Determination of the Chilled Water Temperature and Flow Rate of the Radiant Floor Cooling System in Residential Buildings

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ABSTRACT

This study aims to derive design data of the supply chilled water temperature and water flow rate for the radiant floor cooling system in Korean residential buildings. At first, prEN-1264 standard and ASHRAE method for the radiant floor cooling system design were reviewed. Secondly, to verify application of the standard, mock-up tests were performed. The results show that prEN-1264 method is appropriate in case supply chilled water temperature is low. By using calculation method presented in prEN-1264 standard, design data for Korean residential buildings was derived. This study would be able to determine the supply chilled water temperature and water flow rate in design process.

1 INTRODUCTION

In Korean residential buildings, the packaged air-conditioner (PAC) has been widely used as a cooling system. However, because this system uses CFCs (chlorofluorocarbon), it creates a negative effect on the environment, also apparently causes a problem of day-time peak of electric power demand in summer (Kim, 2000). To reduce problems caused by PAC, a radiant floor cooling system has been suggested (Kim, 2002).

Studies on the radiant floor cooling system have focused on control methods and on the operation of the system. However, few studies have been carried out on the design method for the radiant floor cooling system. Before the system can be generally applied to residential buildings, research and data are required for design of the radiant floor cooling system. In previous research, verified standards (prEN-1264, ASHRAE) were used to determine the chilled water temperature, chilled water flow rate and to design the floor panel.

Calculation results obtained by using verified standards are based on the floor panel type constructed in Europe. Because the European floor panel type differs from that of the Korean floor panel type, the design data needs to reflect the Korean condition. Furthermore, there are differences between the calculation results using prEN-1264 and those using ASHRAE. In the prEN-1264 method the surface emittance, surface temperature and the altitude above sea level are not considered in the process of heat transfer calculation on the surface. The pipe spacing and the panel thickness do not have a significant influence on the ASHRAE methods compared with the prEN-1264 method.

The aim of this paper is to provide quantitative design data for the supply chilled water temperature and the water flow rate while taking into consideration the type of floor construction used in Korean apartment buildings. Firstly, in order to obtain the design cooling capacity, the supply water temperature and the water flow rate are determined by using the calculation method of verified standards. Mock-up experiments are conducted to compare the calculation results of the two standards. By considering the experiment results, calculation method to derive the design data will be selected. And then, the design data of the supply chilled water and the water flow rate for various floor types was calculated.

2 REVIEW OF PREN-1264 AND ASHRAE

The cooling capacity calculation methods are presented in prEN-1264: ‘Water based surface embedded heating and cooling systems part 2, part 5’ and Ch. 6 Panel Heating and Cooling of ASHRAE System and Equipment Handbook. If the cooling capacity and floor construction type are fixed, the supply chilled water temperature can be calculated by using two calculation methods.

Table 1 : Comparison prEN-1264 method and ASHRAE method

	prEN-1264	ASHRAE
Room temperature	Operative temperature	Dry bulb temperature, AUST
Calculation of heat transfer on a surface	Overall heat transfer (sum of convective coefficient and radiative coefficient) is used	Convection and radiation is separated
Analysis model for conduction within panel	2-dimensional FEM	fin model, 1-dimenstional conduction,
Temperature rise of chilled water	Logarithmically	Linearly

The cooling capacity depends on the heat exchange between the floor surface and the room. Radiation and convection heat transfer occur simultaneously on the panel surface. In the prEN-1264 calculation method, the surface heat transfer coefficient is the sum of the radiative heat transfer coefficient and the convective heat transfer coefficient, and the coefficient is constant (6.5 W/m^2 · K). Conversely, in the ASHRAE method, the radiative heat transfer and the convective heat transfer are calculated separately, and the coefficient varies according to the panel surface temperature and the room set temperature. A comparison between the prEN-1264 calculation methods and the ASHRAE methods is shown in table 1. Multi dimensional conductive heat transfer occurs within the floor panel. In order to solve the temperature distribution within the panel, the FEM is used in the prEN-1264. In the ASHRAE method, heat transfer within the panel is assumed 1-dimensional and the minimum panel surface temperature is calculated by using fin efficiency.

The supply chilled water temperature which is inlet water temperature of the pipe is determined by assuming the temperature difference between the supply water and the return water. In the prEN-1264 calculation method it is assumed that the temperature varies logarithmically while in the ASHRAE method the temperature varies linearly.

In the prEN-1264 method, the chilled water temperature is calculated from the following equations.

$$q = K_c \cdot \Delta T_c$$

$$K_c = \frac{K_{H,Floor}}{1 + \frac{\Delta R_\alpha + R_c}{R_c^*}\left(\frac{K_{H,Floor}}{K_{H,Floor}^*} - 1\right)}$$

$$\Delta T_C = \frac{T_S - T_R}{\ln \frac{T_S - T_R}{T_R - T_i}}$$

Where,

- q : heat flux on the surface, (W/m^2)
- K_c : equivalent heat transmission coefficient, (W/m^2·K)
- ΔT_c : cooling medium differential temperature, (℃)
- T_S : supply chilled water temperature, (℃)
- T_R : return chilled water temperature, (℃)
- T_i : operative temperature in a room, (℃)
- ΔR_c : additional thermal transfer resistance (0.0613 m^2·K/W)
- R_c : thermal resistance of floor covering, (m^2·K/W)
- R^*_c : higher thermal resistance of floor covering (0.15 m^2·K/W)
- $K_{H,Floor}$: equivalent heat transmission coefficient of the same system with the thermal resistance of the covering R_c=0 m^2·K/W obtained from radiant floor heating system. (W/m^2·K)
- $K^*_{H.Floor}$: equivalent heat transmission coefficient of the same system with the thermal resistance of the covering R_c=0.15 m^2·K/W obtained from radiant floor heating system. (W/m^2·K)

In the ASHRAE method, the following equation is used for the calculation method.

$$T_w = (q + q_b)PR_t + T_d$$

Where,

- T_w : average chilled water temperature, mean of supply chilled water temperature and return chilled water temperature, (℃)
- q_b : heat flux of back and perimeter heat gains, (W/m^2)
- P : pipe spacing, (m)
- R_t : thermal resistance of pipe wall per unit pipe spacing in a hydronic system, (m·K/W)
- T_d : average skin temperature of pipe, (℃)

The average skin temperature of the pipe is calculated from the following equations.

$$T_d = T_a + \frac{(T_p - T_a)P}{2W\eta + D_O} + q(R_p + R_c + R_s P)$$

Where,

- T_a : dry-bulb temperature in a room, (℃)
- T_p : average panel surface temperature, (℃)
- 2W : net spacing between pipe, P-D_O (m)
- D_O : outside diameter of pipe, (m)
- R_p : thermal resistance of panel body, (m^2·k/W)
- R_c : thermal resistance of active panel surface covers, (m^2·k/W)
- R_s : thermal resistance between pipe and panel body, (m·k/W)

The fin efficiency is determined from the following equation.

$$\eta = \frac{\tanh(fW)}{fW}$$

$$f \approx \left[\frac{q}{m(T_p - T_a)\sum_{i=1}^{n} k_i x_i}\right]^{1/2}$$

Where,

- η : fin efficiency
- m : 2+R_c/R_p
- f : fin coefficient
- n : total number of different material layers, including panel and surface covers
- x_i : characteristic thickness of each material layer, (m)
- k_i : thermal conductivity of each layer (W/m·K)

The calculation results of the cooling capacity according to the supply chilled water temperature are shown in figure 1. The input data of the prEN-1264 calculation method is the same as that of the ASHRAE calculation method. The input data is shown in table 2. Because the set temperature of the prEN-1264 method is an operative temperature, the dry bulb temperature and the AUST (area-weighted ceiling, floor, windows, doors, etc) used for the set temperature in the ASHRAE method are transformed to an operative temperature.

When the supply chilled water temperature are equal, the differences in the cooling capacity between the calculation results of prEN-1264 and ASHRAE are approximately 10W/m^2. Considering that the cooling load of a typical room in the mid-floor of an apartment building is 50W/m^2 to 60W/m^2, these calculation results should not be overlooked.

3 INVESTIGATION OF CALCULATION RESULTS BY PERFORMING THE MOCK-UP EXPERIMENTS

To verify the application of the prEN-1264 method or the ASHRAE method, the experiments were conducted

3.1 Experiment method

The experiments were carried out in a mock- up test cell. The cell is equipped with a radiant heating and cooling system. The floor construction

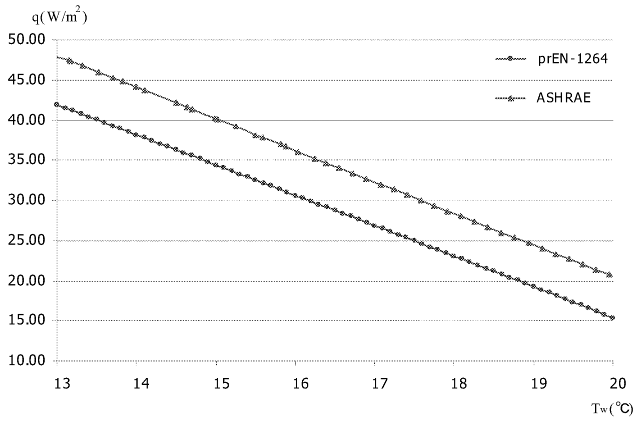

Figure 1 : comparison cooling capacity calculated by the prEN-1264 and the ASHRAE

Table 2 : Calculation input data

Variable	Value
Altitude above sea level (m)	0
Emittance of panel surface	0.9
Indoor design temperature (℃)	26
Outdoor design temperature (℃)	31.1
The number of room surfaces exposed outdoor	1
Panel surface area (m^2)	20
Type of floor coverings	Linoleum
Thick. of the mortar above the pipe (m)	0.03
Type of pipes	XL(Ø 15)
Thermal resistance below the pipe (m^2· K/W)	1.13

Table 3 : Floor construction

Parameters	Thickness (m)
Linoleum	0.002
Mortar	0.05
XL pipe	-
Plywood	0.03
Insulator	0.2
Moisture-proofing Vinyl	-

is similar to that of a Korean residential building. The section of floor construction is shown in table 3. To minimize heat transfer from the cell to the outdoors, a 200mm thick insulating material is installed in the ceiling and in the walls, while the same temperature (26℃) of the external space of the cell was maintained by PAC. To make a sensible cooling load in the cooling season, a stainless steel wall panel was installed. Hot water was supplied to the stainless steel wall panel. The wall panel was maintained at 34℃ for making maximum cooling capacity ($40W/m^2$), at 37℃ for making peak load of the cooling season ($60W/m^2$). Set temperature of the wall panel to make load was calculated by splitting radiation and convection on the wall transfer, the star circuit model was used. To calculate convective heat transfer, the equation presented ASHRAE was used.

Chilled water from the chiller was supplied to the floor panel, and the chilled water temperature was controlled by a 3 way valve. The chilled water flow rate was manually controlled by the valve opening. The temperature of the supply and return water, and the surface temperature of the walls, the floor and the ceiling were measured by T-type thermocouples. The experiments were performed until floor panel surface temperature was in stable condition. The control time step was 2 minutes taking into account the valve actuating time.

The chilled water temperature ranges from 13℃ to 16℃ due to the minimum temperature of the chilled water while the cooling performance of the high temperature cooling was verified. The experiment conditions of the chilled water are shown in table 4.

In the prEN-1264 method, in order to obtain a cooling capacity of $40W/m^2$, the average chilled water temperature was 15.1℃. The supply chilled water temperature could therefore not

Table 4 : Test conditions

Case NO.	Set temp. wall panel (℃)	Chilled water temp. (℃)	Calculation method	△T (K)	Flow rate (lpm)
1	34.0	13.0	ASHRAE	8.5	0.7
2	34.0	13.0	prEN-1264	4.0	1.4
3	34.0	14.0	ASHRAE	6.5	0.8
4	34.0	14.0	prEN-1264	2.1	2.6
5	34.0	15.0	ASHRAE	4.5	1.2
6	34.0	16.0	ASHRAE	2.5	2.2
7	37.0	13.0	prEN-1264	4.0	1.4
8	37.0	14.0	ASHRAE	6.5	0.8
9	37.0	14.0	prEN-1264	2.1	2.6
10	37.0	15.0	ASHRAE	4.5	1.2
11	37.0	16.0	ASHRAE	2.5	2.2

within the pipe, the water velocity should not exceed 1.2m/s. The water velocity could be transformed to the water flow rate by considering the diameter of the pipe. The water flow rate should not exceed 14.48lpm when using an XL pipe (Ø15). According to the calculation results, when the chilled water temperature was 15℃, the water flow rate was 25.26lpm. Therefore, the case where the water temperature is 15℃ was not considered.

3.2 Experiment results and discussions

The results of experiments are shown in table 5. The cooling capacity is calculated by multiplying the temperature difference of chilled water by flow rate and the specific heat of water when the floor surface temperature is under stable condition. Also, the overall heat transfer coefficient is calculated by dividing the cooling capacity by temperature difference between surface temperature and operative temperature in the room.

In all cases of the wall panel set temperature is 34℃, the value of cooling capacity was lower than $40W/m^2$. The cooling capacity of cases designed by prEN-1264 was close to $40W/m^2$ than those cases designed ASHRAE. It is considered that chilled water temperature differences of ASHRAE cases were too small compared assumed temperature difference.

In cases of the wall panel set temperature is 37℃, the cooling capacity of case 7 and case 9 were higher than $40W/m^2$ but others were lower than $40W/m^2$. In the same way, the chilled water temperature differences of the ASHRAE cases were too small. In consequence, if the supply

Table 5 : Comparison design data and test results

Case No.	Set temp. of wall panel (℃)	Calculation method	Flow rate (lpm)	Water temp. (℃)		△T (K)		Cooling capacity (W/m^2)	Overall heat transfer coefficient ($W/m^2 \cdot K$)
				Design data	Test results	Design data	Test results		
1	34.0	ASHRAE	0.7	13.0	13.4	8.5	3.8	18.2	3.1
2	34.0	prEN-1264	1.4	13.0	13.3	4.0	3.0	29.8	5.3
3	34.0	ASHRAE	0.8	14.0	14.1	6.5	2.4	15.0	2.4
4	34.0	prEN-1264	2.6	14.0	14.0	2.1	1.7	31.0	4.8
5	34.0	ASHRAE	1.2	15.0	15.0	4.5	1.9	18.1	3.2
6	34.0	ASHRAE	2.2	16.0	15.6	2.5	1.4	21.2	3.8
7	37.0	prEN-1264	1.4	13.0	13.1	4.0	4.2	42.2	6.4
8	37.0	ASHRAE	0.8	14.0	14.0	6.5	4.7	28.8	4.6
9	37.0	prEN-1264	2.6	14.0	13.7	2.1	3.1	55.6	8.3
10	37.0	ASHRAE	1.2	15.0	14.9	4.5	2.3	20.0	2.9
11	37.0	ASHRAE	2.2	16.0	15.8	2.5	1.4	23.7	2.8

chilled water temperature is designed 13℃ or 14℃, it is satisfactory that prEN-1264 methods are appropriate.

The temperature difference ranges between 2.96K and 4.15K where supply water and 1.37 K and 1.44K where supply water temperature is 16□. According to experimental results, it is considered to assume temperature difference 2K to 5K where supply water temperature is 13℃ or 14℃, 2K to 3K where supply water temperature is 15℃ to 16℃ in design process.

4 SUPPPLY CHILLED WATER TEMPERATURE AND WATER FLOW RATE TO OBTAIN COOLING CAPACITY

4.1 Determination of floor construction

Various floor construction types will be made by varying the locations, types and thicknesses of materials. Also, if the pipe spacing varies, then the floor construction is also varied. By considering the most effective parameters for heat flow density and the floor construction types for Korean residential buildings, the representative floor panel type is selected. The design data according to the representative floor panel type is then suggested. According to previous research (Shin, 2008), the pipe spacing significantly influences the heat flow density, followed by the thermal resistance of the floor covering and the heat conductivity of the mortar. If PB pipe is used, the pipe spacing varies from 150mm to 250mm. Linoleum and woods covering are mainly used for the floor covering. The thickness of the mortar, the diameter of the pipe, the thickness of the pipe and the heat conductivity of the pipe do not have a significant influence.

4.2 Supply chilled water temperature and flow rate according to floor construction type

By using prEN-1264 method, the supply chilled water and the water flow rate were calculated for various floor types. The cases designed by prEN-1264 that the supply chilled water Temperature is 15℃ or 16℃ were not confirmed experimentally. Therefore, the design data in those cases should be used by considering those limitations. The design data is shown in table 6.

5 CONCLUSION

In this study, the design data of the supply chilled water temperature and the flow rate for the radiant floor cooling system in residential buildings were derived by using calculation method presented prEN-1264 standard. To verify application of the standard, experiments were conducted. The experimental results showed the calculation results of the prEN-1264 can be used in design process, in case the temperature of supply chilled water is low (13℃, 14℃). If the temperature of supply chilled water is higher than 15℃, calculation results need to be adjusted.

This study, however, experiments were conducted under the floor construction was fixed. If the pipe spacing or the floor covering is varied, the supply chilled water temperature and the water flow rate can be vary under the set

Table 6 : Cooling capacity for different pipe spacing, floor coverings, supply chilled water temperature and water flow rate

Floor Coverings	Supply chilled water temp. (℃)	ΔT (K)	Pipe spacing (mm)									
			150		180		200		230		250	
			Flow rate (lpm)	Cooling capacity (W/m^2)	Flow rate (lpm)	Cooling capacity (W/m^2)	Flow rate (lpm)	Cooling capacity (W/m^2)	Flow rate (lpm)	Cooling capacity (W/m^2)	Flow rate (lpm)	Cooling capacity (W/m^2)
Linoleum	13	5	2.74	40.97	2.46	36.71	2.06	35.03	2.18	32.67	2.09	31.19
		4	3.63	43.37	3.25	38.87	2.73	37.09	2.89	34.58	2.76	33.02
		3	5.09	45.67	4.56	40.93	3.83	39.06	4.06	36.42	3.88	34.77
		2	8.01	47.90	7.18	42.92	6.02	40.96	6.39	38.19	6.10	36.46
	14	5	2.46	36.74	2.20	32.93	1.85	31.42	1.96	29.30	1.87	27.97
		4	3.28	39.19	2.94	35.12	2.46	33.51	2.61	31.25	2.49	29.83
		3	4.63	41.52	4.15	37.21	3.48	35.51	3.69	33.11	3.52	31.61
		2	7.32	43.76	6.56	39.22	5.50	37.42	5.83	34.90	5.57	33.31
	15	3	4.16	37.36	3.73	33.48	3.13	31.95	3.32	29.79	3.17	28.44
		2	6.63	39.62	5.94	35.51	4.98	33.89	5.28	31.60	5.04	30.16
	16	3	3.70	33.19	3.32	29.75	2.78	28.39	2.95	26.47	2.82	25.27
		2	5.93	35.48	5.32	31.80	4.46	30.34	4.73	28.29	4.52	27.01
Woods covering	13	5	2.20	32.89	2.00	29.94	1.69	28.73	1.81	27.01	1.73	25.94
		4	2.91	34.82	2.65	31.70	2.24	30.42	2.39	28.60	2.30	27.46
		3	4.09	36.67	3.72	33.38	3.14	32.03	3.36	30.12	3.22	28.92
		2	6.43	38.46	5.85	35.01	4.94	33.59	5.28	31.58	5.07	31.32
	14	5	1.97	29.50	1.80	26.86	1.52	25.77	1.62	24.23	1.56	23.26
		4	2.63	31.46	2.39	28.64	2.02	27.49	2.16	25.84	2.07	24.81
		3	3.72	33.34	3.38	30.35	2.85	29.12	3.05	27.38	2.93	26.29
		2	5.88	35.14	5.35	31.99	4.51	30.69	4.83	28.86	4.63	27.70
	15	3	3.34	30.00	3.04	27.31	2.57	26.20	2.75	24.64	2.64	23.65
		2	5.32	31.81	4.84	28.96	4.09	27.79	4.37	26.13	4.19	25.08
	16	3	2.97	26.65	2.70	24.23	2.28	23.28	2.44	21.89	2.34	21.01
		2	4.76	28.49	4.34	25.93	3.66	24.89	3.91	23.40	3.76	22.46

cooling capacity. To establish accurate design data, experiments or simulation should be conducted for various floor construction types.

Despite those limitations, this study provides quantitative design data of radiant floor cooling systems for Korean residential buildings. These data can be used to determine chilled water temperature and water flow rate in design process of radiant floor cooling system.

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