Experimental analysis and design of hydraulic thermoelectric radiant cooling panel

Minseong Kim[1], Hye-Jin Cho[1], Soo-Jin Lee[1], and Jae-Weon Jeong[*1]

1 Department of Architectural Engineering, Hanyang University
222, Wangsimni-ro, Seongdong-gu, Seoul, Republic of Korea
**Corresponding author: jjwarc@hanyang.ac.kr*

ABSTRACT

Thermoelectric technology has developed as a substitute for existing refrigerants in heating, ventilation, air-conditioning, and refrigeration(HVAC&R) system applications for building decarbonization. Hydraulic thermoelectric radiant cooling panel operated based on the Peltier effect is one of the best way to alternate conventional cooling panels using a chiller with refrigerators. However, there are limitations to apply to building energy simulation and performance evaluation because there are few guidelines and no standard model of a water-cooled thermoelectric radiant cooling panel. Therefore, the main objective of this research is to investigate desirable flow rate and temperature of cooling water which is produced by free cooling systems to obtain valid cooling performance and power consumption of the thermoelectric radiant cooling panel. A thermoelectric radiant cooling panel was constructed and tested under a controlled laboratory environment by using the developed mock-up models based on the previous studies. The tested thermoelectric radiant cooling panel was made of aluminium panel with four thermoelectric modules installed on the top side of the panel, and a water blocks were attached on the hot side of thermoelectric module to release heat to water through the water blocks. In this case, a quarter of each thermoelectric module is set up as effective area to analyze the cooling performance of one thermoelectric module. From the experimental analysis, the cooling capacity of the thermoelectric radiant cooling panel model was in reasonable agreement with the measured flow rate and temperature of cooling water through water blocks according to the previous studies. In addition, the parametric experiment was conducted to validate empirical model for evaluating the effects of design factors on the cooling performance of the thermoelectric radiant cooling panel. The results showed that the temperature of cooling water as heat removal factor to release heat from hot side of the thermoelectric modules was the main design variables to be calculated the cooling performance and power consumption of the thermoelectric radiant cooling panel. On the other hand, the flow rate of cooling water had a relatively less effect rather than the temperature of cooling water.

KEYWORDS

Thermoelectric module, Radiant cooling panel, water-cooled system, Empirical model, Design factor

1 INTRODUCTION

Thermoelectric technology has attracted much attention as non-vapor compression refrigeration owing to its advantages of compact size, fast response, no moving parts, non-noise, and non-vibration without refrigerant (Enescu et al., 2014). The solid state thermoelectric refrigerator based on the Peltier effect is recently proposed and developed as an alternative cooling system to the conventional hydraulic ceiling radiant cooling panel since early 2000s (Luo et al., 2017). The performance of the thermoelectric module-based radiant cooling panel is directly affected by the amount of heat rejection from the heat sink, and there are air-cooled system and water-cooled system for heat dissipation.

In this case, a free-cooling system using cooling tower can be combined with a water-cooled heat dissipation system with relatively effective heat dissipation efficiency. Even though the outlet temperature produced by the cooling tower is difficult to use for removing the indoor cooling load directly due to the slight high coolant temperature, using this for heat dissipation of the thermoelectric radiant cooling panel can contribute to energy saving because it compensates for the low performance of the thermoelectric module.

Therefore, the range of the outlet temperature from cooling tower that can be produced in the Korean climate is investigated, and the performance prediction model of hydraulic thermoelectric radiant cooling panel using this cooling water for heat dissipation is presented through the experiment.

2 HYDRAULIC THERMOELECTRIC RADIANT COOLING PANEL

The hydraulic thermoelectric radiant cooling panel is used for the purpose of removing the indoor sensible cooling load as a parallel system. As shown in Figure 1 and Figure 2, The heat absorbing surface of the thermoelectric module is attached to an aluminium panel to transfer the heat absorbed from the room to the dissipating surface of the thermoelectric module, and the heat transferred to the heat dissipating surface is removed by exchanging heat with the cooling water produced from the cooling tower. At this moment, the phenomenon in which heat is transferred from the heat absorbing surface to the heat dissipating surface of the thermoelectric module by applying electricity is called the Peltier effect (Figure 3). It is driven by direct current, and the temperature difference between the heat absorbing surface and heat dissipating surface is proportional to the magnitude of the voltage formed by the direct current.

Because thermoelectric radiant cooling panel can control the cooling capacity by the amount of power applied, it is possible to quickly and precisely control the temperature of the panel surface according to the indoor sensible cooling load and the temperature of the cooling water in the heat sink unlike conventional radiant cooling panel that cooling performance is directly affected by the chilled water temperature (Lim et al., 2018). The outlet temperature of the cooling water produced from cooling tower changes in proportion to the outdoor air wet-bulb temperature. Therefore, by utilizing the quick control of the thermoelectric radiant cooling panel, more precise comfort control is possible in response to the outdoor temperature and the indoor cooling load.

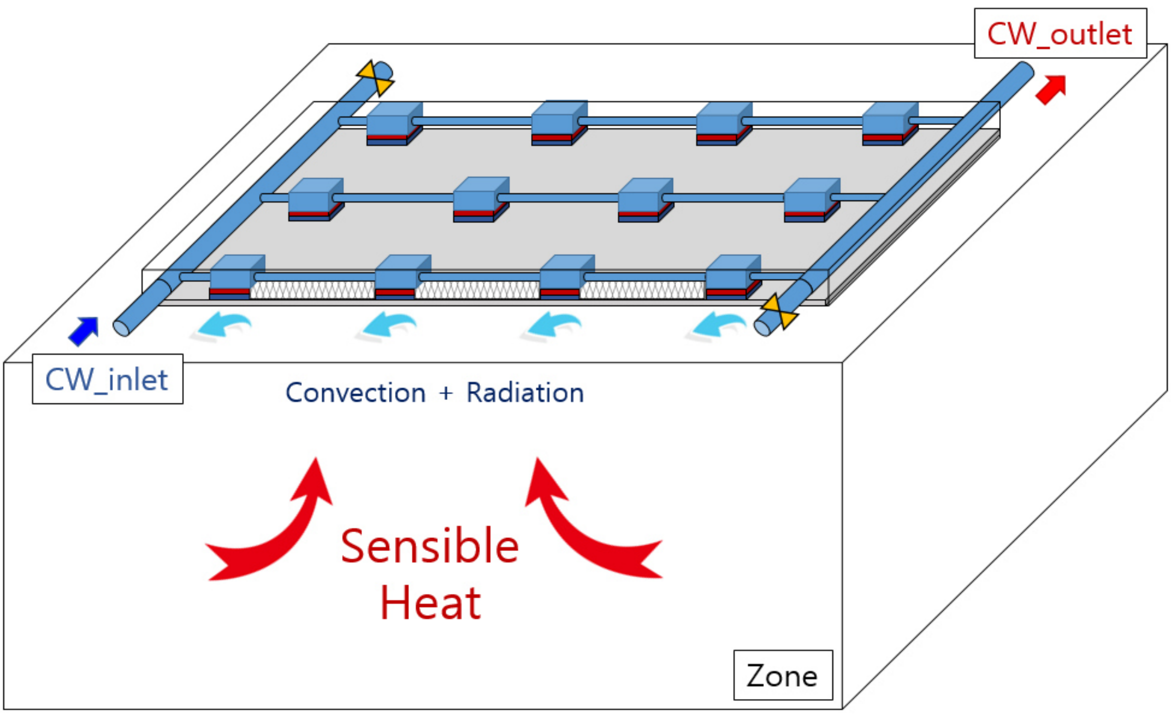


Figure 1: Schematic of the hydraulic thermoelectric radiant cooling panel in the zone

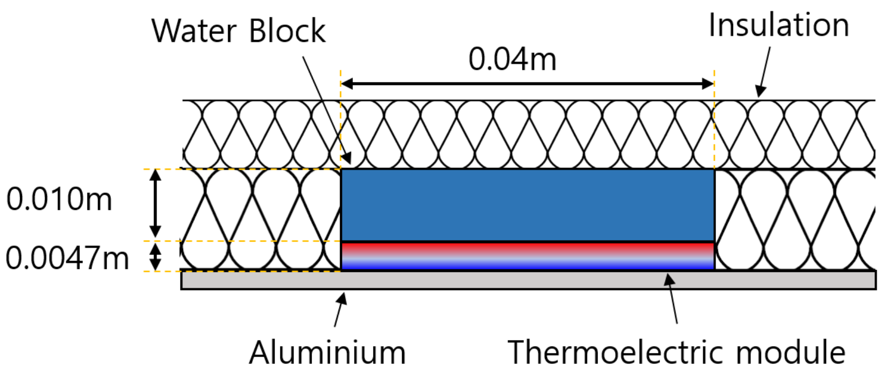


Figure 2: Section diagram of the hydraulic thermoelectric radiant cooling panel

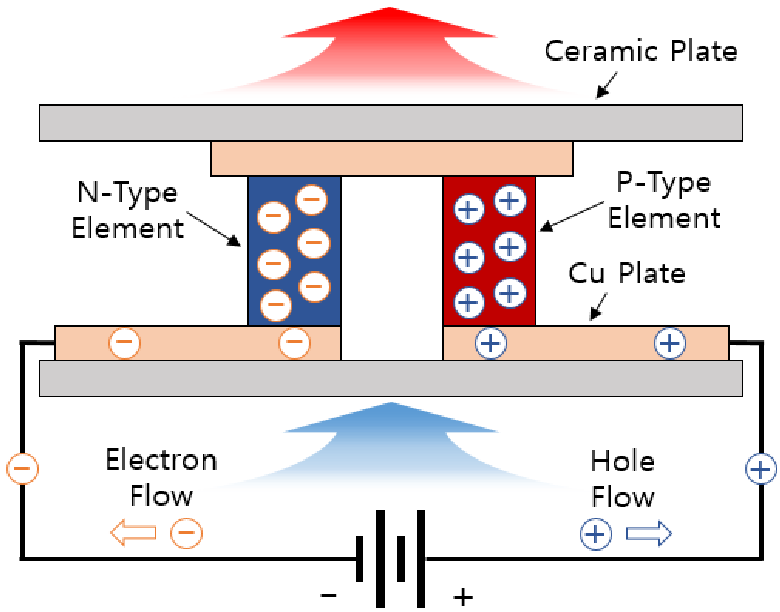


Figure 3: Principle of the Peltier effect in thermoelectric module

3 PERFORMANCE EVALUATION AND PERFORMANCE PREDICTION MODEL DEVELOPMENT USING TEST RIG

3.1 Configuration of test rig and experimental method

Figure 4, 5 shows the test rig and hydraulic thermoelectric radiant cooling panel used for cooling panel performance evaluation. In summer indoor temperature and humidity conditions (25℃, 50%), multiple points of the temperature on panel were measured by thermocouples (Omega type T) and the amount of applied power were measured by switched-mode power supply (SMPS). In consideration of indoor temperature and humidity, the lowest temperature point of the panel was set to 16℃ to prevent condensation, and the panel was configured so that the temperature difference from the highest temperature point was within 3℃ according to The American Society of Heating, Refrigeration and Air Conditioning Engineers guideline for radiant cooling panel design (ASHRAE, 2016). In the case of the water piping system on the heat sink side, the cooling tower outlet temperature range of 24℃ to 28℃ was set as the cooling water temperature range referring to the previous study (Ha et al., 2020). Experimental cases were classified laminar flow zone and turbulent flow zone per unit area calculated according to the water pipe configuration. Table 1 is presented all experimental cases.

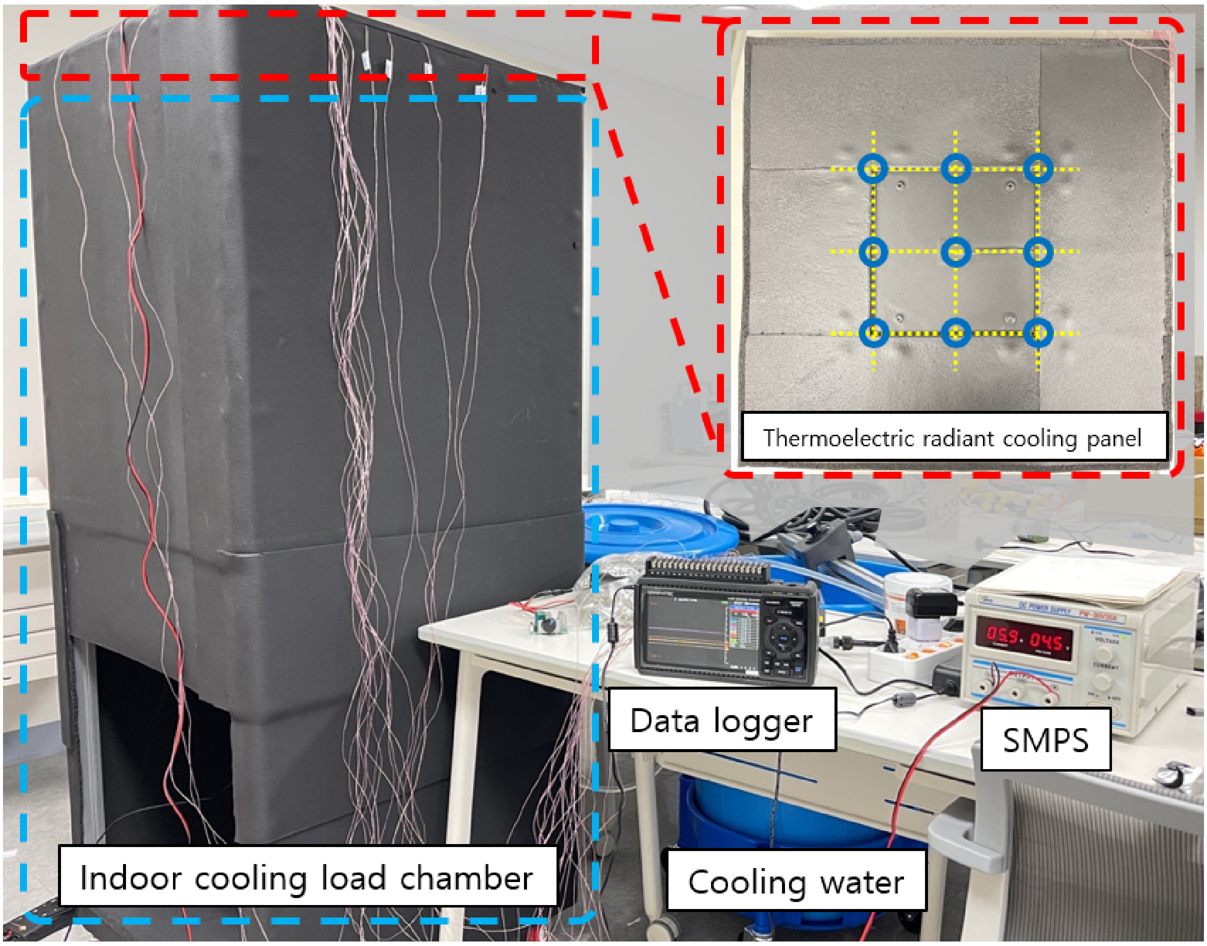
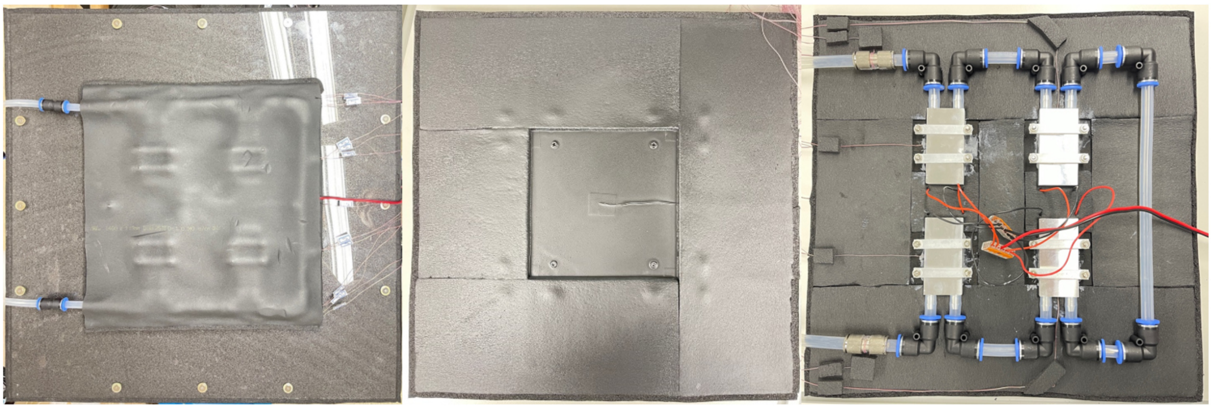


Figure 4: Configuration of test rig



(a) Top view (b) Bottom view (c) Inside view

Figure 5: Test setup of hydraulic thermoelectric radiant cooling panel

Table 1: Experimental cases

Temperature	Laminar flow zone (0.045 kg/s/m^2)	Turbulent flow zone (0.09 kg/s/m^2)
24℃	Case 1	Case 4
26℃	Case 2	Case 5
28℃	Case 3	Case 6

3.2 Evaluation of cooling performance and power consumption

Table 2 shows the cooling performance and power consumption of the hydraulic thermoelectric radiant cooling panel per unit area derived from each experimental case. The colder cooling water, that is, the better heat rejection on the hot side of thermoelectric module is, the lower power consumption tends to be. However, the flow rate of cooling water did not significantly affect power consumption compared with the temperature of cooling water, therefore it was confirmed that the flow rate of cooling water had a low effect on the cooling performance of the hydraulic thermoelectric radiant cooling panel.

Table 2: Cooling performance and power consumption per unit area

Flow rate / Temperature	Cooling performance		Power consumption	
	0.045 kg/s/m²	**0.09 kg/s/m²**	**0.045 kg/s/m²**	**0.09 kg/s/m²**
24°C	130 W/m²	123.3 W/m²	38.5 W/m²	39.3 W/m²
26°C	125.2 W/m²	126.7 W/m²	62.6 W/m²	60.2 W/m²
28°C	121.6 W/m²	120.9 W/m²	79.3 W/m²	78.1 W/m²

3.3 Development of performance prediction model

Based on the measured experimental data, the following performance prediction model equation was derived by using Analysis of Variance (ANOVA) of Design-Expert 13. Equation (1) is the power consumption according to the temperature and flow rate of the cooling water, and Equation (2) is the cooling performance according to the power consumption. Figure 6, 7 are graphs of power consumption and cooling performance per unit area calculated from model equations. It derived from the temperature range of cooling water that can be produced by cooling towers in the Korean climate.

$$P = 10.20569 * T_{inlet} - 28.30051 * \dot{m} - 203.26069 \quad (1)$$

$$q_c = -0.13278 * P + 132.53923 \quad (2)$$

P : Power consumption per unit area [W/m²]

T_{inlet} : Temperature of cooling water [°C]

$\dot{m}$: Flow rate of cooling water per unit area [kg/s/m²]

q_c : Cooling performance per unit area [W/m²]

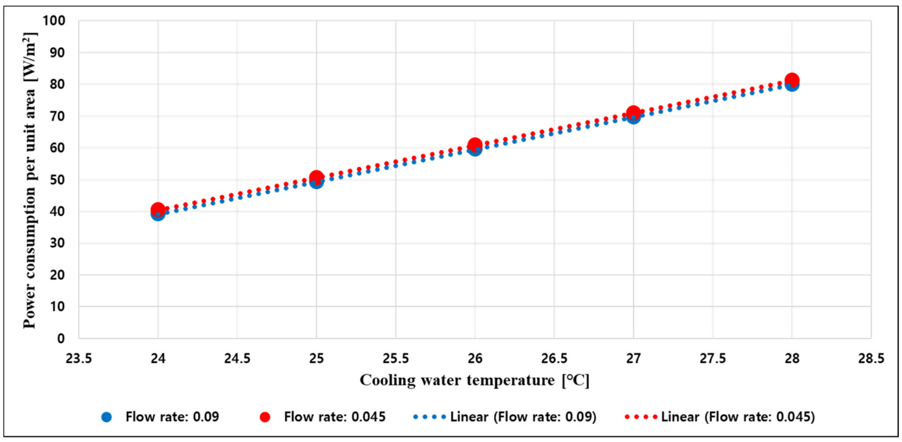


Figure 6: Power consumption per unit area calculated by model equation (1)

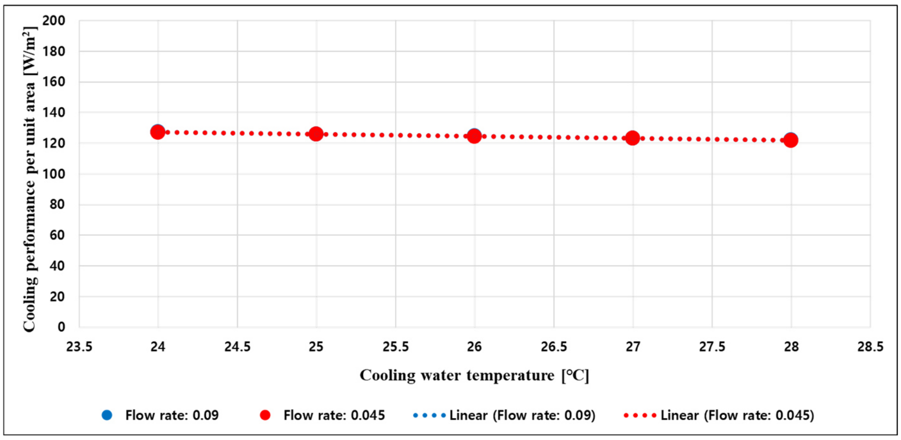


Figure 7: Cooling performance per unit area calculated by model equation (2)

4 CONCLUSIONS

In this study, a test rig that can evaluate the performance of hydraulic thermoelectric radiant cooling panel is configured, and the measured values of the test rig are used as input values for ANOVA to develop model equations for prediction the power consumption and cooling performance according to the temperature and flow rate of cooling water. As a result of the experiment, it was confirmed that the heat removal performance of the thermoelectric module has a close influence on the cooling performance and power consumption of the cooling panel. The temperature of cooling water has a large effect on the heat removal performance and the flow rate has little effect. In the further research, dedicated outdoor air system (DOAS) as a primary cooling system will be reflected in the building model to conduct detailed comparative analysis of the annual energy consumption between hydraulic thermoelectric radiant cooling panel and conventional ceiling radiant cooling panel.

5 ACKNOWLEDGEMENTS

This work was partly supported by the National Research Foundation of Korea(NRF) grant funded by the Korea government(MSIT) (No. 2022R1A2B5B02001975).

6 REFERENCES

Enescu, D., Virjoghe, E. O. (2014). *Renewable and Sustainable Energy Reviews*, 38, 903-916.

Hansol Lim, Jae-Weon Jeong. (2018). Energy saving potential of thermoelectric radiant cooling panels with a dedicated outdoor air system, *Energy & Buildings*, 169, 353-365.

Ju-Wan Ha, Yu-Jin Kim, Hwan-Yong Kim, Young-Hak Song. (2020). Verification of Low-temperature Condenser Water and Operation Time considering Climate Zones, *Journal of KIAEBS*, 14, 298-309.

Luo, Y., Zhang, L., Liu, Z., Wu, J., Zhang, Y., Wu, Z. (2017). Three dimensional temperature field of thermoelectric radiant panel system: Analytical modeling and experimental validation, *International Journal of Heat and Mass Transfer*, 114, 169-186.

The American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE). (2016). *ASHRAE Handbook: HVAC Systems and Equipment, Chapter 6: Radiant Heating and Cooling*.