A Study on the Hybrid Air-conditioning system Coupled with Radiant Floor Cooling and Ventilation System

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Abstract
In this study, the concept of the Hybrid air-conditioning system utilizing convection and radiation heat exchange will be suggested. In this paper, the heat removal characteristics of Hybrid air-conditioning system will be described by theoretical review and experimental methods. Also the ratio of cooling load removed by Hybrid air-conditioning system could be divided as radiation and convection heat exchanges.
The methods could be used to system design of Hybrid air-conditioning system.

Keywords: Hybrid Air-conditioning system, Radiant floor cooling, Energy

Introduction

The survival of the human race is being threatened by the increase of various disasters from climate change such as global warming, and globally concerted efforts are being made to cope with these problems. In architecture, demand for energy reduction is rising, and many studies are being conducted to find measures to save cooling and heating energy in buildings in particular. On the other hand, with the rising demand for improvement of the quality of life and comfortable indoor environment, energy use in buildings is growing. In this context, as a comfortable cooling and heating system with energy efficiency energy, a hybrid air-conditioning system which combines the conventional radiant floor cooling system with ventilation system is being spotlighted.

As an existing study on hybrid air-conditioning systems, Song et al. (2004) [1] proposed a cooling system that combines radiant floor cooling, dehumidification, natural ventilation, and free cooling, and examined the possibility of indoor environment adjustment and energy saving effects of the proposed system through experiments. However, they did not investigate the calculation method for heat removal by convection and radiation which is the most important for actual application of a hybrid air-conditioning system to buildings.

There are some studies that reported on heat removal by convection and radiation mainly through simulations [2], but there are few examples that investigated it through experiments. Olsen and Carli (1995) [3] determined the heat transfer characteristics and heat removal by different indoor temperatures of a radiant floor cooling system through experiments. Furthermore, Fisher and Pederson (1997) [4] established a calculation method for convective heat transfer coefficient and heat removal according to the changes in air flow rate of a forced convection system. Mcadams et al. investigated the characteristics of natural convection according to differences in indoor temperature.

This study aims to establish a theoretical equation for heat removal of the hybrid air-conditioning system that combines convection and radiation heat exchange on the basis of the findings of Olsen, Fisher, Mcadams, and others, and present a calculation method for heat removal features by convection and radiation of the hybrid air-conditioning system.

Outline of the Hybrid Air-conditioning System

The hybrid air-conditioning system for consists of a radiant floor cooling system utilizing floor hot water coils which installed in residential building in Korea and a cooling/dehumidifying ventilation system attached to walls.

In summer season, the radiant floor cooling system is used and chilled water is supplied to the ventilation system for cooling/dehumidifying the outside air which introduced indoors for ventilation. When indoor humidity increases and condensation occurs on the floor, the outside air inlet is closed and the inside air is circulated which removes humidity from the inside air. In mid-season when the outside air condition is relatively favorable to control indoor environment, the outside air is directly brought to the inside to remove indoor heat and contaminant. Furthermore, under the condition where natural ventilation is possible, outside air is brought in through natural ventilation; otherwise, mechanical ventilation is used. If room temperature cannot be controlled by the radiant floor cooling system only due to rapidly increasing outside air temperature and internal cooling load, the ventilation system removes surplus load to control the room temperature to a comfortable level.

The hybrid air-conditioning system proposed in this study removes indoor heat through convective and radiant heat exchange. To define the heat removal performance of this system, therefore, it is important to investigate the characteristics of convective and radiant heat exchange.

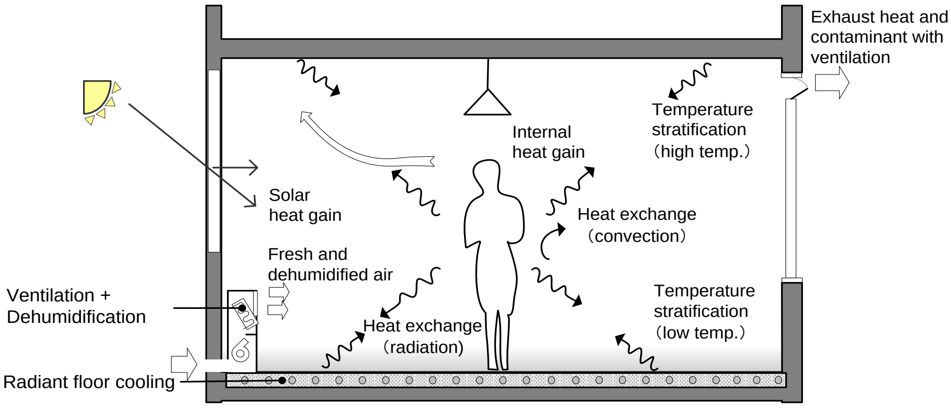

Fig. 1 Concept of hybrid air-conditioning system

Calculation of Heat Removal by the Hybrid Air-conditioning System

1) Calculation of heat removal by radiant floor cooling

The total heat transfer of radiant floor cooling system can be divided into the radiant heat exchange between surface and surrounding walls, the convective heat exchange between the cooling surface and the ambient air. But it is very difficult to calculate these two values simultaneously because their mechanisms are different.

Table 1 Parameter and variable

Q_{rad}	radiant heat transfer(W/m^2)
$Q_{f,conv}$	forced convective heat transfer(W/m^2)
$Q_{n,conv}$	natural convective heat transfer(W/m^2)
Q_{floor}	total radiant heat transfer(W/m^2)
h_{rad}	radiant heat exchange coefficient(W/m^2K)
$h_{f,conv}$	forced convective heat exchange coefficient(W/m^2K)
$h_{n,conv}$	natural convective heat exchange coefficient(W/m^2K)
T_f	absolute temperature of floor surface(K)
T_i	absolute temperature of surface i(K)
T_{room}	Average indoor temperature (K)
T_o	Absolute temperature of outdoor(K)
$T_{f,s}$	absolute temperature of centilation system(K)
$X_{f,s}$	absolute humidity of centilation system(kg/kg')
X_o	absolute humidity of outdoor(kg/kg')
ε_i	emissivity of the other surface
ε_f	emissivity of floor surface
Σ	Stefan – boltzmann constant($5.67 \times 10^{-8} W/m^2K^4$)
$F_{A_f-A_i}$	view factor between floor surface A_f and surface A_i
C	specific heat water(J/m^5K)
q_w	water floor rate(m^3/s)
Q	air floor rate(m^3/s)

Thus, in the case of radiant floor cooling, it is important to determine the characteristics values of the convective or radiant heat transfer (for example, convective heat transfer rate, convective heat transfer rate, etc.). The indoor heat removal of the radiant floor cooling system is defined by the following expression (1):

$$Q_{floor} = Q_{n,conv} + Q_{rad} \quad \text{(Eq. 1)}$$

For calculation of the heat exchange by floor radiation in the radiant floor cooling system, if we assume that the whole surface is gray, the heat flux of other surfaces than the floor surface can be expressed as follows [5]:

$$Q_{rad} = \varepsilon_f \sigma T_f^4 - \sum_{j=1}^{N} \varepsilon_f \sigma T_i^4 F_{A_f - A_i} \qquad \text{(Eq. 2)}$$

Here, the emissivity of the gray surface of the internal wall is 0.9～0.95. The above expression can be linearized as follows:

$$Q_{rad} = \varepsilon_f \sigma \sum_{j=1}^{N} \theta_{f,i} (T_f - T_i) F_{A_f - A_i} \qquad \text{(Eq. 3)}$$

Here, $\theta_{f,i}$ which can be expressed as

$$\theta_{f,i} = \frac{T_f^4 - T_i^4}{T_f - T_i} \qquad \text{(Eq. 4)}$$

is the temperature difference between the floor surface and other surfaces determined by experiments. $\theta_{f,i}$ can be changed to the constant θ. Therefore, expression (4) can be converted to expression (5):

$$Q_{rad} = \varepsilon_f \sigma \theta \sum_{j=1}^{N} (T_f - T_i) F_{Af-Ai} \qquad \text{(Eq. 5)}$$

$$Q_{rad} = h_{rad} \sum_{j=1}^{N} (T_f - T_i) F_{Af-Ai} \qquad \text{(Eq. 6)}$$

F_{AF-Ai} is the view factor between the floor surface and all the other surfaces. The radiant heat exchange coefficient h_{rad} can be expressed as follows:

$$h_{rad} = \varepsilon_f \sigma \theta \qquad \text{(Eq. 7)}$$

For the convective heat transfer of the radiant floor cooling and heating system, heat exchange results from the heat transfer by natural convection which is caused by the temperature gradient between the floor surface and ambient temperatures rather than from the heat transfer by forced convection caused by forced outside condition difference. Because the flow velocity of the natural convection is much lower than that of the forced convection, the convective heat transfer rate must be, too. But this must be considered because it is essential for determination of the heat transfer characteristics.

According to many papers and reports on heat transfer, the heat transfer by natural convection can be expressed as a function of the temperature difference ΔT between the floor (T_f) and the indoor air (T_{room}) [3, 6].

In particular, the heat transfer of radiant floor cooling can be simply expressed as expression (8) in consideration of the length of the floor surface.

$$h_{n,conv} = 0.59(\Delta T/L)^{0.25} \qquad \text{(Eq. 8)}$$

Therefore, this study calculated the heat removal by natural convection in the radiant floor system by defining of the heat transfer coefficient as a function of ΔT as in expression (8). The heat removal by natural convection can be expressed as expression (9):

$$Q_{n,conv} = 0.59(\Delta T/L)^{0.25}(T_{room} - T_f) \quad \text{(Eq. 9)}$$

2) Calculation of the heat removal by the ventilation system

The heat removal by the ventilation system which corresponds to the forced convection can be defined as follows:

$$Q_{f,conv} = h_{f,conv}(T_{room} - T_s) \quad \text{(Eq. 10)}$$

3) Calculation of heat removal through experiment

① Space for experiment

For the space for experiment, the test cell in the architectural environment laboratory of the Sungkyunkwan University was used. It has the dimensions of 2.2(m) 2.2(m) 2.4(m). With the exclusion of the ondol-floor(0.224$W/m^2{}^\circ C$), the ceiling and walls are composed of 2(cm) veneer board+16(cm) Styrofoam+2(cm) veneer board (0.232$W/m^2{}^\circ C$). The southern surface of the test cell is interfacing with the outside of the laboratory and all the other surfaces are interfacing with the inside of the laboratory. To minimize the effect of outside air and the indoor load variations by sunlight, a 5cm thick Styrofoam was attached to the southern surface of the laboratory. X-L pipes were buried in the floor for ondol, and cool water was circulated inside the test cell by a loop pump for radiant cooling.

② Details of experiment

The temperature of the supplied chilled water during radiant floor cooling is controlled by the temperature setting of the heat exchange. The heat exchange is controlled by flow changes via a 3-way valve which was controlled by DAQ system using LABVIEW program running on a PC. Based on the lower limit of comfortable floor surface temperature determined by Olsen [3], the lower limit of the floor surface temperature was set to 21℃. The hybrid ventilation system is a convective cooling and heating system that supports cooling, heating, and ventilation. In this experiment, the ventilation system was operated in cooling mode in order to find the heat transfer rates of the ventilation system and the radiant cooling system, and the indoor set point was converged to 26℃. To measure the heat conducted from the walls, this study installed a heat flow meter. To measure the heat that flowed into the test cell, the feed and return water temperatures and the flow rate of the pump were determined. Furthermore, to determine heat removal by the ventilation system, supply air velocity and supply air temperature were measured.

The indoor temperature measuring points are shown in Fig. 2 and 3. To maintain constant heat flow through the walls interfacing with the indoor side excluding the surface interfacing the outside air of the test chamber, the temperature of the external space was set to 28℃

using the an air conditioner. For the cooling het source, a 2HP compression refrigerator was used. The total system was controlled by the LABVIEW program.

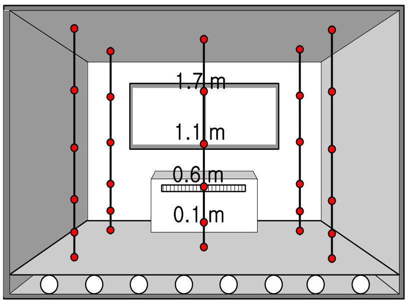

Fig. 2 Vertical temperature measuring points in the test cell

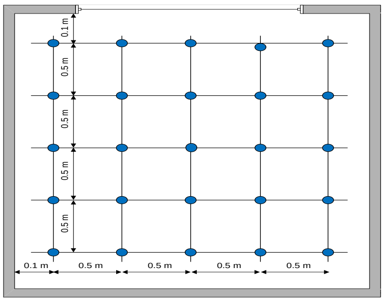

Fig. 3 Floor temperature measuring points in the test cell

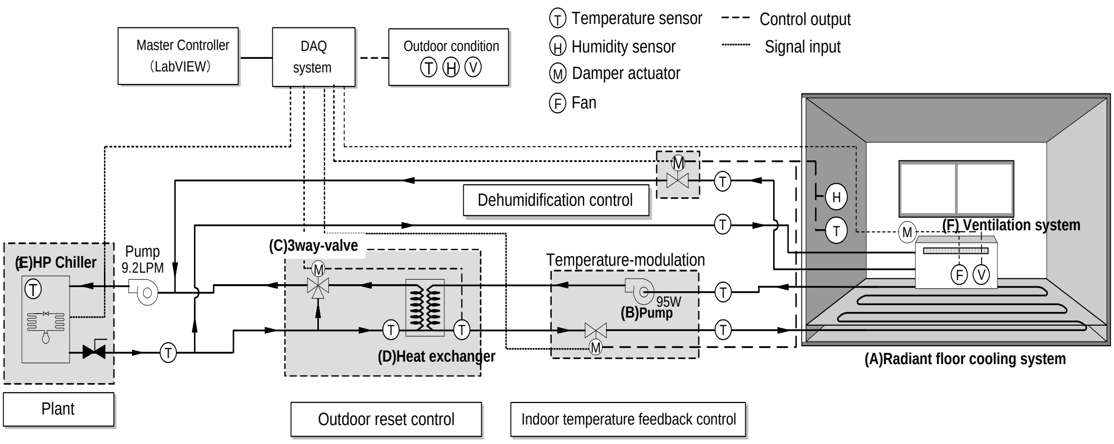

Fig. 4 Test cell system configuration

③ Calculation of heat removal

The hybrid air-conditioning system takes long until the temperature in a structure becomes constant because it is combined with radiant floor cooling. Thus, this experiment examined the heat transfer rate and heat removal of the system in the state where the indoor floor temperature converged to a constant temperature and in the state where the indoor temperature converged to the set point.

Assuming that the target space is in steady state, the heat input/output elements can be defined as follows: Q_w is the heat transferred from the cool water pipes to the room in the radiant floor cooling system; Q_{vent} is the indoor heat removal of the ventilation system which is transferred from the supply air velocity to the room; Q_{ki} is the heat conducted from each wall toward the outside; Q_{down} is the heat loss conducted downward from the cool water pipes; and Q_{inf} is the heat of the outside air supplied to the room by the infiltration the outside air. Therefore, the indoor energy equilibrium equation by the hybrid air-conditioning system becomes as follows:

Table 2 Measurement item

	Measurement item	Measuring instruments	Measuring interval
Indoor and outdoor temperatures and humidity	Indoor temp. (vertical) -30points	Thermocouple (K-type thermo couple) + data-logger	10sec
	Wall temp. – 12 points		10sec
	Floor temp. – 25 points		10sec
	Indoor humidity (at 0.6m)	SK-SATO	10sec
	Indoor humidity (at 0.1m)	KIMO thermo-hygrometer	10sec
Wind velocity, temperature, and humidity of the ventilation system	supply air velocity, temperature and humidity -2 points (outlet, room center)	Hotwire anemometer (KANOMAX)	10sec
Heat flow rate	Wall heat flow rate - 5points Under-floor heat flow rate - 1 point	Heat flow meter + data-logger	10sec
Cool water temperature	Cool water supply and return temperatures	Water temperature meter (testo)	10sec
Outside air conditions	Temperature·humidity,·wind	Weather station	1 min

	velocity·wind, direction		
Infiltration	Measurement of indoor infiltration using CO2 concentration decay method	CO2 meter	5min

$$Q_{tot} = Q_w + Q_{vent} - Q_{ki} - Q_{down} - Q_{inf} \quad \text{(Eq. 11)}$$

Where

$Q_w = cq_w(T_s - T_r)$

$Q_{vent} = q_S + q_L, \quad q_S = 0.24 \times 1.2 \times q(T_{f,s} - T_{room}), q_L = 597.3 \times 1.2 \times q(X_{f,s} - X_o)$

$Q_{inf} = 0.24 \times 1.2 \times q(T_{room} - T_o)$

Heat (Q_{ki}) and heat loss (Q_{down}) can be measured by the heat flow meter, and the heat loss by infiltration (Q_{inf}) can be defined by the calculation of infiltration quantity by the CO2 concentration decay method.

Expression (11) is the energy equilibrium equation for calculation through experiments.

As described above by literature review about radiant floor cooling and convective heat exchange, the indoor energy equilibrium equation can be expressed as follows in consideration of the radiation, forced convection, and natural convection:

$$Q_{tot} = Q_{rad} + Q_{f,conv} + Q_{n,conv} \quad \text{(Eq. 12)}$$

Therefore, based on expressions (11) and (12), the energy equilibrium equation from theory and experiment can be expressed as follows:

$$Q_{tot} = Q_{rad} + Q_{f,conv} + Q_{n,conv} = Q_w + Q_{vent} - Q_{ki} - Q_{down} - Q_{inf} \quad \text{(Eq. 13)}$$

In expression (13), the convective heat transfer of the hybrid air-conditioning system can be expressed as follows:

$$Q_{f,conv} = Q_w + Q_{vent} - Q_{rad} - Q_{n,conv} - Q_{ki} - Q_{down} - Q_{inf} \quad \text{(Eq. 14)}$$

Therefore, the convective heat transfer rate of the ventilation system which is essential for determination of the capacity of the hybrid air-conditioning system is as follows:

$$h_{f,conv} = \left[\frac{Q_{vent}+Q_w-\left\{h_{rad}\sum_{j=1}^{N}(T_f-T_i)F_{Af-Ai}\right\}-0.59(\Delta T/L)^{0.25}(T_{room}-T_s)-Q_{ki}-Q_{down}-Q_{inf}}{(T_{room}-T_s)}\right] \quad \text{(Eq. 15)}$$

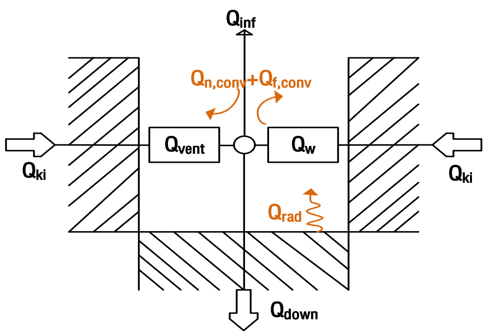

Fig. 5 Heat transfer exchange of Hybrid air-conditioning system

Meanwhile, the view factors (F_{AF-Ai}) between the floor surface and all the other surfaces for definition of the radiant heat exchange are as shown in Table 3.

Table 4 shows the values of θ that have been calculated by substituting in the expression (4) the surface temperatures and the floor temperature which have been determined through experiments.

Table 5 shows the radiant heat exchange ratios calculated by expression (7) based on the internal surface emissivity (0.9～0.95) and different θ values. Thus, the mean value of the radiant heat transfer coefficient was 5.53(W/m^2K). Furthermore, the heat transfer coefficient of natural convection based on the floor surface temperature of radiant cooling calculated by expression (8) was 0.72 (W/m^2K). This is within the general range of natural convective heat transfer coefficient which is 0.4～0.8(W/m^2K) in temperature range between 0 and 10℃[6].

Table 6 shows the values of convective heat transfer coefficients of the ventilation system calculated by expression (15). The heat exchange coefficients by forced convection were indicated by dividing the measured wind velocity of the system to 1.0, 1.5, and 2.0(m/s). The convective heat transfer coefficient was 3.56~4.35(W/m^2K).

Figure 6 shows the heat removal values of the hybrid air-conditioning system which were determined with the convective heat transfer ratio of the ventilation system and the convective and radiant heat transfer ratios of the radiant cooling system that have been calculated above.

The heat removal by radiation of the radiant floor cooling system was 42.745(W/m^2K), the heat removal by natural convection was 3.32(W/m^2K), and the heat removal of the ventilation system (forced convection) per unit area was 41.23(W/m^2K).

Table 3 View factor of experimental space

	View factors					
	Ceiling	East wall	West wall	South wall	North wall	Window
Floor	0.178	0.206	0.206	0.138	0.206	0.067

Table 4 Surface temperature

T_f(℃)	T_i(℃)	$\theta(K^3)$
21.2℃	25.3	1.05×10^8
	25.4	
	26.6	
	25.7	
	27.1	1.06×10^8

Table 5 Radiant heat transfer

$\sigma(W/m^2K^4)$	E	$\theta(K^3)$	$h_{rad}(W/m^2K)$
5.67×10^{-8}	0.9	1.05×10^8	5.36
		1.06×10^8	5.41
	0.95	1.05×10^8	5.65
		1.06×10^8	5.71

Table 6 Forced convection heat transfer

Air Velocity(m/s)	T_s(℃)	T_{room}(℃)	$h_{f,conv}(W/m^2K)$	$Q_{f,conv}(W/m^2)$
1.0	15.5	26.5	3.56	32.04
1.5	15.1	26.1	3.82	37.1
2.0	14.7	25.5	4.35	43.82

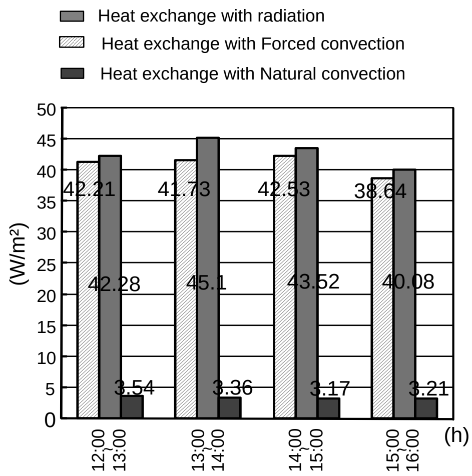

Fig. 6 Heat removed by Hybrid air conditioning system

Conclusions

In order to establish the design methodology of the hybrid air-conditioning system that combines convection and radiation heat exchange, this study presented methods for calculating the heat transfer rate such as convective heat transfer rate, radiant heat transfer rate and for calculating the heat removals by convective and radiant heat exchanges through experiments on the basis of relevant theoretical equations. The findings from this study enable the determination of system capacity which is essential for application of the hybrid air-conditioning system to actual buildings.

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