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A simplified calculation method for estimating heat flux from ceiling radiant panels

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ABSTRACT

In this paper, we have developed a calculation method for estimating heat fluxes from ceiling radiant panels, using pipe density on panels and the temperature difference between the room air and the supply water. We then measured heat fluxes from panels in an environmental test room. After comparing the values estimated by our calculation method to the experiment's data, the calculated values closely match the values obtained from experiments, which means that this calculation method is practical in estimating the radiant panel performance in the design phase.

1. Introduction

In a space where radiant cooling/heating system is used, the distribution of room temperature becomes more homogeneous and the thermal comfort can be higher, compared with the space where conventional air conditioning system is installed, which agitates air within the room to condition room temperature [1]. Furthermore, by using radiant system, it is possible to get similar comfort with less energy than the conventional system [2,3]. This means that the temperature of the supply water to panels can be set higher in the case of cooling and that it can be set lower in the case of heating, which is expected to increase the coefficient of performance of heat source equipment. For this reason, radiant cooling/heating is the air conditioning system which combines comfort and energy conservation.

Although the radiant system has such good qualities, the number of radiant cooling/heating systems is still much less than conventional systems in Japan. One of the main reasons is that there is little information on the characteristics of radiant panels. There have been some previous studies on assessment using particular sizes of panels, piping material and insulation material [4], but there have been few studies on panels using common materials.

In this study, we developed a calculation method for estimating heat fluxes from ceiling radiant panels, using pipe density on panel (effective piping length on panel) and the temperature difference between the room and the supply water. Then we measured heat fluxes from panels (aluminum panels bonded with polyethylene piping). We confirmed that values estimated by the calculation method had closely matched the values obtained from experiments. Here we will give an outline of the experiment and the calculation method.

2. Outline of experiment

2.1. Experiment system

Experiments were made in an environmental test room, which regulated room temperature. We measured the heat flux from the radiant panels. The ambient temperature was kept constant. Air conditioning system used in the experiment is shown in Fig. 1.

2.2. Measurement method

Measurement equipment used in the experiment is shown in Table 1. On the panel surface, thermocouples were installed to measure surface temperature, and heat flow meters and radiant heat flux meters were fitted to measure heat flux. The convective heat flux was calculated as the difference between the measurement of heat flow meter and the measurement of radiant heat flux meter.

2.3. Detail of radiant panels

Two types of panel were developed and used in the experiment: (A) meandering piping type and (B) spiral piping type. The specification of each panel is shown in Table 2 and Fig. 2.

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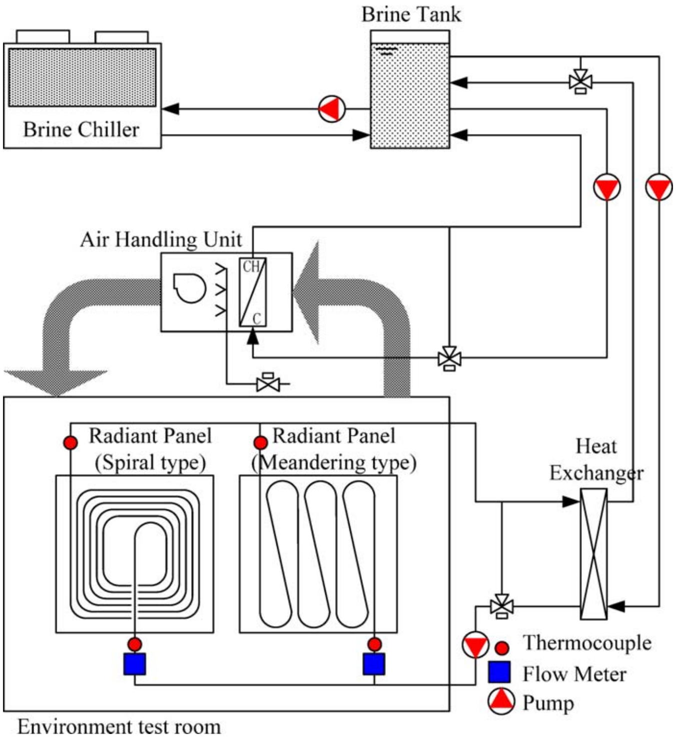

Fig. 1. Experiment system.

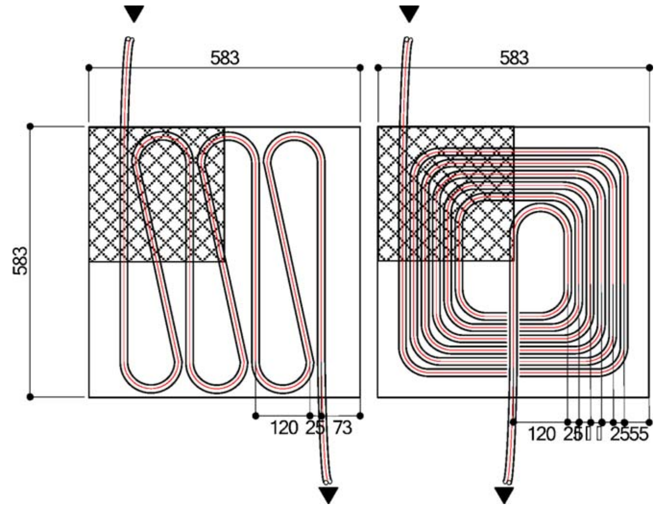

Fig. 2. Detail of panels used in the experiment: (left) meandering type and (right) spiral type. (Cross-hatched area is heat flow sensor)

Table 1
Measurement equipment for the experiment.

Measurement item	Equipment	Sensor name
Flow rate	Electromagnetic flowmeter	FD-M10T, Keyence
Heat flux	Heat flow sensor	MF-190, Eko Instruments
Radiant heat flux	Radiant flux meter	RF, Captec
Panel surface temperature, water temperature and Floor surface temperature	Thermocouple	JIS-T type
Data logging	Data logger	DA-100, Yokogawa Electric

Table 2
Panel specification for the experiment.

	Specification
Panel	Aluminum panel, 583 mm × 583 mm × 0.6 mm^t
Pipe	Aluminum reinforced polyethylene pipe, inside diameter: 10.1 mm, outside diameter: 14.1 mm

Measurements in 7 cases, as shown in Table 3, were done in the experiment. We used 2 types of insulation on panels; one is air layer type (air layer 100 mm and foam polystyrene 50 mm) and the other is glass wool type (glass wool (24 K) 25 mm). Measurement was done at 1 min intervals for 1 h after the room temperature and the supply water temperature became stable.

3. Cooling experiment

In the cooling experiments, the supply water flow rate was 2.5 L/min, heat fluxes were measured in 4 cases.

Fig. 3 presents average values of radiant and convective heat flux. Heat fluxes from spiral piping type panel, in which pipe density is higher, were bigger than meandering piping type. In each type of piping, radiant and convective heat flux had a ratio of 60–40%. And there was little difference in the ratio between the insulation specifications.

3.1. Surface temperature of panels

Fig. 4 presents thermal images for Case 03. Surface temperature for the spiral piping, which had higher pipe density, became lower than meandering type. In the case of the spiral type, the distribution of surface temperature was more homogeneous in the area in which the pipe density was high, but in the central area and in the corner areas, surface temperature was higher.

Table 3
Measured items in the experiment.

Case	Room temp.[a] (°C)	Water temp.[a] (°C)	Insulation on panels	Measurements[b]			
				Surface temp.	Thermal image	Heat flux	Radiant heat flux
Cooling							
01	28	12	Air layer	–	–	○	–
02	28	15	Air layer	–	–	○	–
03	28	18	Air layer	○	○	○	○
04	28	18	Glass wool	○	○	○	○
Heating							
11	18	36	Air layer	○	○	○	–
12	18	33	Air layer	○	○	○	○
13	18	33	Glass wool	○	○	○	○

[a] Temperature means set temperature.
[b] Circles mean items measured in the experiment.

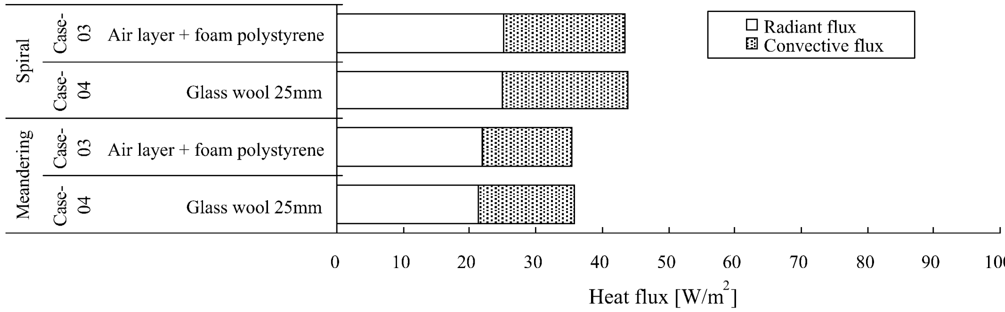

Fig. 3. Breakdown of heat flux for Case 03–04 (cooling, room temperature 28 °C, supply water temperature 18 °C).

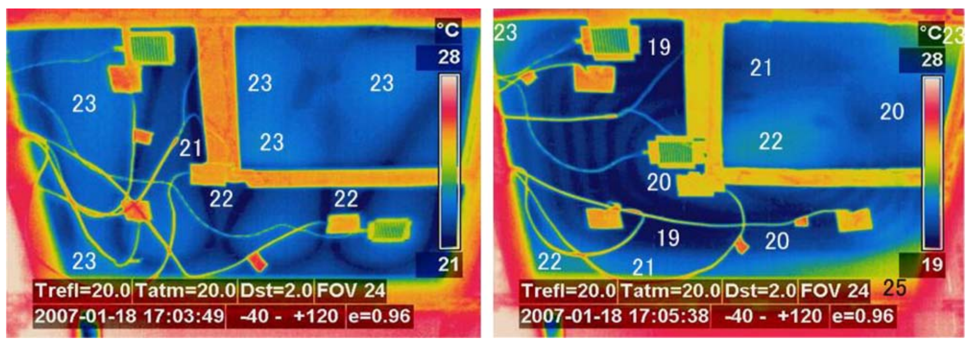

Fig. 4. Thermal images for Case 03 (left) meandering and (right) spiral (cooling, room temperature 28 °C, supply water temperature 18 °C).

4. Heating experiment

In the heating experiments, the supply water flow rate was 2.5 L/min. Heat fluxes were measured in 3 cases.

Fig. 5 presents average values of radiant and convective heat flux for Cases 12∼13. Heat fluxes from spiral piping type panel, in which pipe density was higher, were bigger than meandering piping type. In each case of piping type, radiant heat flux ratio was bigger than the flux ratio in the cooling experiments (meandering piping 74–80%, spiral piping 69–71%). And there is little difference in the ratio between the insulation specifications.

Fig. 6 presents thermal images for Case 12. Surface temperature for spiral piping type were higher than for the meandering type. In the case of spiral type, the difference between maximum temperature and minimum temperature was bigger, because the surface temperature became lower in the corner and central areas. But in the case of meandering type, surface temperature distribution was more homogeneous and the temperature difference was smaller.

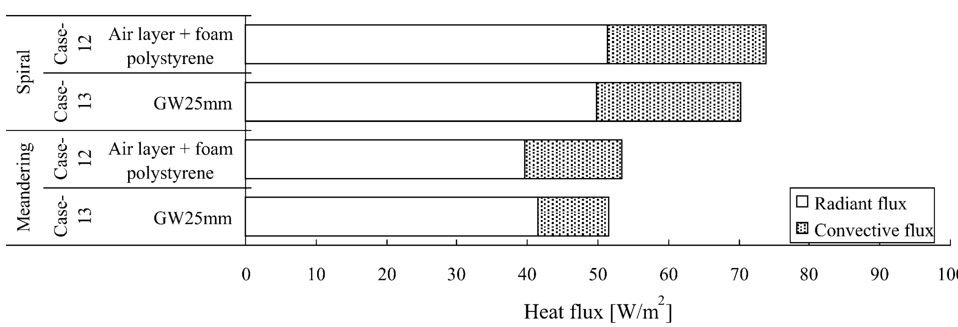

Fig. 5. Breakdown of heat flux for Case 12–13 (heating, room temperature 18 °C, supply water temperature 33 °C).

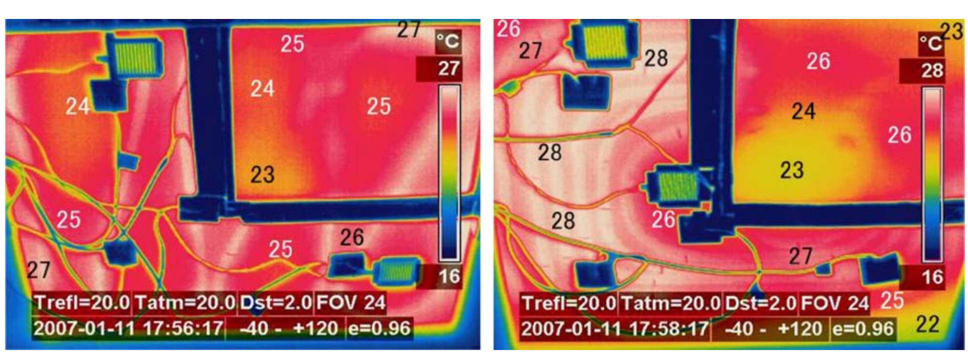

Fig. 6. Thermal images for Case 12 (left) meandering and (right) spiral (heating, room temperature 18 °C, supply water temperature 33 °C).

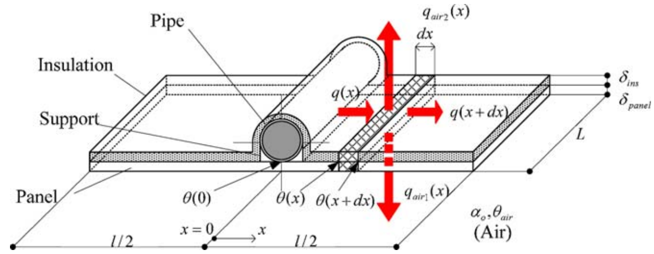

Fig. 7. Model for a panel bonded with piping.

5. Calculation method for estimating heat fluxes from panel

Here we express heat fluxes from panels bonded with pipe in formula. We define the length of piping per unit area as pipe density ρ (Fig. 7).

Heat flux from panel q is expressed in Eq. (1) as the difference of average supply water temperature $\theta_{\rm w}$ and air temperature $\theta_{\rm air}$ [5]:

$$q = \frac{C_1 C_2 C_3}{C_1 C_2 + C_2 C_3 + C_3 C_1}(\theta_{\rm w} - \theta_{\rm air}) \tag{1}$$

where

$$C_1 = 2\sqrt{(K_1 + \alpha_0) L \lambda_{\rm panel} A}\left(\frac{e^{\beta/\rho} - 1}{1 + e^{\beta/\rho}}\right) = 2\sqrt{(K_1 + \alpha_0) L \lambda_{\rm panel} A}\tanh\frac{\beta}{2\rho} \tag{2}$$

$$C_2 = aL\alpha_{\rm w} \tag{3}$$

$$C_3 = \frac{bL}{r_1 + \sum(\delta_i/\lambda_i) + r_2} \tag{4}$$

$$\beta = \sqrt{\frac{\alpha_0 + K_1}{\lambda_{\rm panel} A} L} \tag{5}$$

$$\alpha_{\rm w} = \frac{(1663 + 24\theta_{\rm w})v^{0.8}}{d_i^{0.2}} \quad (6)[6]$$

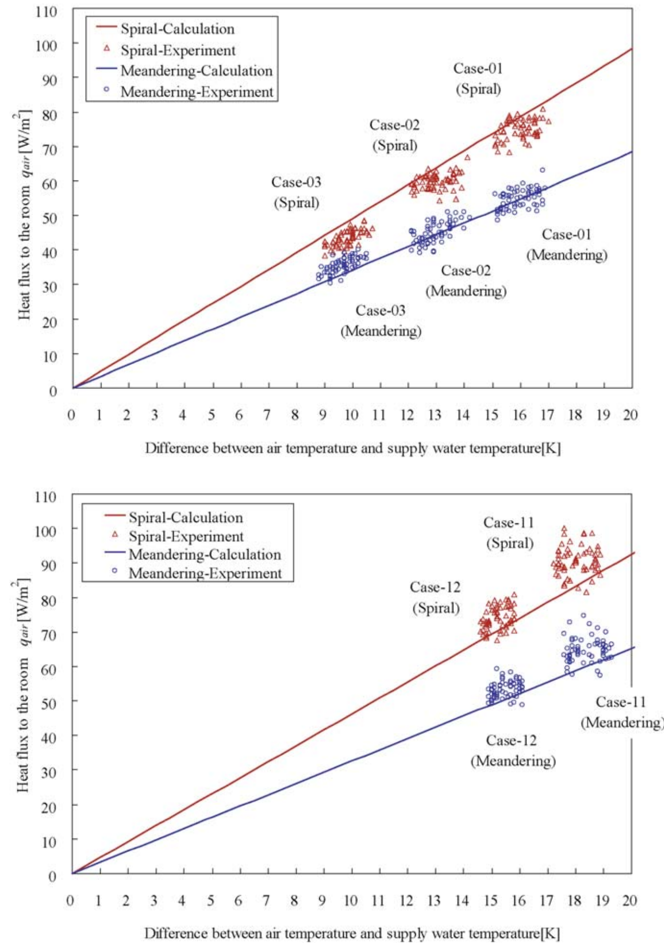

Fig. 8. Comparison between calculation and experiment data: (above) cooling and (below) heating.

where K_1 is the coefficient of heat transmission between the panel and the air above the panel [W/(m^2 K)], α_0 is the overall heat transfer coefficient for panel surface [W/(m^2 K)], $\alpha_{\rm w}$ is the heat transfer coefficient for inner surface of pipe [W/(m^2 K)], $\lambda_{\rm panel}$ is the coefficient

Table 4
Condition for the comparison.

Pipe density	ρ	Spiral	28.1	m/m^2
		Meandering	19.4	m/m^2
Panel	$\delta_{\rm panel}$	Thickness	0.6	mm
	$\lambda_{\rm panel}$	Coefficient of thermal conductivity	228	W/(m K)
Piping	d_0	Outside diameter	14.1	mm
	$d_{\rm i}$	Inside diameter	10.1	mm
	δ_1	Thickness	2.0	mm
	λ_1	Coefficient of thermal conductivity	0.47	W/(m K)
	Q	Flow rate	2.5	L/min
	v	Flow velocity	0.520	m/s
	r_1	Thermal contact resistance between piping and bonding material	0.000088	m^{2}K/W [7]
	r_2	Thermal contact resistance between bonding material and panel	0.000088	m^{2}K/W [7]
Bonding material	δ_2	Thickness	2.5	mm
	a	Length of bonding between piping and bonding material	3.5	mm
	b	Average width of bonding material for piping and panel	3.5	mm
	λ_2	Coefficient of thermal conductivity	1.6	W/(m K)

	Cooling	Heating	Notes
Meandering (W/(m^2 K))			
Radiant heat transfer coefficient	5.65	5.65	Average value of all cases
Convective heat transfer coefficient	2.54	1.69	Average value for cooling/heating
Spiral (W/(m^2 K))			
Radiant heat transfer coefficient	6.05	6.05	Average value of all cases
Convective heat transfer coefficient	2.54	1.69	Average value for cooling/heating

Table 5
Comparison between calculation and experiment data.

	Cooling					Heating			
	Air layer				GW25	Air layer			GW25
	Case 01	Case 02	Case 03	Total	Case 04	Case 11	Case 12	Total	Case 13
Supply water temperature (°C)	12.0	15.0	18.0	–	18.0	36.0	33.0	–	33.0
Meandering									
Average heat flux (W/m^2)									
Experiment (a)	54.7	45.0	35.5	45.1	35.8	64.7	53.4	59.0	51.5
Calculation (b)	54.8	44.6	33.1	44.1	32.5	60.3	50.8	55.6	48.6
(a)/(b)	1.00	1.01	1.07	1.02	1.10	1.07	1.05	1.06	1.06
Standard deviation σ	2.46	2.41	2.86	2.58	3.61	5.75	3.49	4.76	3.68
Spiral									
Average heat flux (W/m^2)									
Experiment (a)	74.9	59.9	43.4	59.4	43.7	90.7	73.9	82.3	70.2
Calculation (b)	78.7	64.0	48.3	63.7	47.7	83.7	70.7	77.2	68.4
(a)/(b)	0.95	0.94	0.90	0.93	0.92	1.08	1.05	1.07	1.03
Standard deviation σ	5.16	4.99	4.86	5.00	4.33	8.41	4.51	6.74	4.10

of thermal conductivity for panel [W/(m K)], λ_i is the coefficient of thermal conductivity for i layer [W/(m K)], r_1 is the thermal contact resistance between piping and bonding material [m^{2}K/W], r_2 is the thermal contact resistance between bonding material and panel [m^{2}K/W], a is the length of bonding between piping and bonding material [m], b is the average width of bonding material for piping and panel [m], L is the panel length [m], δ_i is the thickness of i layer [m], A is the cross-section of panel [m^2], v is the flow velocity of water [m/s], and d_i is the inside diameter of piping [m].

6. Comparison between estimated values and resulting experiment data

We compared estimated value and resulting experiment data under the condition shown in Table 4. Heat fluxes from panels calculated with Eq. (1) and experiment data are graphed out using the difference of average supply water temperature θ_w and air temperature θ_{air} as the horizontal axis. Fig. 8 presents heat fluxes for panel with air layer for cooling and heating. The comparison of calculated value and experiment data for each case is shown in Table 5.

In the cooling experiments, the predicted estimated values were a little smaller in the case of meandering type, and in the case of spiral type the estimated values were a little bigger, than the experiment data. And for heating, the estimated values were a little smaller than experiment in each type of piping. For cooling, the difference between the average of estimated values and the one of experiment data was 0.0–10.2% for meandering type, and 2.7–8.4% for spiral type. For heating, the difference of them was 5.0–7.2% for meandering type and 2.7–8.4% for spiral type. Overall, aside from these minor discrepancies, the predicted calculation shown in Eq. (1) was accurate in evaluating the panel performance.

7. Conclusion

We developed radiant cooling/heating panels bonded with piping, using common materials, and evaluated the cooling and heating efficiency in controlled environmental settings. And we also made an equation to predict panel performance which resulted in the following findings.

Both in cooling and heating cases, as the pipe density becomes higher, heat flux from panels becomes bigger. There was little difference between insulation specifications.

The ratio of radiant heat flux to total heat flux was 60% in cooling and 70–80% in heating, and did not depend on pipe density.

As the pipe density became higher, the surface temperature of panels became lower in cooling and higher in heating. In the case of the spiral piping, the temperature distribution was more homogeneous in the area in which pipe density was higher. But the difference between the surface temperature in higher pipe density area and in lower pipe density area was bigger than the case of meandering piping. In the case of the meandering piping, which had lower pipe density, the difference of panel surface temperature was smaller, and showed more homogeneous temperature distribution in heating.

We expressed heat flux from radiant panel bonded with pipe as Eq. (1), using these 2 factors: (1) pipe density and (2) difference between the room air temperature and the supply water temperature. This equation can predict the performance of panels made with common materials.

By comparing the values estimated by the calculation method to the experiment data, the estimated values closely match the values obtained from experiments, which means that this calculation method is practical in estimating the radiant panel performance in the design phase.

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