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A Study on Cooling Systems with Cold Water Panels in the Walls of Small Buildings

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소형 건축 벽면의 냉수 패널에 의한 냉방시스템에 관한 연구

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ABSTRACT

This study was conducted on cooling systems in which, for the first time at home and abroad, cold water panels are embedded in the walls of small buildings for radiant cooling by heat absorption with cold water. In summer, cold water is circulated through cold water (chiller) circulation tubes embedded in three walls (two side walls and one rear wall) of a building to implement radiant cooling by the coldness of the water. From the results of this study, the experimental and theoretical natural convection heat transfer coefficients were relatively well-matched over the entire experimental range, thereby verifying the reliability of the experimental results. The surface temperature reduction rate of the walls in which cold water panels are embedded was large whereas that of the walls where no cold water panels are embedded was very small.

Keywords : Cold Water Panels(냉수 패널), Cooling System(냉방시스템), Small Building Walls(소형 건축 벽면), Radiant Cooling(복사냉방), Natural Convection Heat Transfer Coefficient(자연대류열전달계수)

1. Introduction

At home and abroad, summer cooling systems for existing houses, offices, pensions, and other such structures are mainly used in spaces not smaller than 8 pyeong, and these cooling systems typically employ convection heat transfer based on the air-circulation method[1-3]. Because demand for buildings with spaces not exceeding 2 pyeong, such as pensions, hwangtobangs, and small accommodations, is gradually increasing, studies on cooling technologies suitable for these spaces are urgently needed[4]. However, the extant research on this topic is inadequate, and currently, such small spaces rely on electric fans and air conditioners, even in hot midsummers. In addition, because the parts (e.g., circulation pump and freezer) suitable for

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cooling systems required in spaces not larger than 2 pyeong do not exist, the parts used in cooling systems meant for spaces larger than 8 pyeong are used instead, leading to large electric power losses and high installation costs[5-9]. Although many studies on small cold-water mat cooling technologies have been reported, these technologies may be harmful to humans because they pose the risk of nerve palsy resulting from the coldness of the mats[10,11]. Moreover, the existing technologies employ forced convection cooling, in which air is circulated forcefully by using air conditioners. By contrast, in this study, a comfortable cooling system that does not pose any health risks is implemented by employing radiant cooling through cold-water panels embedded in the walls of small buildings without any air movement or circulation. In addition, the present work aimed to reduce electric power consumption and manufacturing costs by studying the parts of cooling systems suitable for spaces not larger than 2 pyeong.

2. Experimental equipment and method

Fig. 1 illustrates a cooling system, in which cooling is achieved using cold-water panels embedded in the walls of a small building. Fig. 2 depicts a three-dimensional design drawing of the aforementioned cooling system. As illustrated in Fig. 1, in this work, a cooling system in which cold-water panels are embedded in the walls of a small building and radiant cooling is implemented through heat absorption by cold water has been studied for the first time to the best of the authors' knowledge. In this system, cold-water (chiller) circulation tubes are embedded in three walls (side wall 2 and rear wall 1) of a building in summer, and cold water is circulated through them to cool the spaces in the building by means of radiant cooling. In addition, during cooling, the wall temperature decreases to a value lower than the dew-point temperature, resulting in condensation on the wall surface. Therefore, red clay walls that control humidity automatically by absorbing moisture when humidity is high and releasing moisture when humidity is low were studied in this work to prevent condensation. The results of this study indicate that the proposed system based on radiant cooling is comfortable and healthy for users because it does not involve any movement or circulation of air, unlike forced-convection cooling systems in which an air conditioner forcefully circulates air. The experimental system for supplying cold water to the cold-water panels was configured as a small refrigeration cycle consisting of an evaporator, a compressor, a condenser, and expansion valves. Existing refrigeration cycles are suitable for cooling houses and offices that are not smaller than 8 pyeong, and they achieve cooling by using the forced convection method. However, none of these systems has been commercialized for small buildings with spaces not larger than 2 pyeong, which have been considered in this work. Therefore, a cooling system that can be used for small buildings, such as pensions not larger than 2 pyeong, was studied herein.

Fig. 1 Cooling system using cold water panels in small building walls

Fig. 3 shows the water inlet and outlet temperature measurement sensors, as well as the sensor for measuring the flow rate of cold water in the refrigeration cycle for internally cooling a small hwangtobang building. As shown in Fig. 3, three Pt 100Ω temperature sensors were installed at each inlet and outlet of the refrigeration cycle to measure temperature and compute the average temperature.

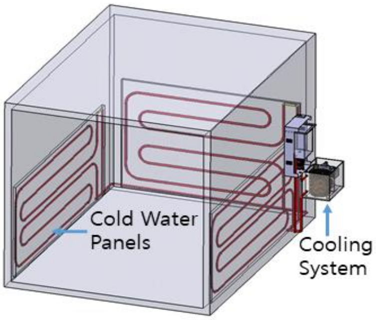

Fig. 2 Cooling system using cold water panels in small building walls

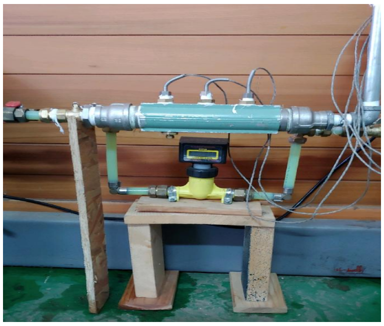

Fig. 3 Cold water chiller inlet and outlet temperature and flow rate measurement sensors

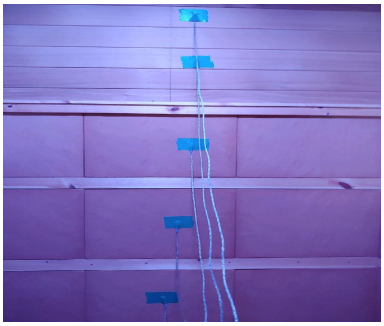

Fig. 4 Pt 100 temperature sensors for measurement of the surface temperature of the cold water panels in a small hwangtobang wall

Fig. 4 depicts the surface temperatures of the walls of the small hwangtobang building. As depicted in Fig. 4, wall surface temperatures were measured by attaching three Pt 100Ω surface-temperature sensors at intervals of 150 mm to the upper, middle, and lower areas of the walls of the said building. In addition, two Pt 100Ω surface-temperature sensors were attached to the top area of the wall of this building, where no cold-water panel was embedded, to measure the surface temperature of the wall.

3. Results and Discussion

Fig. 5 shows the thermal equilibrium between the quantity of heat absorbed by the cold-water chiller and the thermal energy lost to air inside the cooling system during the refrigeration cycle. The experimental system was configured to ensure that the cold-water chiller absorbs thermal energy during the refrigeration cycle. The thermal energy absorbed by the cold-water chiller is given by Equation (1).

$$Q_c = m_c Cp_c (T_{c2} - T_{c1}) \tag{1}$$

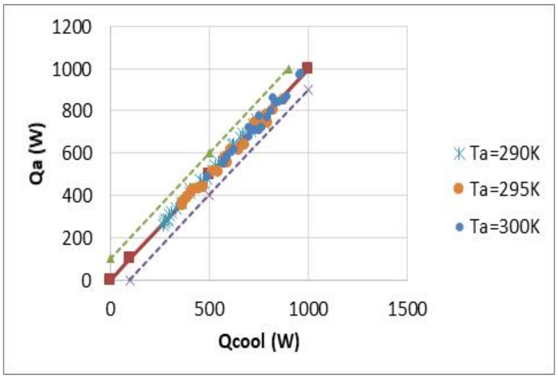

Fig. 5 Thermal equilibrium between the quantity of heat absorbed by the cold water chiller and the thermal energy lost by the air inside the cooling system through the operation of the refrigeration cycle

where Q_c represents the thermal energy (W) absorbed by the cold-water chiller, and $\dot{m}_c$ represents the mass flow rate(kg/s) of the cold water chiller. T_{c1} and T_{c2} denote the initial and final temperatures (K) of the cold-water chiller, respectively. In addition, the quantity of heat lost to air inside the cooling system is given by Equation (2).

$$Q_a = m_a Cp_a (T_{a2} - T_{a1}) \tag{2}$$

where Q_a denotes the quantity of heat (J) lost to air inside the cooling system, m_a the mass flow rate (kg/s) of air, and T_{a1} and T_{a2} the initial and final temperatures (K) of air, respectively.

As depicted in Fig. 4, the proposed system achieved a good thermal equilibrium of $\pm 5\%$ between the quantity of heat absorbed by the cold-water chiller and the thermal energy lost to air inside the cooling system during the refrigeration cycle. Therefore, the experimental results obtained in this study can be considered reliable.

Fig. 6 presents a comparison of the theoretical and experimental natural convection heat transfer coefficients of the proposed cooling system. The experimental heat transfer coefficient of natural convection was calculated using Equation (3).

$$h_{ex} = \frac{q}{A(T_\infty - T_s)} \tag{3}$$

where q represents the heat-transfer rate (W) of natural convection, A the heat-transfer surface area (m^2) of the cooling system wall, T_∞ the indoor air temperature(K) and T_s the temperature (K) of the cooling system wall.

The Rayleigh number was calculated using Equation (4).

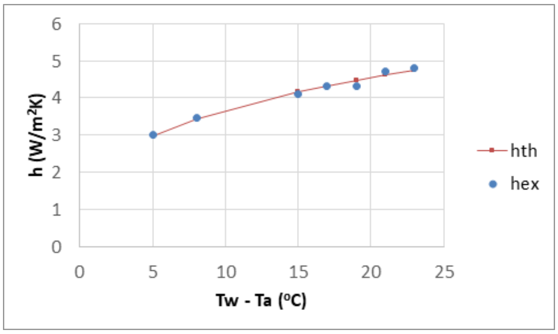

Fig. 6 Comparison of the experimental natural convection heat transfer coefficient and the theoretical natural heat transfer coefficient of the cooling system

$$Ra_L = \frac{g\beta(T_s - T_\infty)L^3}{\nu\alpha} \tag{4}$$

where g represents gravitational acceleration (m/s^2), β the volume thermal expansion coefficient ($1/K$). ν the kinematic coefficient of viscosity (m/s^2), α the thermal diffusibility (m/s^2), and L the vertical length (m) of the cooling system wall.

The Nusselt number of heat transfer through natural convection was calculated using Equation (5).

$$N_L = 0.825 + \frac{0.387 Ra_L^{1/6}}{[1 + (0.492/\mathrm{Pr})^{9/16}]^{8/27}} \tag{5}$$

where Pr denotes the Prandtl number. The theoretical heat transfer coefficient of natural convection was obtained using Equation (6).

$$h_{th} = \frac{k_f}{L} N_L \tag{6}$$

where, k_f denotes the thermal conductivity coefficient (W/mK) of air. As depicted in Fig. 4,

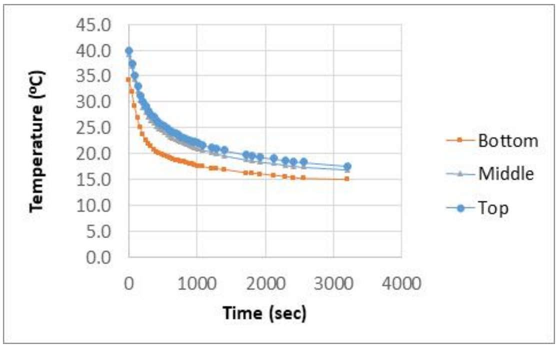

Fig. 7 Indoor air temperature in a small hwangtobang building

the experimental and theoretical heat transfer coefficients of natural convection obtained using Equations (3) and (6), respectively, exhibit good agreement throughout the experimental range. Therefore, the experimental results obtained herein can be considered reliable.

Fig. 7 depicts the indoor air temperature inside a small hwangtobang building. As depicted in this figure, three Pt 100Ω temperature sensors were installed at the top, middle, and bottom of the space inside the small hwangtobang at intervals of 300 mm to measure indoor air temperature. In the temperature measurement, the internal temperature was increased to 40 °C by supplying heat using a heater, and a room-cooling experiment was conducted thereafter. The temperature gradient was large as the indoor temperature decreased from 40 °C to 20 °C, but it was somewhat smaller as the indoor temperature decreased from 20 °C to 17 °C. On the basis of the results of this experiment, we verified that radiant cooling through the cold-water panels embedded in the inner walls of the small hwangtobang building operated as intended. In addition, good radiant cooling performance was achieved. Fig. 8 depicts the surface temperature of the wall of the small hwangtobang building considered herein. The wall surface temperature was measured by attaching three Pt 100Ω surface temperature sensors to the upper, middle, and lower areas of the wall surface at intervals of 150 mm. In addition, two Pt 100- surface temperature sensors were attached to the top area of the wall, where cold-water panels were not embedded. The temperature measured using these two sensors was compared with the temperature measured using the sensors attached to the areas of the walls with embedded cold-water panels. As shown in Fig. 8, the surface temperature of the part of the wall with the embedded cold-water panels decreased rapidly, while the surface temperature of the part of the wall with no embedded cold-water panels decreased slowly. This result indicated that the proposed radiant cooling system based on cold-water panels embedded in the walls of a small building was implemented and functioned as intended.

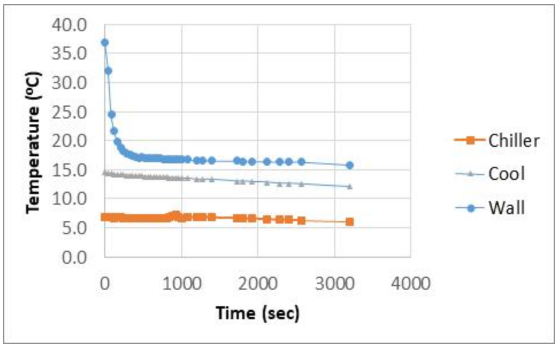

Fig. 8 Surface temperatures of a wall embedded with the cold water panels and those of a wall where no cold water panel was embedded

Fig. 9 shows the inlet and outlet temperatures of the refrigeration cycle employed in the proposed radiant cooling system. As shown in Fig. 9, three Pt 100Ω temperature sensors were installed at each inlet and outlet of the refrigeration cycle, and average values of the temperature data recorded by these sensors were computed. As shown in Fig. 9, the inlet and outlet temperatures of the refrigeration cycle were 6 °C and 1 °C, respectively. These

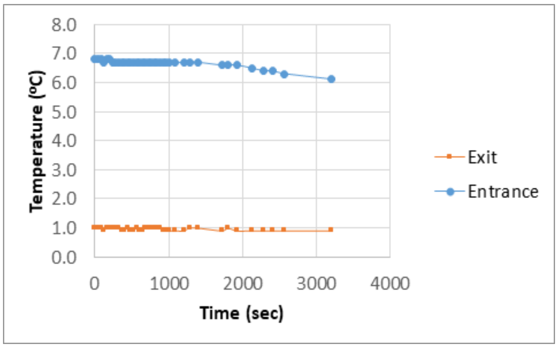

Fig. 9 Refrigeration cycle operating temperature for internal cooling of a small hwangtobang building

values indicate that the refrigeration cycle of the novel radiant cooling system implemented herein operated normally with good cooling performance.

4. Conclusion

In this work, a radiant cooling system based on cold-water panels embedded in the walls of a small hwangtobang building to implement radiant cooling was proposed in which water cold water absorbs heat from a space to cool it, and the following results were obtained.

1. A good thermal equilibrium of ±5% was achieved between the quantity of heat absorbed by the cold-water chiller and the thermal energy lost to the air inside the cooling system.
2. The experimental and theoretical heat transfer coefficients of natural convection agreed well over the entire experimental range, which indicated the reliability of the experimental results obtained in this study.
3. The temperature gradient was large as the indoor temperature decreased from 40 °C to 20 °C, but it was somewhat smaller as the indoor temperature decreased from 20 °C to 17 °C.
4. The rate of surface temperature reduction of the wall embedded with the cold-water panels was high but that of the wall with no embedded cold-water panels was very low.
5. The proposed radiant cooling system based on cold-water panels embedded in the walls of a small hwangtobang building operated normally, and the radiant cooling performance of the system was high.

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