Although the heat transfer rate around the floor can be easily obtained with one-dimensional floor model using this fin efficiency, the delay of the calculated thermal response of the floor was found to be too short from the comparison with the results of two-dimensional calculation.

Improved calculation methods of steady state heat transfer of the floor using fin efficiency were studied by Kilkis (1995) and by Ishino (1998). The steady state heat transfer rate from the floor to the space can be well estimated. It is necessary to develop a simplified one-dimensional floor model that is applicable to intermittent operation of floor heating systems, because the two-dimensional floor model is not fit to link space thermal comfort and energy simulation models based on one-dimensional heat transfer calculation methods.

It is possible to develop a new model if the floor can be converted into the floor that has a uniform heat generating plate and has the response characteristics similar to that of the actual floor. This research is a basic numerical analysis for the final aim of developing a simplified one-dimensional heat transfer simulation model of the floor of hydronic floor heating systems. The purpose of this research is twofold. First, this paper clarifies the response characteristics of the two-dimensional heat transfer of the floor of hydronic floor heating systems for a step change of pipe surface temperature. This paper also clarifies the differences in the response characteristics between the two-dimensional floor model and one-dimensional floor model, in which a uniform heat generating plate instead of the pipe is assumed.

In this research, the characteristics immediately after the start of the operation are referred. The other side, the control of continuously heated radiant floor-heating system has been addressed in the literatures. A semilinear model of a proportionally flux-modulated radiant slab is studied by MacCluer (1994), and the control performance of proportional flux-modulation of various types of temperature-modulation is studied by MacCluer et al. (1994).

CALCULATION CONDITIONS AND THE CALCULATION METHOD

The calculations were performed on the type of hydronic floor heating system that has the pipe embedded in the floor material, resulting in a large thermal storage capacity. The calculations were conducted on three different floor types. In floor type A, the layer in which the pipe is embedded is concrete and is disassociated from the slab. In floor type B, the pipe embedded layer is mortar and is disassociated from the slab. And in floor type C, the pipe embedded layer is concrete and is unified with the slab. The cross-sections of the three standard floor configurations are shown in Figure 1.

For the three floor types, calculations were performed after changing the thickness of the pipe embedding layer, the pipe layer depth, and the pipe pitch. The ratio of the pipe pitch to the pipe diameter was fixed at 10:1. Calculations were also performed on different floor conditions. The pipe diameter with a fixed pipe pitch was altered, the thickness of thermal insulation was changed, and different floor covering materials were used. Detailed descriptions of the different cases are provided in Table 1.

The two-dimensional heat conduction calculations were performed using the finite-element method. The division of the model into elements is shown in Figure 2. It is assumed that the floor comes from a middle story of a building. The temperature of the floor, the pipe, and the vertical space is initialized at 20 ^{o}C. The response of heat transmission rate from the pipe surface to the ambient spaces and the response of heat absorption rate from the pipe surface to the floor materials around the pipe were simulated for a step change of pipe surface temperature from 20 ^{o}C to 40 ^{o}C. Time step of calculation is 10 minutes.

THE HEAT TRANSMISSION AND ABSORPTION RESPONSE CHARACTERISTICS

First, the response characteristics for the two-dimensional heat transmission and absorption were analyzed. Below, the total heat transmission to both the upper and lower floor surfaces and the heat absorption by the floor from the pipe surfaces are discussed. The amount of heat stated is the value per unit area. The cumulative difference between the heat transmission rate and heat absorption rate is the thermal storage rate of the floor.

Standard Floor Conditions

Figure 3 shows the heat transmission and absorption responses under the standard floor conditions. The heat transmission response is similar for all three floor types. In addition, the heat absorption response is almost the same for floor types A and B, showing that the effect of the different pipe embedded layer materials is relatively insignificant. The heat absorption response of floor type C, on the other hand, shows a large delay.

Effect of the Pipe Embedding Layer Thickness

The effect of the pipe embedding layer thickness is shown in Figure 4(a). The heat transmission response is only slightly affected, but the heat absorption response experienced a large effect. The thicker the embedding layer, the longer it takes to reach a steady state.

Effect of the Pipe Pitch

The effect of the pipe pitch is shown in Figure 4(b). The effect on both the heat transmission and the heat absorption responses is large, especially in the first two hours of the heat absorption response. The narrower the pipe pitch, the larger the heat transmission and absorption rate.

Effect of the Pipe Diameter

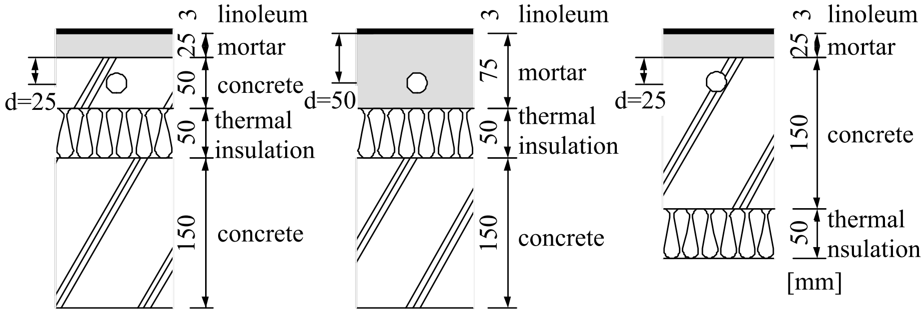
The effect of the pipe diameter is shown in Figure 4(c). When the pipe pitch is fixed, the larger the pipe diameter, the larger the heat transmission and absorption rate. However, the effect of the pipe diameter is not as significant as that of the pipe pitch.

Effect of the Pipe Embedded Depth

The effect of the pipe embedded depth is shown in Figure 4(d). When compared to the other factors, the effect of the pipe embedded depth on the heat transmission and heat absorption responses is very large. The deeper the pipe embedded depth, the smaller the heat transmission and absorption rate.

Effect of the Thermal Insulation Thickness

The effect of the thermal insulation thickness is shown in Figure 4(e). As can be seen in the figure, the effect of the thermal insulation thickness is not substantial. In general, the thinner the layer of thermal insulation, the larger the heat transmission and absorption rate. However, except for the 0-mm case, there is almost no difference in the responses. Also, the responses of floor types A and B differ from that of floor type C. For floor types A and B, a difference appears in the heat absorption response for the 0-mm case, although a difference doesn't appear in the



(1) floor type A (2) floor type B (3) floor type C

coefficient of heat transfer
by convection and radiation : upper floor surface 10.5W/m^2
lower floor surface 6.4W/m^2

Figure 1. Cross sections of standard floor conditions

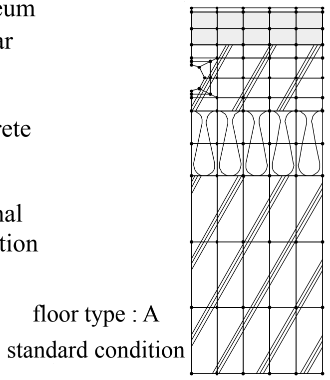


Figure 2. The division of the model into finite elements

Table 1. The calculated floor conditions

floor type	pipe embedding layer kind	pipe embedding layer thickness	pipe embedded depth	pipe pitch (diameter)
A	concrete	50mm	(d=25mm)	
		100mm	upper(d=25mm)*	
			middle(d=50mm)	100mm
			lower(d=75mm)	(10mm)
B	mortar	50mm	(d=25mm)	150mm
		100mm	upper(d=25mm)*	(15mm)
			middle(d=50mm)	200mm*
			lower(d=75mm)	(20mm)
		75mm	(d=50mm)	250mm
		125mm	upper(d=50mm)*	(25mm)
			middle(d=75mm)	300mm
			lower(d=100mm)	(30mm)
C	concrete	150mm	upper(d=25mm)*	
			middle(d=75mm)	
			lower(d=125mm)	

▨ are standard conditions

The floor conditions with a *
are also calculated for the case shown below.

pipe diameter [mm]	thermal insulation thickness [mm]	floor covering material kind	floor covering material thickness [mm]	floor covering material specific heat [kJ/m^3·K]	floor covering material coefficient of heat transfer by convention and radiation [W/m·K]
	0	linoleum	3	1500	0.190
10	10	carpet	6	320	0.080
20	25	flooring	20	720	0.190
30	50	*tatami*	40	290	0.150
	100	cork	7	250	0.059
		tile	13	2000	1.300

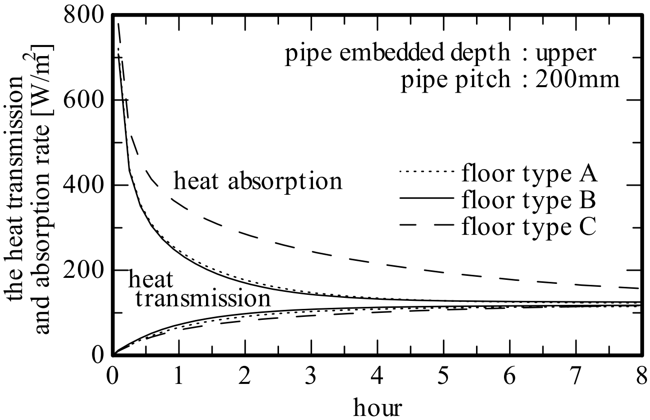
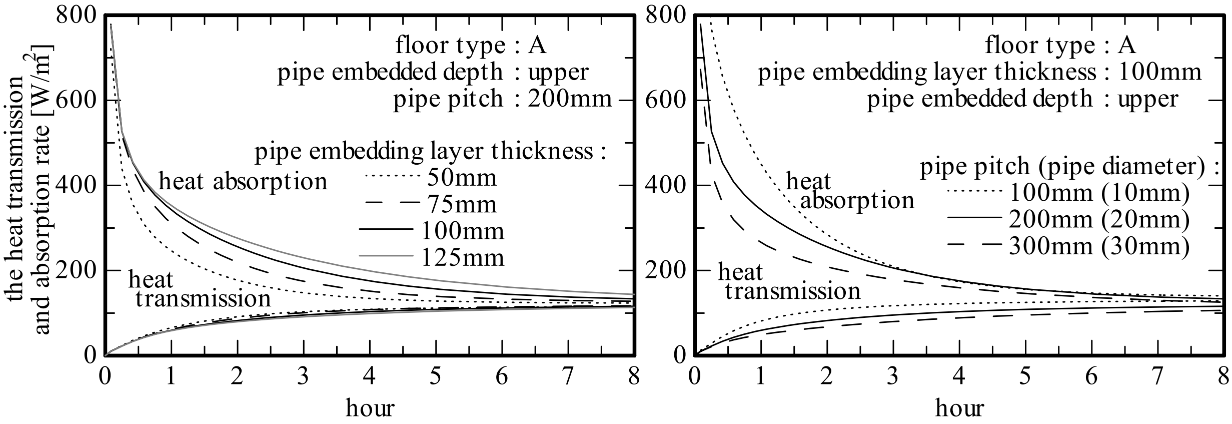
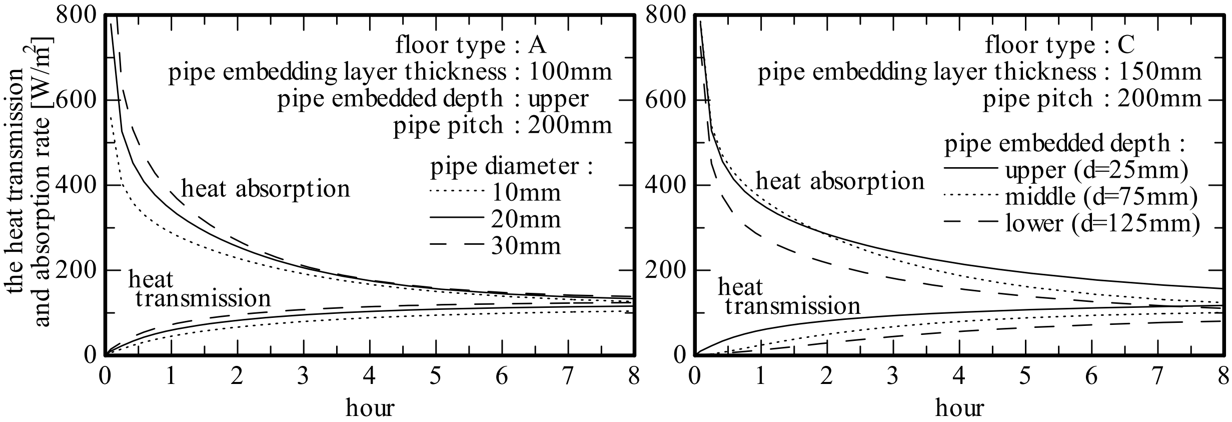


Figure 3. Heat transmission and absorption responses (standard floor conditions)



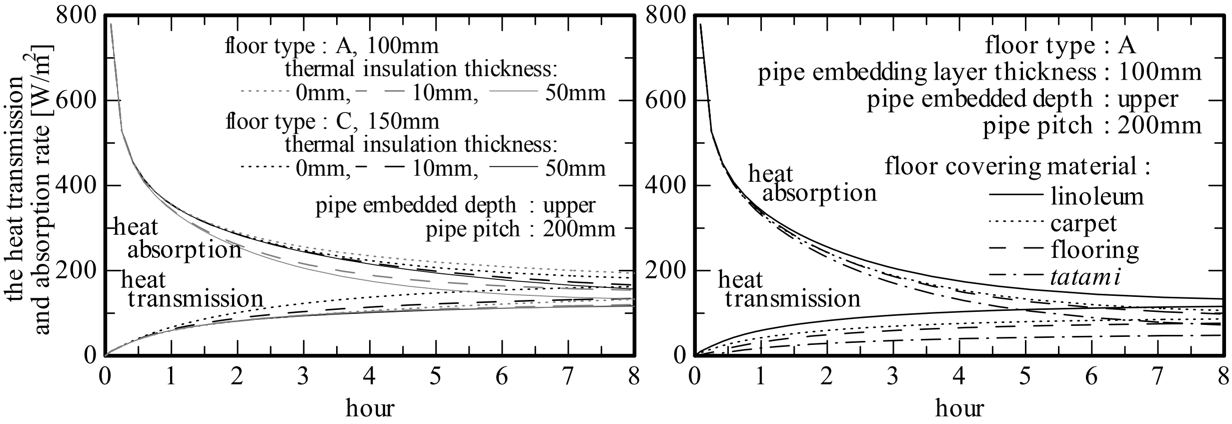
(a) effect of the pipe embedding layer thickness

(b) effect of the pipe pitch



(c) effect of the pipe diameter

(d) effect of the pipe embedded depth



(e) effect of the thermal insulation thickness

(f) effect of the floor covering material

Figure 4. Heat transmission and absorption responses (effect of factors)

heat transmission response. For floor type C, though, a difference doesn't appear in the heat absorption response for the 0-mm case, but a difference does appear in the heat transmission response.

Effect of the Floor Covering Material

The effect of the floor covering material is shown in Figure 4(f). Immediately after a step change in temperature, the heat absorption response is barely affected by the material. However, as time passes, the effect of the floor covering on the heat absorption and transmission rate becomes very large. It was found that floor covering materials with higher heat insulation performances result in smaller the values of heat transmission and absorption.

THE HEAT TRANSMISSION RATIO RESPONSE CHARACTERISTICS

The heat transmission ratio is defined as the ratio of the total heat absorption rate to the total heat transmission rate over time. When this ratio is large, the heat transmission rate is said to be high, and when this ratio is small, the thermal storage rate is said to be high.

Standard Floor Conditions

Figure 5 shows the heat transmission ratio under the standard floor conditions. Floor types A and B exhibit almost the same heat transmission ratios, but the heat transmission performance of the mortar layer proves to be somewhat better than that of the concrete layer. When compared with floor types A and B, though, floor type C exhibits considerably larger the thermal storage rate, resulting in a low heat transmission ratio.

Effect of the Pipe Embedding Layer Thickness

The effect of the pipe embedding layer thickness is shown in Figure 6(a). The effect of the layer thickness is large. When the layer is thin, the heat transmission ratio is large, but when the layer is thick, the heat transmission ratio is small and the thermal storage rate is large.

Effect of the Pipe Pitch

The effect of the pipe pitch is shown in Figure 6(b). As can be seen in this figure, the pipe pitch has almost no effect on the heat transmission ratio.

Effect of the Pipe Diameter

The effect of the pipe diameter is shown in Figure 6(c). As with the pitch, there is almost no effect on the heat transmission ratio.

Effect of the Pipe Embedded Depth

The pipe embedded depth proves to have a relatively large effect on the heat transmission ratio, as can be seen in Figure 6(d). The heat transmission ratio is the largest when the pipe is embedded near the surface, and the heat transmission ratio decreases with depth.

Effect of the Thermal Insulation Thickness

The effect of the thermal insulation thickness is shown in Figure 6(e). The thermal insulation thickness has a converse effect on floor types A and B and floor type C, although the overall effect is relatively small. In the floor types A and B, if the insulation is thin, the thermal storage rate of the slab becomes large, and the heat transmission ratio becomes small. In floor type C, on the other hand, if the insulation is thin, the heat transmission rate from the lower surface becomes large, resulting in a large heat transmission ratio.

Effect of the Floor Covering Material

The effect of the floor covering material is shown in Figure 6(f). The influence of the different materials is large. In the higher thermal insulation performance materials, the heat transmission ratio is small, and after 2 hours, the heat transmission ratio is 0.14 for linoleum and 0.05 for *tatami*.

STEADY STATE HEAT PHYSICAL PROPERTIES VALUES AND THERMAL STORAGE CHARACTERISTICS

Figures 7 and 8 display the steady state the steady state thermal storage rate, the heat capacity ratio, the total accumulation of heat after 10 hours, and the heat transmission ratio. The heat capacity ratio is defined as the ratio of the heat capacity of the entire floor to the additional thermal storage rate when the piping temperature changes by 1 degree K.

Steady State Thermal Storage Rate

The effect of the pipe embedding layer thickness is considerable, while the effect of the pipe pitch, the pipe diameter, the pipe embedded depth, and the floor covering material is relatively smaller. The effect of the thermal insulation thickness is large, when compared to the other factors. When the thermal insulation is thin for floor types A and B, the thermal storage rate increases because the thermal storage rate in the slab increases. On the contrary, when the thermal insulation is thin for floor type C, the thermal storage rate decreases.

Heat Capacity Ratio

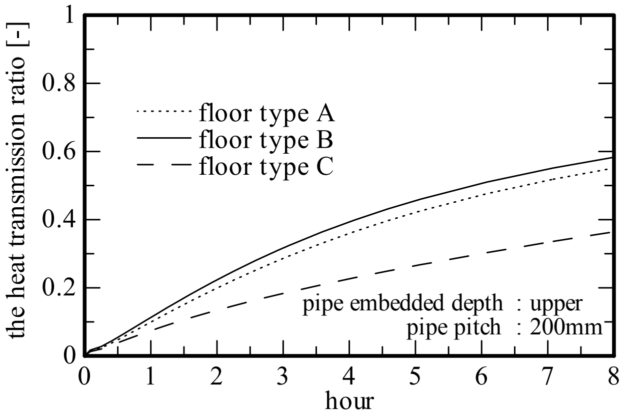
The heat capacity ratio is small in floor types A and B, in which the pipe embedded layer is disassociated from the slab, and is large in floor type C. In the cases where the pipe embedding layer is thick and the pipe embedded depth is near the upper surface, the heat capacity ratio is large. The effect of the pipe pitch, the pipe diameter, the pipe embedded depth, and floor covering material is not as large. As with the thermal storage rate measure, when the thermal insulation is thin for floor types A and B, the ratio is large. However, when the thermal insulation is thin for floor type C, the ratio is small.

Heat Accumulation (after 10 hours) and the Heat Transmission Ratio

Although the heat absorption rate is almost the same for floor types A and B, the heat transmission ratio of floor type B is larger than that of A because the heat transmission is larger and the thermal storage rate is smaller in floor type B. The heat absorption rate is greatly affected by the pipe embedding layer thickness, the pipe pitch, the pipe diameter, and the pipe embedded depth. The heat transmission rate is greatly affected by the pipe pitch, the pipe embedded depth, and the floor covering material. Consequently, the heat transmission ratio is sensitive to the thickness of the pipe embedding layer and the floor covering material.

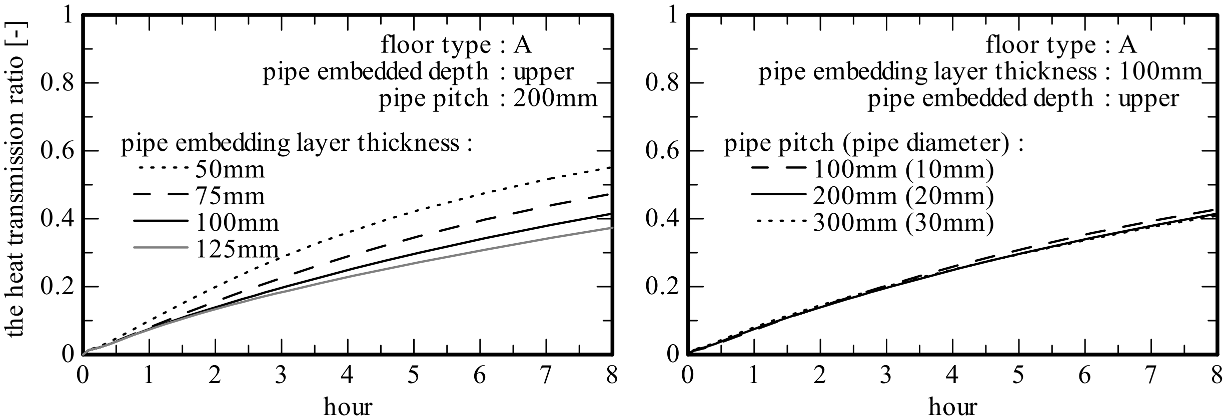
A COMPARISON OF THE NON-DIMENSIONAL HEAT TRANSMISSION AND ABSORPTION RESPONSE CHARACTERISTICS BETWEEN THE ONE-DIMENSIONAL MODEL AND THE TWO-DIMENSIONAL MODEL

In order to compare the response characteristics of the one-dimensional floor model with the two-dimensional floor model, the one-dimensional floor model was

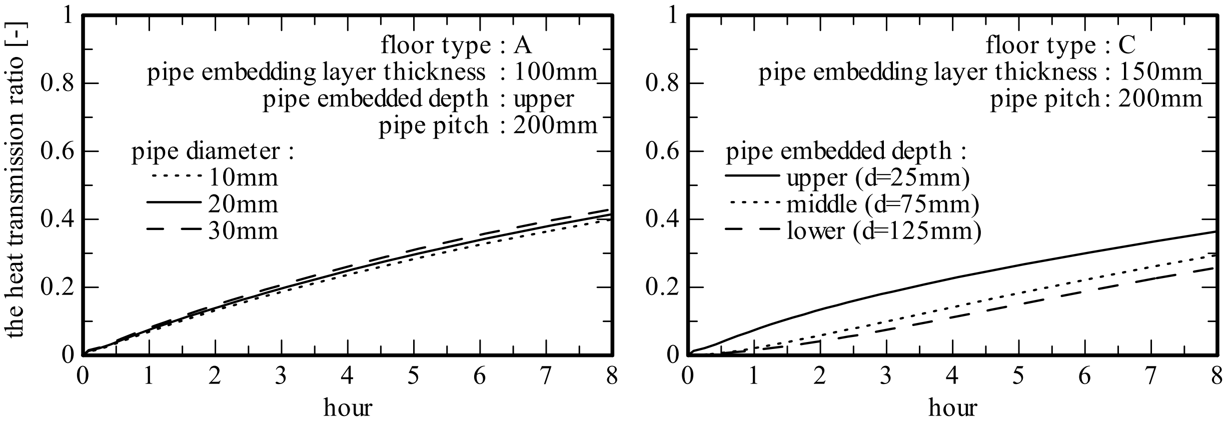


$$\text{the heat transmission ratio} = \frac{\text{the total heat transmission rate}}{\text{the total heat absorption rate}}$$

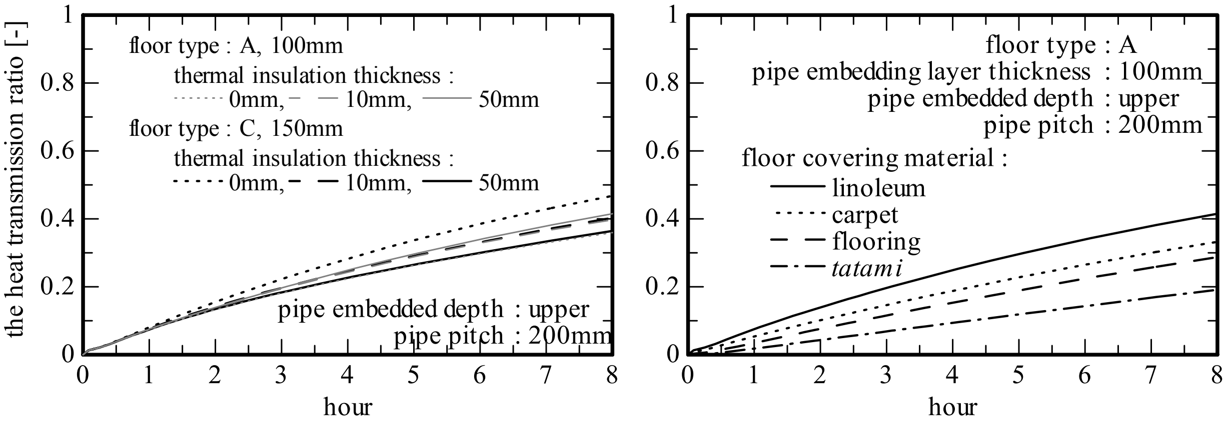
Figure 5. The heat transmission ratio (standard floor conditions)



(a) effect of the pipe embedding layer thickness (b) effect of the pipe pitch



(c) effect of the pipe diameter (d) effect of the pipe embedded depth



(e) effect of the thermal insulation thickness (f) effect of the floor covering material

Figure 6. The heat transmission ratio (effect of factors)

assumed and the non-dimensional responses of the floor were calculated using both two models. In the one-dimensional floor model, the pipes embedded in the actual floor are replaced with a uniform heat generating plate. This plate is at the same depth as that of the center of pipes in the actual floor. The non-dimensional heat transmission and absorption responses can be obtained by dividing the upper heat transmission and absorption responses by their steady state value. The non-dimensional heat transmission and absorption responses are shown in Figure 9.

Non-Dimensional Heat Transmission Response

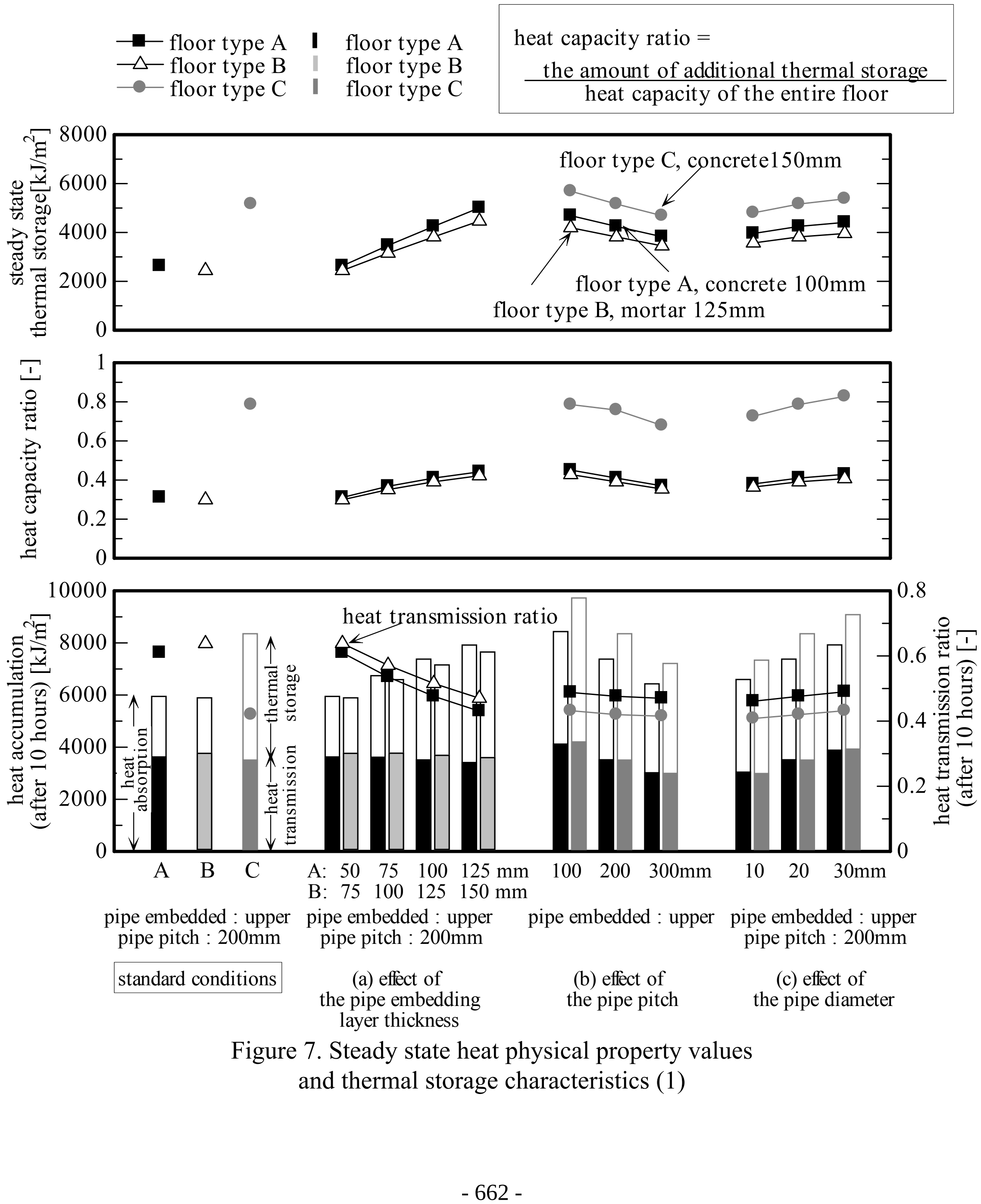
The non-dimensional heat transmission response of the one-dimensional model reaches steady state in only a short time. On the other hand, the two-dimensional model exhibits a longer delay. In many cases, the heat transmission response has not reached the steady state even after 6 hours. Although the effect of the thermal insulation thickness and the floor covering material is significant in the heat transmission rate, there is no effect in the non-dimensional heat transmission response. The non-dimensional heat transmission response is affected by the pipe pitch, the pipe diameter, the pipe embedding layer thickness, and especially the pipe embedded depth. When the pipe is embedded lower, the effect is very large.

Non-Dimensional Heat Absorption Response

In the one-dimensional model, the floor rapidly absorbs heat from the pipe after a change in pipe temperature and quickly reaches a steady state. In two-dimensional model, the heat absorption response is not significantly affected by the pipe diameter and the pipe embedded depth. The effect of the pipe pitch is relatively large, but the effect lasts only 3 hours. The effect of the pipe embedding layer thickness, the thermal insulation thickness, and the floor covering material is large, and the effect lasts a long time.

CONCLUSION

The heat transmission and absorption characteristics for two-dimensional heat conduction calculations have been clarified. The heat transmission and absorption



standard conditions

(a) effect of the pipe embedding layer thickness

(b) effect of the pipe pitch

(c) effect of the pipe diameter

Figure 7. Steady state heat physical property values and thermal storage characteristics (1)

responses are very slow for the two-dimensional floor model.

The pipe embedded depth and the floor covering material affect the heat transmission rate. The pipe embedding layer thickness and the thermal insulation thickness affect the thermal storage performance. The non-dimensional heat transmission response is affected by the pipe pitch, the pipe diameter, the pipe embedding layer thickness, and the pipe embedded depth. The non-dimensional heat absorption response is affected by the pipe embedding layer thickness, the thermal insulation thickness, and the floor covering material.

REFERENCES

ASHRAE, ASHRAE Handbook Fundamentals, 2001

Inoue U., Pocket Book of Heating, Ventilating, Air Conditioning and Plumbing, Sagami Publishing Co., 1983

Inoue U., Ishino H. and Kohri K., A Study on Estimation Methods of Heat Output In Hot Water Floor Heating Systems, Journals of Architecture, Planning and Environmental Engineering (Transactions of AIJ), No.494, 1997

Ishino, A Proposal on a Estimation Method of Steady State Heat Transfer Rate in Floor Heating Systems Using Improved Fin Assumption, Summaries of Technical Papers of Annual Meeting AIJ, 1998

Ishino H. and Kohri K., An Assessment Research for Radiant Heating and Cooling System Design, Journals of Architecture, Planning and Environmental Engineering (Transactions of AIJ), No.470, 1995

Kilkis B. and S. Sager, A Simplified Model for the Design of Radiant In-Slab Heating Panels, ASHRAE Transactions, Vol.101(1), 1995

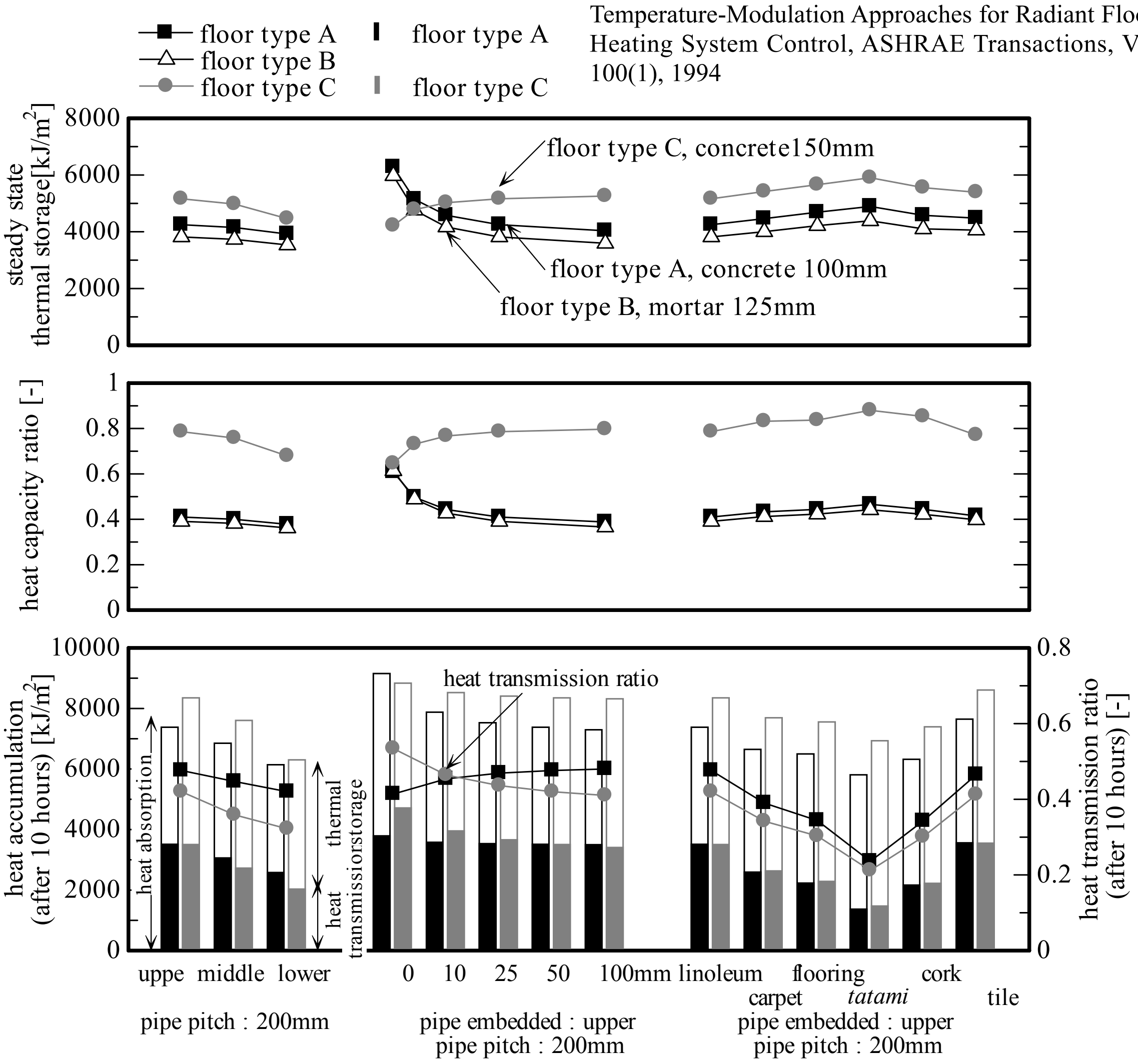
Kollmar A. and Liese W., Die Strahlungs heizung, R. Oldenbourg, 1967

MacCluer C. R., Analysis and Simulation of Outdoor Reset Control of Radiant Slab Heating Systems, ASHRAE Transactions, Vol.96 (1), 1990

Udagawa M, Calculation Method for Air-Conditioning and Heating Using Personal Computer, Ohmu Publishing Co., 1986

MacCluer C. R., Stability of Flux-Controlled Radiant Slabs, ASHRAE Transactions, Vol. 100(2), 1994

MacCluer C.R., Leigh S.B., Comparative Study of Proportional Flux-Modulation and Various Types of Temperature-Modulation Approaches for Radiant Floor-Heating System Control, ASHRAE Transactions, Vol. 100(1), 1994

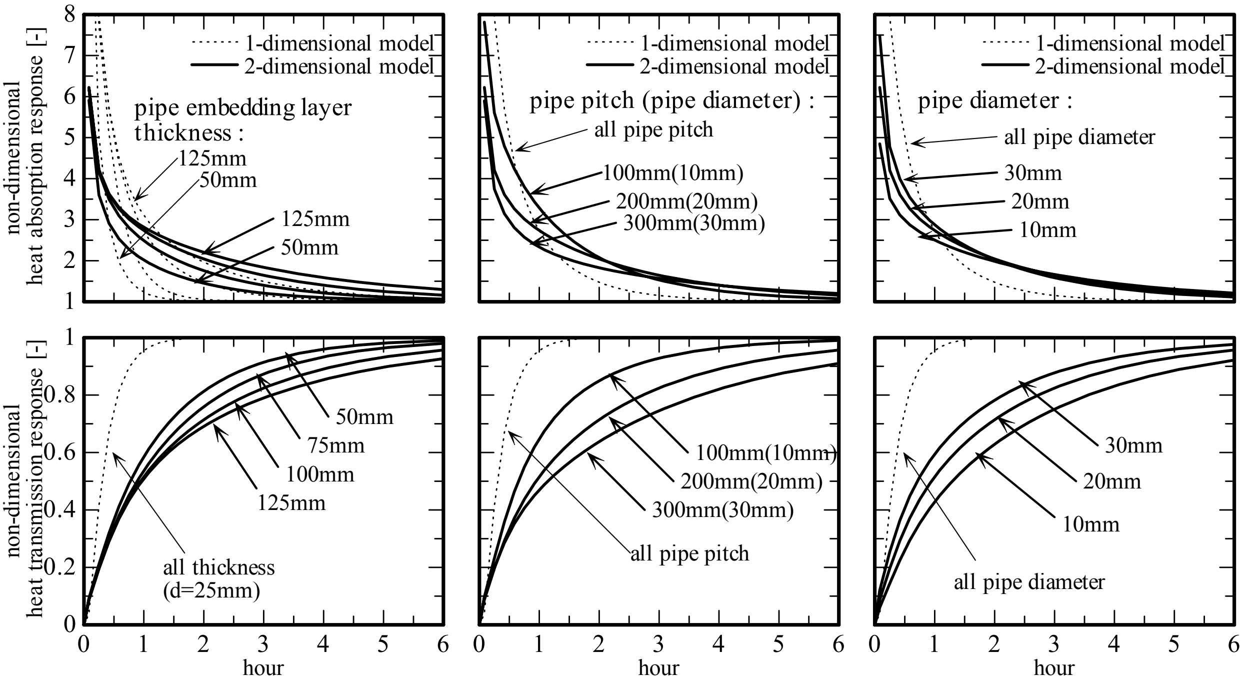


(d) effect of
the pipe embedded depth

(e) effect of
the thermal insulation thickness

(f) effect of
the floor covering material

Figure 8. Steady state heat physical property values and thermal storage characteristics (2)



(a) effect of the pipe embedding layerof thickness

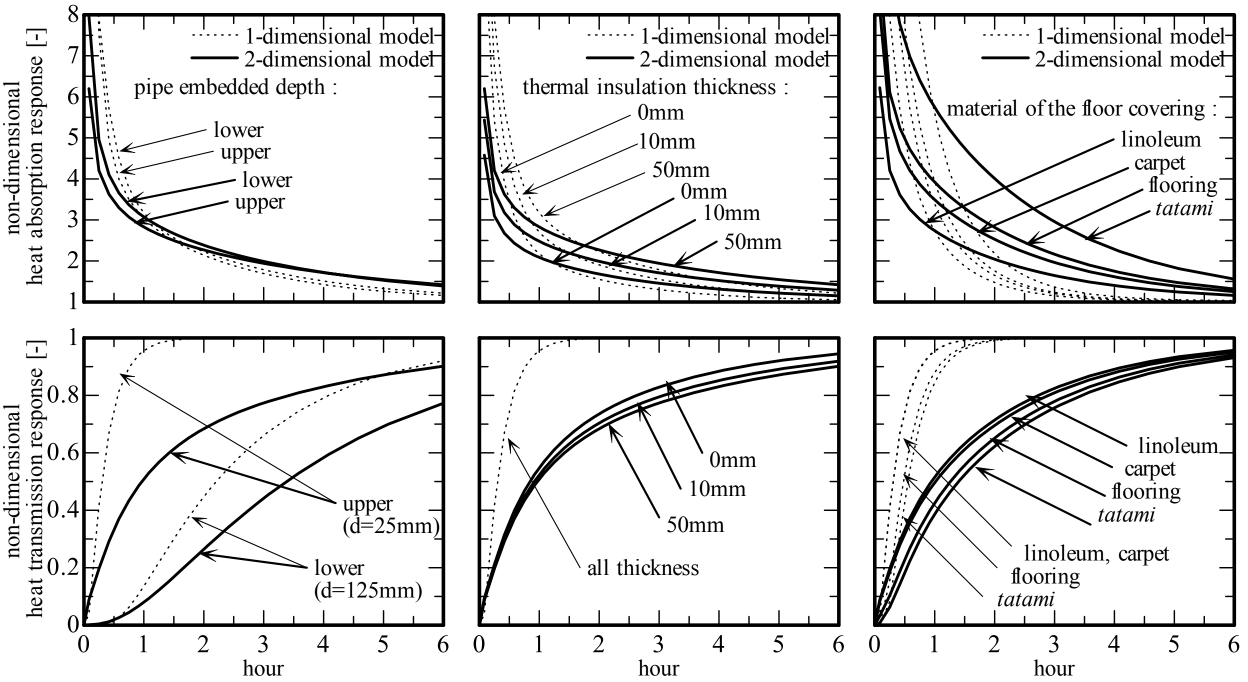
floor type : A
pipe embedded depth : upper
pipe pitch : 200mm

(b) effect of the pipe pitch

floor type : A
pipe embedding layer thickness : 100mm
pipe embedded depth : upper

(c) effect of the pipe diameter

floor type : A
pipe embedding layer thickness : 100mm
pipe embedded depth : upper
pipe pitch : 200mm



(d) effect of the pipe embedded depth

floor type : C
pipe embedding layer thickness : 150mm
pipe pitch : 200mm

(e) effect of the thermal insulation thickness

floor type : C
pipe embedding layer thickness : 150mm
pipe embedded depth : upper
pipe pitch : 200mm

(f) effect of the floor covering material

floor type : A
pipe embedding layer thickness : 100mm
pipe embedded depth : upper
pipe pitch : 200mm

Figure 9. Non-dimensional heat transmission and absorption resopnses