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ENERGY PERFORMANCE OF THERMOELECTRIC CEILING RADIANT PANELS WITH A DEDICATED OUTDOOR AIR SYSTEM IN HIGH-SPEED TRAIN CABINS

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ABSTRACT

This study aims to investigate the energy performance of thermoelectric radiant panel (TERP) with a dedicated outdoor air system (DOAS) for use in high-speed train cabins. The DOAS treats the latent loads of the cabins and operates as a 100% outdoor air ventilation system. The selected DOAS consists of a cross-type membrane heat exchanger, a direct expansion coil, and an electric heating coil. Sensible heating and cooling loads are accommodated using TERP. A thermoelectric module (TEM) is a solid-type heat pump without refrigerant, and therefore it can operate for radiant cooling and heating by simply inverting the direction of the input current. The TERP consists of an aluminum panel, TEMs, thermal insulation, and heat fins for heat exchange. The heat fins were installed to be exposed to the outside air, and therefore, the heat rejection and absorption could be achieved based on the air flowing on the surface of the high-speed train. This decoupling concept of ventilation and air-conditioning functions can prevent cross-contamination and increase the air quality. In addition, the TERP in a high-speed train was expected to reduce the operating energy owing to the free cooling and heating from the outside air without fan operation. In this study, detailed energy simulations were conducted to compare the energy saving potentials of the proposed system compared with a variable air volume (VAV) system. An empirical model for the chiller, a semi-black box model for the TEM, and mathematical models for other equipment were used to predict the performance of each component. The Korean train express from Seoul to Busan in South Korea was selected for thermal load calculation using TRNSYS, and an annual simulation was conducted. As a result, the proposed system showed a total system energy savings of 30% annually compared with the conventional VAV system.

KEYWORDS

Thermoelectric module, Dedicated outdoor air system, Radiant cooling panel, High-speed train, Energy simulation

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INTRODUCTION

High-speed trains are an essential means of transportation in Asia and Europe, and research and development in the railway industry has been directed toward achieving higher speeds and comfortable indoor environments, such as thermal comfort, air quality, and acoustic comfort (Liu and Zeng, 2012).

For those purposes, there are some studies that investigated the air quality and thermal comfort of transportation using computational fluid dynamics, mock-up modeling, and in situ measurements (Masyita and Nornadiah, 2017, Duan et al., 2015, Zhang et al., 2009). In the previous studies, the researchers considered air diffuser types or air flow to prevent the cross-infection and thermal discomfort. However, there is no study that suggested using a 100% outdoor air system such as a dedicated outdoor air system (DOAS). This is because a DOAS requires using parallel cooling and heating units for air conditioning, which takes a lot of space; however, high-speed train cabins have limited space.

Therefore, we suggest using a DOAS with a thermoelectric radiant panel (TERP) as a parallel unit in high-speed train cabins. A thermoelectric module (TEM) is compact, without refrigerant, noise, and vibration (Lim et al., 2018). The only disadvantage of TEMs is the low coefficient of performance (COP). However, this can be overcome by optimizing the operating condition and reducing the energy consumption for heat removal at the hot side of the TEM during operation. In a high-speed train, the rejected heat at the hot side of the TEM can be removed naturally using the air flow at the external surface of the running train. Additionally, in a previous study, TERP showed a very high COP during the intermediate season, owing to the small temperature difference between the cold and hot sides of the TEM (Lim and Jeong, 2018).

Hence, the energy performance of a DOAS with TERP in high-speed train cabins was investigated to evaluate the feasibility of this heating, ventilation, and air conditioning (HVAC) application by detailed energy simulations. Furthermore, a variable air volume (VAV) system was selected as a conventional HVAC system for comparison purposes. The empirical and mathematical models for each system component were applied via a series of energy simulations.

VARIABLE AIR VOLUME SYSTEM

The VAV system in a high-speed train cabin consists of a mixing plenum, direct expansion (DX) cooling coil, and heating coil as shown in Figure 1. The minimum required ventilation air is mixed with the return air to reduce the cooling and heating loads of the DX and heating coil. The supply air is 13℃ and 80% relative humidity in the cooling mode and 45℃ dry bulb temperature in the heating mode. In the intermediate season, air-side economizer control is used to reduce the energy consumption without the mixing process when the enthalpy of the outdoor air is lower than that of the return air.

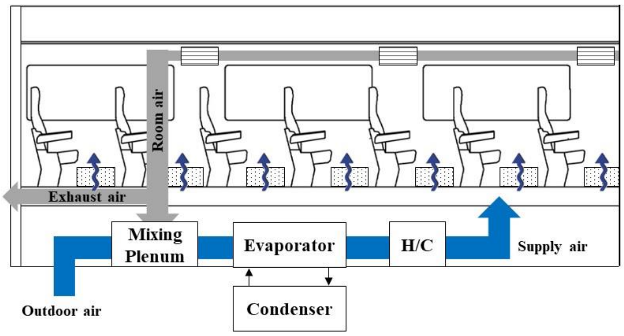
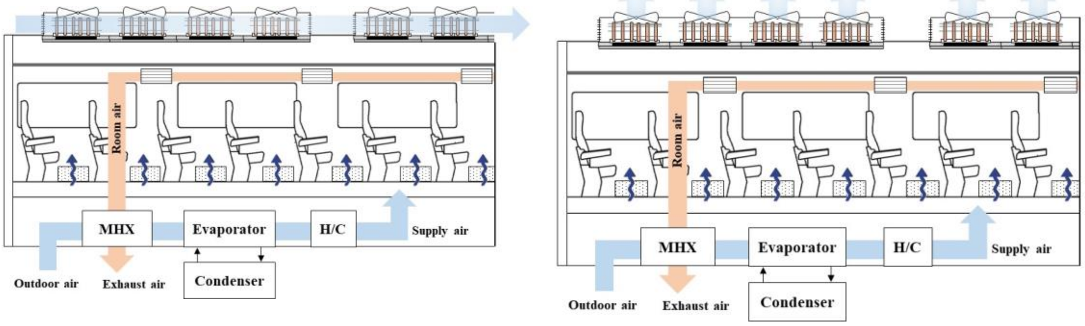


Figure 1. Variable air volume system in a high-speed train cabin

DEDICATED OUTDOOR AIR SYSTEM WITH THERMOELECTRIC RADIANT PANEL

The DOAS with TERP is shown in Figure 2. The DOAS accommodates the latent loads and supplies the fresh air for ventilation to the high-speed train cabin. The remaining sensible loads can be removed by using TERP as a parallel cooling unit. In the DOAS, the membrane heat exchanger (MHX) is used instead of a mixing process by enthalpy exchange. The supply air was set to be 13℃ in the cooling season and neutral temperature in the heating season. The target humidity ratio of the supply air can be derived based on the latent loads in the cabin.

In Figure 3, the TERP consists of an aluminum panel for radiation, a thermoelectric module (TEM), insulation to prevent unnecessary heat transfer, a heat fin, and a pipe to improve the heat exchange effectiveness. The TEM works based on the Peltier effect, such that the electricity generates a temperature difference by heat absorption and rejection at the cold and hot sides of the TEM. It is necessary to remove the heat at the hot side of the TERP in the cooling mode for stable operation. We considered using an air-cooled type for the TERP and there are two operation modes of the TERP according to the conditions of the high-speed train. During running (Fig. 2a), the air flow at the exterior surface of the train removes the rejected heat at the hot side of the TERP naturally. The mean speed of the high-speed train is 167 km/h (i.e., 46.5 m/s), and therefore, the heat is perfectly removed. During the stopping condition (Fig. 2b), vertical axial fans are operated to remove the rejected heat.



(a) Operation during running (b) Operation during stopping condition

Figure 2. Dedicated outdoor air system with thermoelectric module-based radiant panel in a high-speed train cabin

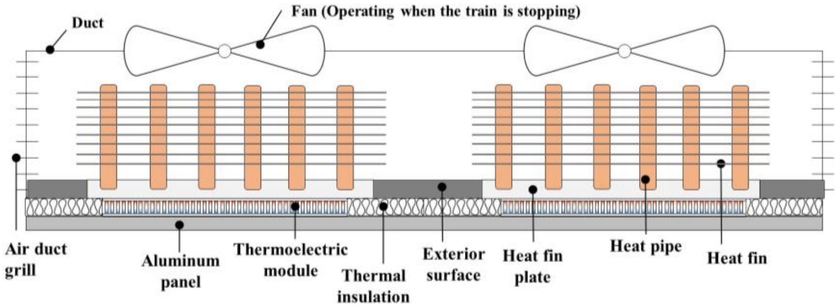


Figure 3. Detailed sectional diagram of thermoelectric module-based radiant panel in a high-speed train cabin

HIGH-SPEED TRAIN CABIN MODEL

The sensible and latent loads of the design space were derived by using TRNSYS 18. The Korea train express (KTX) was selected for the model space. It has a floor area of 36.4 m^2 and height of 2.2 m for 48 passengers. Twelve windows with an area corresponding to 8.7 m^2 were located on the east and west exterior walls. The window-to-wall ratio was 0.25. The sensible and latent heat generation rates per occupant were 75 W and 45 W based on the ASHRAE Standard 90.1. The occupancy and system schedules were applied based on the actual operation timetable of the KTX. The set points of the indoor temperature and relative humidity corresponded to 24℃ and 50 %, respectively, for the cooling mode and 20℃ for heating mode, respectively. All U-values for the roof, ceiling, wall, and windows were used based on the actual materials applied in the KTX. As shown in Figure 4, the sensible cooling load was dominant in the high-speed train cabin due to the high occupant densities compared with the general office room.

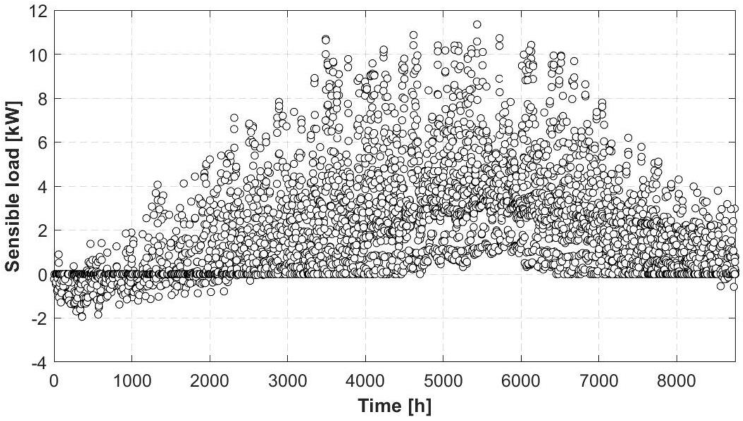


Figure 4. Sensible loads of a high-speed train cabin

VARIABLE AIR VOLUME SYSTEM MODEL

The supply air flow rate ($\dot{m}_{SA}$) of the system was determined according to the sensible and latent loads of the zone including the minimum required outdoor air flow rate.

The state of the mixing air was calculated based on the ratio of the return air to outdoor air (Lim and Jeong, 2018). The DX coil sensibly cools or dehumidifies the process air depending on the state of the mixed air, therefore the cooling loads of the DX coil were derived based on its operation using Eqs. (1) and (2). After the DX coil, the heating coil meets the supply air temperature if necessary and the heating coil loads can be calculated using Eq. (3).

$$\dot{Q}_{cooling} = \dot{m}_{SA} c_{p,a} (T_{MA} - T_{SA}) \tag{1}$$

$$\dot{Q}_{cooling} = \dot{m}_{SA} c_{p,a} \left(T_{MA} - T_{SA,dew}\right) \tag{2}$$

$$\dot{Q}_{heating} = \dot{m}_{SA} c_{p,a} (T_{SA} - T_{DX}) \tag{3}$$

where $c_{p,a}$ is the specific heat of air, T_{MA} is the mixing air temperature, T_{SA} is the supply air temperature, $T_{SA,dew}$ is the dew point temperature of the supply air, and T_{DX} is the outlet air temperature of the cooling coil.

DEDICATED OUTDOOR AIR SYSTEM MODEL

In the DOAS, the supply air flow rate is constant with the minimum required outdoor air flow rate. There is no mixing process but there is enthalpy exchange through the MHX. The sensible and latent heat exchange efficiencies (eff_{sen}, eff_{lat}) were assumed to be 0.7 and 0.6, respectively (Choi et al., 2018). The outlet temperature (T_{MHX}) and humidity ratio (ω_{MHX}) at the MHX can be derived using Eqs. (4) and (5). The air conditioning process after the MHX is same as that in the VAV system.

$$T_{MHX} = T_{OA} - eff_{sen}(T_{OA} - T_{RA}) \tag{4}$$
$$\omega_{MHX} = \omega_{OA} - eff_{lat}(\omega_{OA} - \omega_{RA}) \tag{5}$$

where T_{OA} is the outdoor air temperature, T_{RA} is the return air temperature, ω_{OA} is the humidity ratio of the outdoor air, and ω_{RA} is the humidity ratio of the return air.

THERMOELECTRIC RADIANT PANEL MODEL

In the TERP, the TEM was simulated using a previously developed model (Chen et al., 2013). The thermophysical properties of a compact TEM (α: Seebeck coefficient, ρ: electrical resistivity, κ: thermal conductivity) were calculated using Eqs. (6) to (8), which involve using the maximum cooling capacity of the TEM (Q_{max}), temperature of the hot side (T_h), maximum temperature difference between the cold and hot sides of the TEM (ΔT_{max}), maximum input current of the TEM (I_{max}), uniform cross-sectional area of the entire TEM (A), and height of the thermoelement (l). The packing fraction of the total TEM area covered by the thermoelement (f) was 0.5. The number of thermocouples in a TEM (N) was 127.

$$\alpha = \frac{Q_{max}(T_h - \Delta T_{max})}{N T_h^2 I_{max}} \tag{6}$$

$$\rho = \frac{Af(T_h - \Delta T_{max})^2}{2T_h^2 l} \frac{Q_{max}}{N^2 I_{max}^2} \tag{7}$$

$$\kappa = \frac{l(T_h - \Delta T_{max})^2}{Af T_h^2} \frac{Q_{max}}{\Delta T_{max}} \tag{8}$$

In the cooling mode of the TERP, the surface temperature of the radiant panel (T_c) was set as 16℃ considering the dew point temperature of the indoor air. At the hot side, the outdoor air dissipated the rejected heat from the TEM. Therefore, the hot side temperature of the TEM (T_h) was assumed based on the outdoor air temperature. In the heating mode of the TERP, the surface temperature of the radiant panel (T_h) was set as 45℃. There is no air flow at all at the hot side of the TEM; however, the cold side temperature of the TEM (T_c) was assumed to be equal to the outdoor air temperature, owing to the fast speed of the train and air flow at the exterior surface. The lumped thermophysical properties (S: Seebeck coefficient, R: Electrical resistivity, K: Thermal conductivity) of the TEM are derived using Eqs. (9) to (11).

$$S = 2N\alpha \tag{9}$$

$$R = \frac{4N^2 l\rho}{Af} \tag{10}$$

$$K = \kappa \frac{Af}{l} \tag{11}$$

Finally, the required input current according to the sensible cooling loads of the zone can be determined using Eq. (12) (Lim and Jeong, 2018). The number of TEMs on the radiant panel (n) was assumed to be 77 based on the optimization process to minimize the operation energy consumptions. The input voltage (V) and the amount of heat rejection (Q_h) are calculated by using Eqs. (13) and (14).

$$I = \left\{ \frac{(nAf\alpha^2 T_c^2) - \sqrt{(nAf\alpha^2 T_c^2)^2 - 2\rho(nAf\alpha^2 T_c^2)(\kappa\Delta Tnaf + lQ_c)}}{nAf\alpha^2 T_c^2} \right\} \times I_{max} \tag{12}$$

$$V = IR + S\Delta T \tag{13}$$

$$P = V \times I = Q_h - Q_c \tag{14}$$

SIMULATION RESULTS

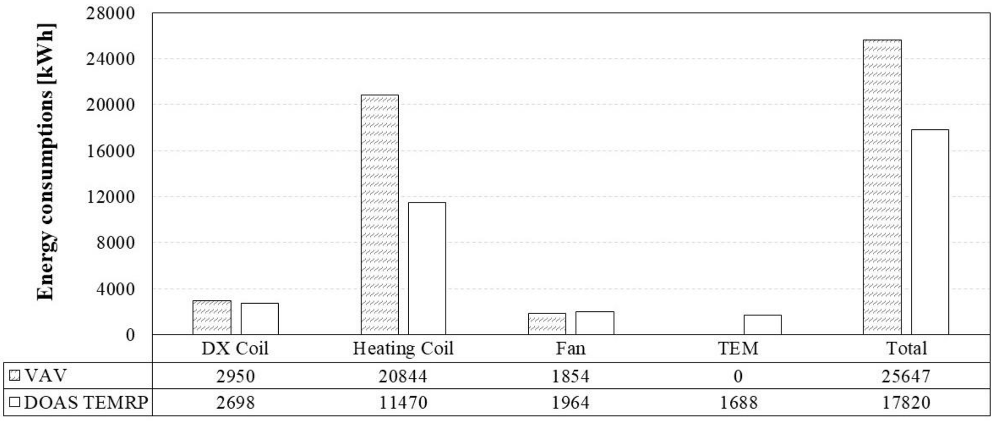
The annual electrical energy consumptions were compared for the system components such as the DX coil, heating coil, fan, and TEM, as shown in Figure 5. An evident difference can be observed at the heating coil. In the heating mode, there is no mixing process because the minimum required outdoor air flow rate of the high-speed train cabin is relatively large compared with the heating loads of the zone. Therefore, there is no way to reclaim the energy from the return air in VAV system. On the other hands, DOAS can recover the energy using the MHX from the return air, even though there is no mixing process, achieving energy savings of 45%.

At the DX coil, the DOAS yields annual energy savings of 8.5%. In a previous study, the DOAS could save approximately 50% of energy from a chiller in a general office building (Lim and Jeong, 2018), owing to the smaller supply air flow rate in summer than that of a VAV system. However, the supply air flow rates of both systems in summer are not that different from the minimum required outdoor air flow rate, because it is too large compared with the cooling loads of the zone.

The reason that the high-speed train has a large minimum required outdoor air flow rate compared with the sensible loads is that there are 48 people in the 36.4 m^2 floor area. Moreover, the local regulations for public transportation in South Korea define the minimum required outdoor air flow rate as 20 m^3/h per person (i.e., a total of 960 m^3/h). Furthermore, the latent loads in the high-speed train cabin are relatively large compared to that of a general office or residential building. Therefore, this results in increased energy consumption of the DX coil for dehumidification in the DOAS.

Likewise, the fan energy consumptions showed little difference in both systems owing to the similar supply air flow rate. The DOAS consumed 5.6% more energy owing to the fan operation to remove the rejected heat from TERP during the train stopping condition. Additionally, the TEM consumed additional energy for sensible cooling and heating. The DOAS also accommodates part of the cooling loads in the cooling mode, and therefore the energy consumption of the TEM is not that high. However, the energy consumption of the TEM mostly occurred when it was operated in heating mode.

On an overall basis, the total energy consumption of the DOAS is 30% lower than that of the VAV system. The greatest energy savings are from the heating coil, owing to the MHX in the DOAS because the thermal loads and the minimum required outdoor air flow rate of the high-speed train cabin are unusual compared with a general building.



	DX Coil	Heating Coil	Fan	TEM	Total
▨ VAV	2950	20844	1854	0	25647
☐ DOAS TEMRP	2698	11470	1964	1688	17820

Figure 5. Annual energy consumption of two systems in a high-speed train cabin

CONCLUSION

In this study, a DOAS with TERP was suggested to be used in high-speed train cabins. To compare the energy performance of the proposed system, an annual energy simulation was conducted and compared with a VAV system. The results showed that the proposed system reduced the annual energy consumption by 30%. The greatest energy savings were from the heating coil, because the DOAS can reclaim the energy from the return air using a MHX. Additionally, the TERP in a high-speed train does not require the additional fan energy for heat removal, and therefore it accommodates the sensible loads only using the energy consumption of the TEM.

Although only the energy performance of the proposed system was investigated in this study, it is already well known that the DOAS provides better air quality without cross-contamination (Jeong and Mumma, 2005) and accurate latent load control compared with the VAV system. Therefore, the DOAS can provide better indoor environmental quality with less energy consumption in high-speed train cabins. In addition, the feasibility of using TERP as parallel cooling and heating unit with a DOAS was revealed in high-speed train cabins. TERP are silent, compact, easy to control, and have fast response without refrigerants. Therefore, they may be a satisfactory solution for air conditioning systems in high-speed train cabins.

ACKNOWLEDGEMENTS

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