Theoretical analysis on active radiant heat reflector integrated phase change material wall

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Abstract. Recently, as interest in increasing energy efficiency of buildings increases, a method of reducing indoor heat gain and loss by integrating phase change materials (PCM) into building walls is being studied. The PCM is a type of heat storage material that can reduce energy consumption of the cooling and heating devices of the building by absorbing or releasing heat from outside. However, the PCM which is integrated into the wall of the building cannot fully achieve thermal performance because it absorbs or releases heat according to the temperature change of the surrounding members in the wall. To solve the problem, this study proposed a new system that improves the thermal performance of the PCM integrated wall by controlling radiant heat transfer inside of the wall. The proposed system adjusts the radiant heat transfer in the wall through an active radiant heat reflector, which controls surface emissivity of the PCM in the design conditions. To evaluate the proposed system, a numerical analysis for 1D transient heat transfer was used based on the energy balance equation for the indoor heat gain and loss with the reference systems. The simulation was conducted with Matlab 2021a software, and weather conditions were data from the summer (Jun-August) and winter (December-February) of IWEC2 Seoul. As a result of the simulation, the proposed system confirmed that indoor heat gains and losses were improved in all periods compared to the reference system. The proposed system reduced the total indoor heat gain by 33.3%-44.1% in summer and the total indoor heat loss by 14.2-29.3 in winter compared to the reference systems.

Keywords. PCM integrated wall, Thermal performance, Radiant heat transfer
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1. Introduction

According to the international energy agency (IEA), energy consumption in buildings accounts for nearly 36% of the world's total energy consumption [1]. Since using a large amount of energy is closely related to increasing energy costs and environmental issues, the energy consumption of the buildings should be reduced and highly efficient. To increase the energy efficiency of the buildings, some studies have been published about improvement of the building envelope. The building envelope is components of a wall system which separate the interior and exterior environments. Several researchers in the world have demonstrated that the improvement of the building envelope is effective in building energy efficiency [2]. Therefore, improving the building envelope is one of the main key factors which determines the energy efficiency of the buildings and indoor environments.

In recent years, research which integrates phase change materials (PCM) with the building envelope is increasing [3]. The PCM is one of the thermal storage materials which can store large amounts of heat energy as the form of latent heat with small temperature change. This property allows the applications of PCM to integrate in the building envelope as they are effective in reducing space heating and cooling loads of the buildings. However, the heat storage and discharge of the PCM in the building envelope cannot be controlled ideally, which is highly dependent on the surrounding temperature. Because of this, traditional thermal insulation envelopes which have fixed thermal resistance, restrains the energy saving potential of the PCM-integrated building envelope [4]. Therefore, to accomplish complete performance of the PCM, a new building envelope system is needed. Extant researchers [4, 5] have studied the new systems to solve the disadvantages of the PCM integrated envelope. Kishore et al. [4] proposed a novel wall design, comprising a layer of PCM between two layers of dynamic insulation material and system(DIMS). Simulations have confirmed that the proposed system can reduce the annual heat gain by

17-72% and the annual heat loss by 7-38% depending on the buildings. Gracia. [5] proposed a novel concept based on the dynamic use of the PCM in building envelopes. Simulations showed that the proposed system achieves a cooling load reduction of 379% in comparison to a system without PCM with optimum design. The analysis which presented studies support the need to develop additional insulation mechanisms to use the PCM integrated envelope or wall.

This study proposes a new novel insulation mechanism to improve the energy potential of the PCM-integrated building. In the proposed system, the thermal performance of the pcm is improved by controls the radiation heat reisistance inside of the wall with an active radiant heat reflector. To estimate the thermal performance of the proposed system, total indoor heat gains and losses of each summer and winter were evaluated via comparison against reference cases.

2. System overview

2.1 Proposed PCM integrated wall system

Fig. 1 depicts the schematic of the proposed PCM integrated wall system in a vertical building envelope. The system has the PCM layer and an auxiliary insulation layer between the building wall's exterior and interior layer. The cavity is located on the front and rear side of the PCM layer. The PCM layer is composed of microencapsulated PCM (M-PCM), aluminum case, and an active radiant heat reflector.

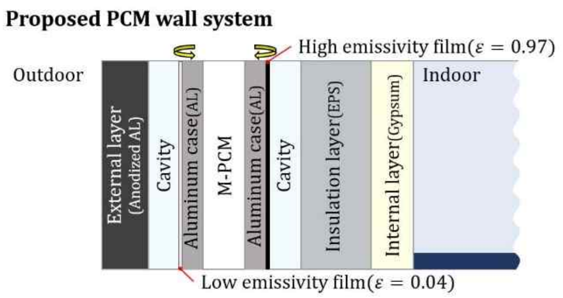

Fig. 1 - Schematic of the proposed PCM wall system in vertical building envelope.

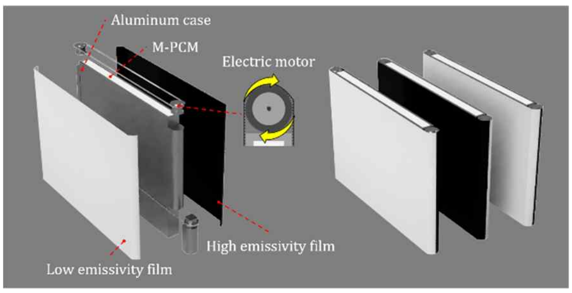

Fig. 2 - Sketch of possible configuration of the PCM with the active radiant heat reflector.

Fig. 2 depicts a sketch of the configuration in the PCM layer with the active radiant heat reflector in the proposed system. The active radiant heat reflector consists of a high-emissivity film part and low-emissivity film part. In the cavity, the high emissivity part increases the radiant heat transfer and the low emissivity part decreases the radiant heat transfer. Each part of the active radiant heat reflector moves through an electric motor to the front and rear side of the aluminum case which contains the M-PCM in the proposed system.

The mechanism, which the active radiant heat reflector controls the radiant heat transfer in the cavity is as follows. **Fig. 3** depicts a schematic of the heat transfer between two different surfaces in the cavity. In **Fig. 3**, the total thermal resistance of the cavity is determined by radiant heat transfer and natural convection heat transfer. From the previous study[6], heat transfer equations on the two different surfaces $(\text{i.e.}, 1\&2, T_1 > T_2)$ are as shown in equations (1) and (2) In the equation (1) the amount of the radiant heat transfer is determined by the emissivity of each surface. The higher emissivity transfers more radiant heat, and the lower emissivity transfers less radiant heat between two surfaces. Therefore, if the emissivity of the surface in the cavity may be actively managed, radiant heat transfer in the cavity also may be actively managed. The proposed system attempted to improve the thermal performance of the PCM integrated wall by using the active radiant heat reflector to control the radiant heat transfer of the cavity in the wall.

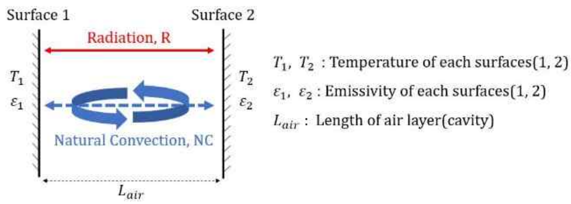

Fig. 3 - Schematic of the heat transfer between two different surfaces in the cross-sectional view (i.e., 1&2).

$$R = A\sigma(T_1^4 - T_2^4)/(\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1) \quad (1)$$

$$NC = k_{air}\, NuA(T_1 - T_2)/L_{air} \quad (2)$$

2.2 Seasonal operation modes

In this study, the operation of the proposed system was considered and analyzed in summer and winter conditions of the Seoul. In the proposed system, operating modes are classified into four different types according to the season and outdoor temperature to improve the thermal performance of the PCM. The description of the each modes is as follows.

Fig. 4 depicts a schematic of the proposed PCM wall system during the summer season. As shown in **Fig. 4-A**, the outdoor heat flux is transferred to the indoor environment during the day of the summer. While outdoor heat flux is transferred to the indoor, the low emissivity film is located on the external wall side of the PCM. The low emissivity film reduces radiant heat transfer from the exterior wall, delaying heat storage time of the PCM. As a result, the amount of heat gain from the wall is decreased. As shown in **Fig. 4-B**, heat stored in the M-PCM is released to the outside on the summer nights. While the stored heat of the PCM is released, the high emissivity film is located on the exterior side of the PCM and the low emissivity film is located on the interior side of the PCM. The high emissivity film increases the amount of the radiant heat transfer to the external wall and the low emissivity film decreases the amount of the radiant heat transfer to the indoor environment. As a result, the proposed system can reduce the amount of the indoor heat gain by improving the thermal performance of the PCM during the summer season.

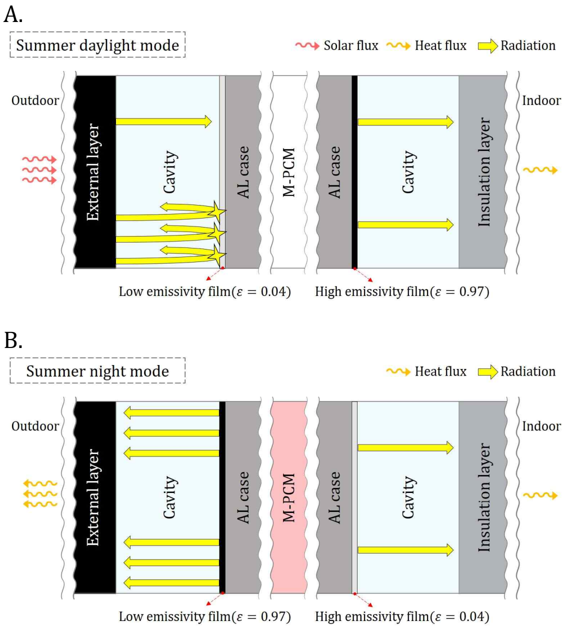

Fig. 4 - Schematic of the proposed system during summer season (A: summer daylight, B: summer night).

Fig. 5 depicts a schematic of the proposed PCM wall system during the winter season. As shown in **Fig. 5-A**, while the sun rises, the heat is transferred from the external wall to the PCM through the solar flux. To maximize the heat storage of the PCM, the high emissivity film moves to the external side of the PCM to increase the amount of the radiant heat transfer. In addition, the low emissivity film is located on the interior side to reduce heat loss from the indoor. **Fig. 5-B** depicts the schematics of the proposed system after the sunset. While the stored heat of the PCM is released, the low emissivity film is located on the exterior side of the PCM and the high emissivity film is located on the internal side of the PCM. The high emissivity film makes The high emissivity film release more heat which is stored at the PCM to the indoor environment. It helps keep the indoor temperature warmer in winter. The low emissivity film restrains the release of heat which is stored in the PCM to the outdoors. As a result, the proposed system can reduce the amount of the indoor heat loss by improving the thermal performance of the PCM during the winter season.

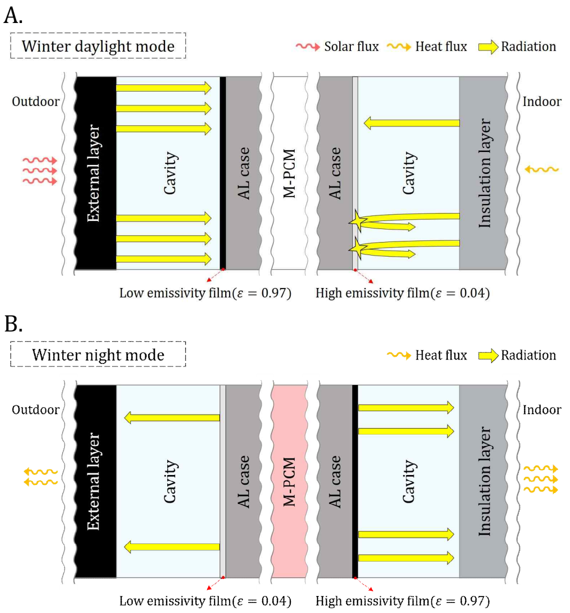

Fig. 5 - Schematic of the proposed system during winter season (A: winter daylight, B: winter night).

3. Simulation setup and overview

3.1 Simulation configuration

Fig. 6 depicts the energy balance equation used in the simulation, briefly. The simulation for each wall system case was conducted using Matlab 2021a by 1-D transient heat transfer method, using the formulas used in previous studies [4,5,6]. The weather data used in the simulation were data from June to August and December to February in IWEC2 Seoul. To simplify the simulation, the time which position of the emissivity films was replaced was fixed, considering the sunrise and the sunset time for each season. **Tab. 1** depicts the basic conditions used in the simulation

Tab. 1 - Basic conditions of the simulation.

Classification	Settings
Weather data	IWEC2 Seoul
Convection heat transfer coefficient	$h_{conv,out}$ = 25W/m^{2}K $h_{conv,in}$ = 7.692W/m^{2}K
Indoor air temperature	T_{RA} = 24°C (summer) T_{RA} = 18°C (winter)
Emissivity change time(The proposed system)	Summer season: 08:00 / 24:00 Winter season: 09:00 / 17:00
Model scale(A)	0.8m(Height) x 0.8m(Width)

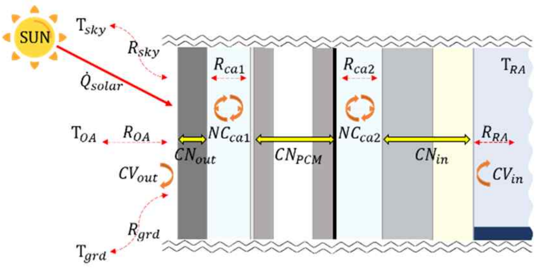

Fig. 6 – Heat transfer model between exterior and interior walls in the simulation.

3.2 Reference wall system cases

To evaluate the thermal performance of the proposed system, those reference wall system cases are selected. Each case is compared and analyzed with the proposed system for indoor heat gain of the summer season and indoor heat loss of the winter season.

Fig. 7 depicts the schematic of the reference case 1 in the vertical building envelope. The case 1 is the conventional PCM integrated wall system which excludes the active radiant heat reflector. The PCM of the case 1 stores and discharges heat through passive heat exchange due to temperature differences.

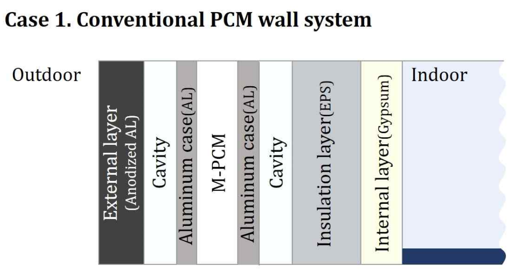

Fig. 7 - Schematic of reference case 1.

Fig. 8 depicts the schematic of the reference case 2 in the vertical building envelope. The case 2 is a wall system using only EPS(Expanded Poly Styrene) insulation without the PCM. The thickness of the EPS which replaced the PCM is same as the proposed system for comparison.

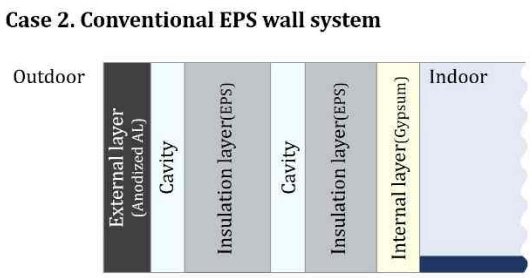

Fig. 8 - Schematic of reference case 2.

Fig. 9 and **Fig. 10** depict schematic of the reference case 9 and 10 in the vertical building envelope. To analysis the effect of radiation transfer which effects the thermal performance of the PCM, reference cases which the emissivity fixed are also simulated. The case 9 and 10 use the same emissivity films as the proposed case, but do not separately control the radiant heat transfer by fixing the position of film.

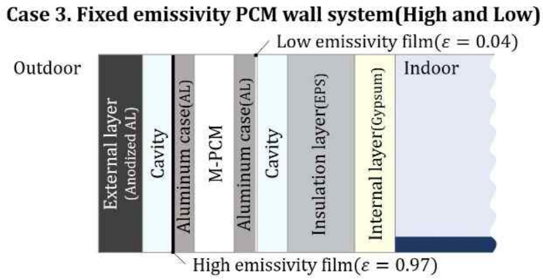

Fig. 9 - Schematic of reference case 3.

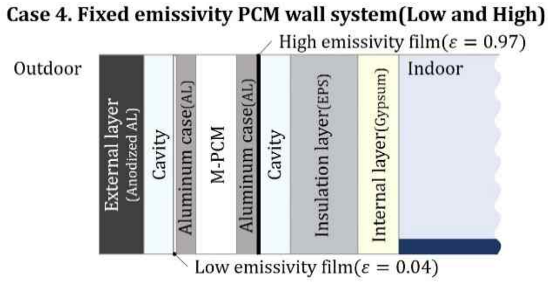

Fig. 10 - Schematic of reference case 4.

3.3 Properties of material of the cases

Each property of the materials of the cases were reflected based on previous studies [6,7,8,9,10]. To compare the thermal performance of the cases, the thermal load to the exterior wall from the outside was set large. In the case of the films, the emissivity value was set for a clear difference in radiant heat resistance value. Also, it was assumed that there was no conduction heat thorough the films because the thickness of the films was very thin. **Tab. 2** depicts the properties of the M-PCM used in this study and **Tab. 3** depicts the properties of the other materials used in this study

Tab. 2 – Properties of the M-PCM.

Classification	Values
Core materials	Paraffin
Melting temperature($T_{m\ et}$)	26°C
Temperature range of phase change(ΔT_{PCM})	±1°C
Latent heat capacity(Q_{PCM})	145 kJ/kg
Specific heat capacity($C_{p,PCM}$)	Solid: 1610 J/kg Liquid: 1995 J/kg
Density(ρ_{PCM})	920 kg/m^3
Thermal conductivity	Solid: 0.24 W/mK Liquid: 0.15 W/mK
Thickness	0.02m

Tab. 3 – Properties of materials of the cases.

Classification	Materials	Thickness (m)	Thermal conductivity $(W/m\,K)$	Density (kg/m^3)	Specific heat (J/kgK)	Emissivity (ε)	Solar absorptance (α)
Exterior wall	Anodized AL	0.02	160	2800	880	0.82	0.95
Insulation	EPS	0.11	0.034	32	1210	0.9	-
Cavity	Air	0.02	0.0255	1.184	1007	-	-
Interior wall	Gypsum board	0.03	0.18	940	1130	0.9	-
Emissivity films	High emissivity	0.0001	-	-	-	0.97	-
	Low emissivity	0.0001	-	-	-	0.04	-
PCM case	AL	0.005	205	2700	910	0.09	-

3.4 Simulation models

The surface temperature of the external wall (T_{ext}) could be determined using equations (3), (4) and (5). The symbols, k_{ext}, ρ_{ext}, C_{ext}, L_{ext} each represent the thermal conductivity (W/mK), density (J/kgK), specific heat (kg/m^3) and length of the external wall. The symbol Δt represents the time interval (s).

$$\dot{q}_{ext} + \frac{k_{ext} A(T^{i+1}_{ext,in} - T^{i}_{ext,out})}{L_{ext}} = \rho_{ext} A \left(\frac{L_{ext}}{2}\right) C_{ext} \frac{\left(T^{i+1}_{ext,out} - T^{i}_{ext,out}\right)}{\Delta t} \quad (3)$$

$$\dot{q}_{ext} = \alpha_{ext} A q_{solar} + h_{conv,out} A(T_{OA} - T_{ext}) + \dot{q}_{ext,rad} \quad (4)$$

The radiation heat transfer equation between the outside air and the external wall $(\dot{q}_{ext,rad})$ could be determined by equation (5). The symbol, ε_{ext} represents emissivity of external wall, and the symbol, σ represents the stefan-boltzmann constant

$$\dot{q}_{ext,rad} = \varepsilon_{ext} A\sigma[(1 - F_{sky})\left((T_{OA})^4 - \left(T^{i}_{ext,out}\right)^4\right) + F_{sky}\left((T_{sky})^4 - (T^{i}_{ext})^4\right)] \quad (5)$$

The temperature of surface B (T_B) among the two surfaces (i.e., $A \cdot B$, $T_A > T_B$) in the cavity could be determined using equations (6), (7), (8).

$$\dot{q}_{cavity,conv} + \dot{q}_{cavity,rad} + \frac{k_B A\left(T^{i}_{B,out} - T^{i}_{B,in}\right)}{L_B} = (\rho_{air} A \left(\frac{L_{air}}{2}\right) C_{air} + (\rho_B A \left(\frac{L_B}{2}\right) C_B \left(\frac{T^{i+1}_B - T^{i}_B}{\Delta t}\right) \quad (6)$$

$$\dot{q}_{cavity,conv} = k_{air}\, Nu(T^{i}_A - T^{i}_B)/L_{air} \quad (7)$$

$$\dot{q}_{cavity,rad} = [\sigma A \left(\frac{\left(T^{i}_A\right)^4 - \left(T^{i}_B\right)^4}{\left(\frac{1}{\varepsilon_A} + \frac{1}{\varepsilon_B} - 1\right)}\right)] \quad (8)$$

The surface temperature of the interior wall (T_{in}) could be determined using equation (9).

$$\varepsilon_{in}\,\sigma A\left(T^4_{RA} - \left(T^{i}_{in,out}\right)^4\right) + \frac{k_{in} A\left(T^{i+1}_{in,out} - T^{i}_{in,in}\right)}{L_{in}} + h_{conv,in} A\left(T_{RA} - \left(T^{in}_{in,in}\right)\right) = \rho_{in} A \left(\frac{L_{in}}{2}\right) C_{in} \left(\frac{T^{i+1}_{in,in} - T^{i}_{in,in}}{\Delta t}\right) \quad (9)$$

The indoor heat gains and losses $(\dot{Q}_{inside})$ by cases through simulation could be determined using equation (10)

$$\dot{Q}_{inside} = \sum_{i=1}^{I}[(T^{i}_{in} + T^{i-1}_{in} - \mathrm{T}_{RA})/2]\Delta t \quad (10)$$

4. Results

4.1 Heat gain through building walls in summer

Fig. 11 depicts the comparison of the monthly indoor heat gain of each case when operating during summer. It can be seen that the proposed system obtains less indoor heat gain than each reference case in all periods. Especially in august, when the load of outside air increases, all cases using the PCM excluding the proposed system obtain more indoor heat than case 2 which uses only EPS insulation. The amount of indoor heat gains of case 1, 3, 4 in august increased by 2.51%, 15.35% and 0.05% compared to case2, while the proposed case decreased by 23.68%

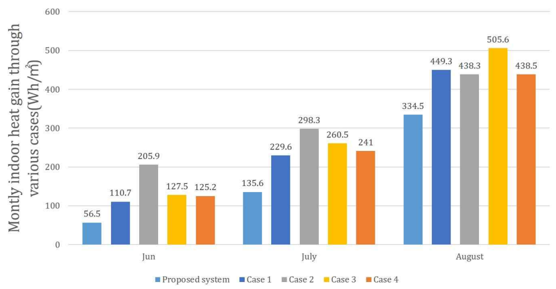

Fig. 11 - Monthly indoor heat gain during summer.

Fig. 12 depicts the comparison of the total indoor heat gain of each case in summer season. Under the summer weather conditions, the proposed system reduced indoor heat inflow by 33.3% compared to case 1, 44.1% compared to case 2, 41.1% compared to case 3 and 34.6% compared to case 4. Therefore, It can be seen that the proposed system obtains less indoor heat gain than each reference case during the summer season. In addition, since the indoor heat inflow amount of cases 3 and 4 using the same emissivity films is significantly different from the proposed system, it can be clearly seen that controlling the radiant heat transfer in the wall improves the thermal performance of the PCM integrated wall.

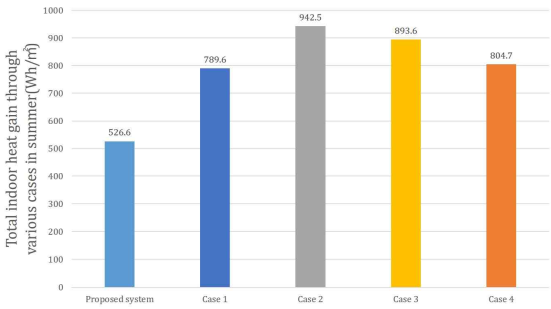

Fig. 12 - Total indoor heat gain during summer.

4.2 Heat loss through building walls in winter

Fig. 13 depicts the comparison of the monthly indoor heat loss of each cases when operating during winter. Since heat can be stored during the daylight through the high solar absorptance of the exterior wall, the cases with PCM had less indoor heat loss than the case 2 that did not. In addition, it can be seen that the proposed system obtains less at least 14% to 24.5% less indoor heat loss than each reference cases during the simulation period.

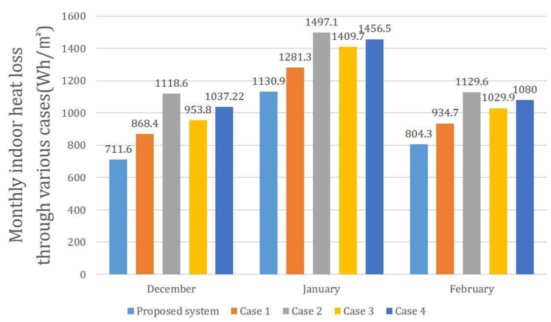

Fig. 13 - Monthly indoor heat loss during winter.

Fig. 14 depicts the comparison of the total indoor heat loss of each case in the winter season. Under winter conditions, the proposed system reduced indoor heat loss by 14.2% compared to case 1, 29.3% compared to case 2, 22% compared to case 3 and 25.9% compared to case 4. It can be seen that the proposed system reduces more indoor heat loss than each reference case during the winter season.

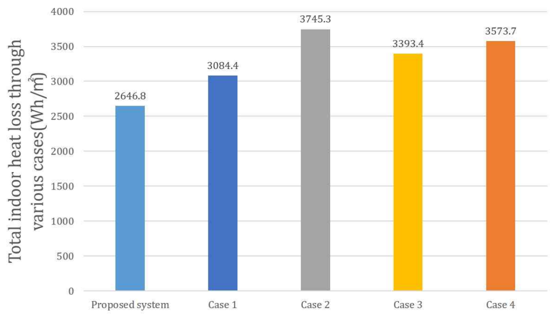

Fig. 14 - Total indoor heat loss during winter.

5. Conclusion

This study proposes a wall system that adjusts the thermal resistance of the cavity in the wall through the active radiant heat reflector to improve the thermal performance of the PCM-integrated wall. In order to compare the thermal performance of the proposed system, the indoor heat gain in summer and the heat the indoor heat loss in winter were compared with the reference cases. The cases were simulated by numerical analysis of 1D transient heat transfer with Matlab 2021a. As a result of the simulation, the proposed system reduced the total indoor heat gain in summer by at least 33.3% up to 44.1% than reference cases. It also reduced the total heat loss in winter by at least 14.2% up to 29.3% compared to the reference cases. Considering that indoor heat gain and loss are directly involved in the cooling and heating load of the building, the simulation results of this study are expected to be effective in terms of energy saving of the building. Also, the annual simulations are being conducted to closely evaluate the thermal performance of the proposed system. In the future, the proposed systems can be considered as one way to reduce energy and increase efficiency of the buildings that integrate PCM and walls.

6. Acknowledgement

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