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Phase Change Material (PCM) Application in a Modernized Korean Traditional House (*Hanok*)

Jaewook Lee [1] and Jiyoung Park [2,*]

[1] Illinois School of Architecture, University of Illinois at Urbana-Champaign, Champaign, IL 61820, USA; jlee764@illinois.edu

[2] Department of Architecture, Inha University, Inharo 100, Namgu, Incheon 22212, Korea

* Correspondence: jypark@inha.ac.kr; Tel.: +82-32-860-7583

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Abstract: Social and policy interest in the modernization and revitalization of the Korean traditional house (*Hanok*) has increased recently in Korea but its low thermal performance is one of its weaknesses. A feasibility study was conducted to evaluate the suitability of a Phase Change Material (PCM) in a modernized *Hanok*. The research method involved a test of the heating and cooling load reduction and Predicted Mean Vote (PMV) analysis for human comfort using an Esp-r simulation adopting multi variable PCM types as the building wall composite. The influence of PCMs on reducing the building energy load was assessed as a criterion for upgrading materials and infiltration to the passive house regulation. Compared to the base case, the heating and cooling load reduction ratio were as follows: Case 1 (old-*Hanok*), 10%; Case 2 (Korean Building Act), 21%; and Case 3 (passive house regulation), 53%. The optimal phase change temperatures of the PCMs were Case 1 (24–26 °C), Case 2 (23–25 °C) and Case 3 (24–26 °C). PMV analysis showed that the use of a PCM can narrow the comfort range and centralize the optimal point. Therefore, the following contents can be presented as the design and material guidelines. First, the optimal PCM temperature can vary according to the combination of materials and local climate. In addition, the infiltration and insulation should be verified and a certain portion of them should be secured. Finally, the addition of insulation to a passive house level should be considered actively using a PCM as a supplement for net zero energy building (nZEB).

Keywords: Korean traditional house; *Hanok*; PCM (Phase Change Material), ESP-r; energy simulation; building materials

1. Introduction

In Korea, there has been increasing interest in *Hanok*, which is the original type of Korean architecture. As the social demand for *Hanok* is expanding, it has great potential for creating various cityscapes and becoming an alternative to new residential environments. Social and policy interest in the modernization and revitalization of *Hanok* has increased and recently a technical development research project was initiated by the Korean Government. Consequently, a modernized *Hanok*, which includes various reinterpretations and recognition of changes to its layout and performance required for modern life, was constructed. The question is whether to accept and apply the characteristics of the traditional *Hanok*. This is an important part of the modernization of *Hanok* and its application to the future [1]. Figure 1 presents typical images of traditional and modern *Hanok*. The main difference is in their construction method. The old-*Hanok* is built using wet construction methods but the modern *Hanok* uses mainly dry construction methods.

(**a**) (**b**)

Figure 1. Typical *Hanok* images: (**a**) old-*Hanok* (*Myeongjaegotak*, Nonsan, Korea, 1709) [2]; (**b**) modernized *Hanok* (*Hwagyeongdang*, Seoul, Korea, 2013) [3].

From this background, some critical issues have emerged, such as narrow space dimensions and the layout for a modern lifestyle, poor insulation, weak fire resistance and expensive construction costs compared to contemporary buildings. In particular, based on a survey dealing with the inconvenience of *Hanok*, ″hot and cold″ sensations were the biggest issues with a reported rate of approximately 18% [4,5]. Moreover, inefficient energy consumption—particularly energy loss through the building envelope—is one of main concerns with *Hanok* [6–8]. Therefore, if hot and cold problems can be solved, it will help reduce energy consumption and carbon dioxide emissions as well as provide indoor human comfort.

One of the easiest ways to improve the thermal performance is to add insulation. The traditional earthen wall made from loess—called *Hwangtoh,* used to construct the traditional *Hanok* [9]—is impractical because of the high thermal conductivity of approximately 1–2 W/m·K [10], which is approximately 10 times higher than that of insulation [11]. Therefore, an appropriate amount of insulation is needed but various difficulties are encountered as the walls of *Hanok* are thickened because of the limitations regarding the thickness and the aesthetic proportions of the wooden pillars.

An additional option is to install a Phase Change Material (PCM), which is a heat storage material. Its basic principle is to absorb a large amount of heat and energy and release it to the indoors or outdoors by melting and solidifying at certain temperatures [12–16]. In addition, its main advantage is to maintain a certain temperature for a long time and improve the energy efficiency in the building energy load.

In previous studies, the PCM for building applications can be classified into two types: the traditional and encapsulated PCM [17]. Based on the classification, a computer simulation and field study were performed to assess the applications of PCMs in walls [18–25], roofs [26,27], windows [28,29] and floors [30,31]. In particular, there are advantages in installing a PCM in wall systems depending on which part is focused on, such as the materials and combinations, which geographic conditions they are testing and whether the tests are conducted under heating or cooling conditions. For example, finite different numeric calculations of a PCM wall system were performed at different melting temperatures and climates for net zero energy buildings (nZEB) based on characteristic days [19,20]. In addition, a thermal comfort test for a PCM wall system was conducted based on lightweight concrete with an encapsulated PCM for residential housing in Hong Kong. The results showed that the application of PCM to lightweight aggregate improved economic feasibility and was expected to have positive results in an environmental evaluation through CO_2 reduction [21]. In terms of the experiment with a numerical evaluation, two identical rooms were used to assess the performance and effectiveness of a shaped-stabilized PCM [22]. In addition, they selected different locations to determine the climate differences and its impact on the performance of PCM. Numerical and experimental analyses were performed based on a nano-PCM to evaluate the application of a PCM and gypsum wallboard; this system showed better energy performance in maintaining the indoor temperature [23]. Microencapsulated PCM with copper foam as a medium was simulated for thermal comfort in Malaysia and the system reduced the cooling energy load [24]. A performance test of an insulated concrete block with PCM was conducted in the United Arab Emirates to determine the energy consumption in the cooling season with natural or mechanical ventilation [25].

As one of the main concerns around maintaining and improving the thermal performance, the phase change temperature should be considered. A PCM has inherent properties, such as the melting temperature, heat of fusion, thermal conductivity and density [14]. Selecting a PCM with a specific melting temperature is very important because it can absorb a large amount of energy and release it to the buildings at a specific temperature as the melting temperature changes. In particular, the energy performance can vary greatly depending on which PCM is selected because the melting temperature ranges from −30 to +66 °C [32,33].

Therefore, the application of a PCM not only reduces the total energy consumption but also affects the peak load reduction positively [34]. The thermal storage function of the PCM also positively affects human thermal comfort [35,36]. In addition, fire retardation, long term stability and enhanced heat transfer are important.

In this study, the effects of PCM application for the selection of the material property in a modernized *Hanok* (so called new-*Hanok*) were simulated. In previous studies, research on the energy analysis of historical buildings was conducted [37,38]. In addition, the performance of PCM has been evaluated after adding traditional materials, lime mortar with PCM [39], but, few studies have assessed the applicability of PCM to the modernization of traditional architecture and one was initially introduced to conference proceedings in 2001 [40]. Compared to previous studies, there have been major amendments of new contents; the building regulations related to the insulation thickness have changed considerably and the latest codes are reviewed in this paper. In particular, a PCM can play a very important role in the planning of new-*Hanok* because the main material of traditional housing is soil and wood, which have poor thermal performance. Finally, the following are addressed: (1) identify how the energy (total consumption) aspects and human comfort change when applying several different types of PCM to a building envelope using an energy simulation; (2) predict the appropriate phase change setting temperature for various cases through sensitivity analysis; and (3) propose a material and engineering guide for how PCM can effectively reduce energy consumption and increase human comfort.

2. Methods

The analysis is presented in three steps, as shown in Figure 2:

(1) select a new-*Hanok* model, materials and simulation assumptions including infiltration;
(2-1) analyze the basic heating and cooling energy load to determine the adoptable PCMs;
(2-2) diversify temperature variables of PCM, which is aimed at minimizing the energy load and the peak-load shift by sensitive analysis; and
(3) analyze and compare the application of several types of PCM on the building model for minimizing the heating and cooling load and optimize the PMV range for human comfort.

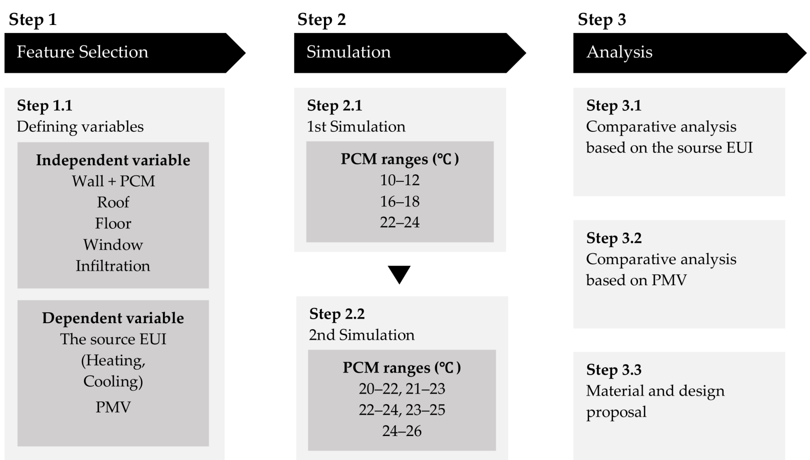
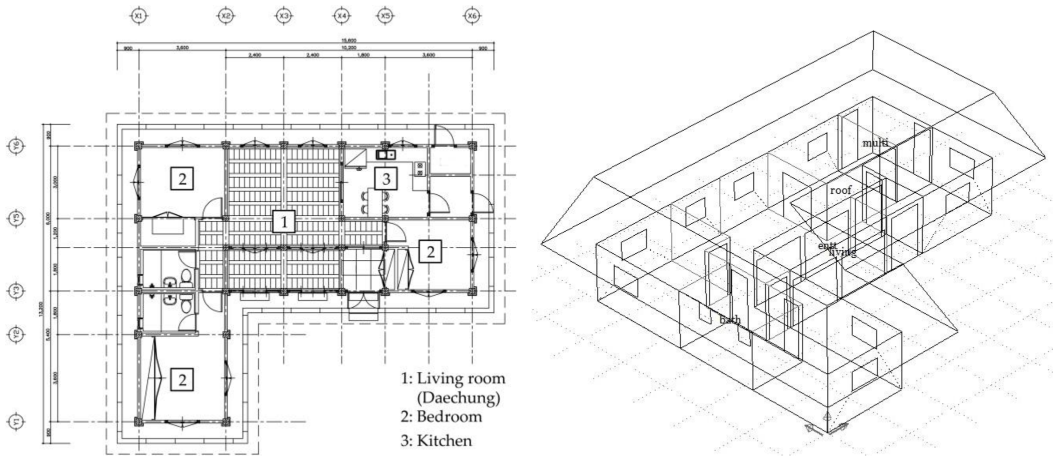


Figure 2. Research diagram.

The procedure for basic design of *Hanok*, material components, simulation settings and criteria for the selection of measures are described below.

2.1. New-Hanok Drawing

As a base model of this study, one of the new-*Hanok* plans by the '*Hanok* Technical Development Research Institute' was selected [41]. Figure 3 shows the plan and perspective drawing for the simulation. The main feature of new-*Hanok* design, '*Daechung*,' which is the living room space, was considered the indoor space while the semi-outdoor space was the unconditioned area in the original *Hanok*. In addition, the room and window size were adjusted to be suitable for modern life and furniture arrangement. This model consisted of three bedrooms, a living room, a kitchen and so forth. The length of the building was 15.6 m; the depth was 13.2 m; the floor to ceiling height was 2.4 m; the area was 102.24 m^2; the volume was 245.38 m^3; and the WWR (Window to Wall Ratio) was 19%.



(**a**) (**b**)

Figure 3. Drawing of the proposed *Hanok* (**a**) Floor Plan [41]; (**b**) 3-d perspective view of the energy simulation modeling.

2.2. Esp-r Computer Simulation and Setting

Esp-r 11.1, which is a dynamic energy simulation tool introduced in 2001, was selected to identify the applications of PCM–*Hwangtoh* (*Hwangtoh* is the traditional earthen wall made by loess) composites for thermal comfort in new-*Hanok* [42,43]. The 'Active Materials' option of Esp-r has been used to conduct research related to the application of PCMs [44]. This research was targeted for integrating the energy simulation with PCM and applying a gypsum board-PCM composite in a building. Therefore, there is a function that enables the application of a PCM to the multilayers of a composite in Esp-r. The basic equation for transient heat conduction with thermophysical properties is shown below [44,45]:

$$\frac{\partial}{\partial t}\rho(T)h(T) = \nabla\cdot[k(T)\nabla \mathrm{T}(r^{\rightarrow},t)] + q(r^{\rightarrow},t)$$

where T is the temperature; ρ is the density; h is the enthalpy; k is the conductivity; and q the heat-generation rate [44].

The weather data was supported by the Esp-r default climate file, which was set to Seoul, Korea ('KOR_SeoulAB'_from Korea Institute of Energy Research (KIER)). According to the ASHRAE climate classification, Seoul belongs to Zone 4A, a moderate climate zone. In terms of the annual weather averages, July is the hottest month in Seoul with an average temperature of 24 °C and the coldest month is January at −4 °C. The annual-average daily global solar radiation is 3.58 kWh/m^2·day [46]. As a HVAC control, the set points of cooling and heating were 24 and 21 °C, respectively [47,48].

The internal loads for the equipment were calculated to be 8.07 W/m^2 (0.75 W/ft^2) peak load and the sensible load per person was 297 W, which is 8.07 W sensible/m^2 (0.75 W sensible/ft^2) [49].

In terms of infiltration, the performance in old-*Hanok* appears to be poor due to deformation and joint problems with wood and *Hwangtoh*. Table 1 lists the infiltration input data described by the actual data in old-*Hanok* [50], ASHRAE standard Leakage Class [51,52] and Passive House Planning Package (PHPP) [53]. The formulation converting from Air Changes per Hour (ACH) (50 Pa) to ACH (0 Pa) is followed by EN 13790 [54].

Table 1. Infiltration properties for the simulation.

Types		ACH (50 Pa)	ACH
Passive House Planning Package (PHPP)		0.6	0.038
ASHRAE	A	1	0.064
	B	2	0.128
	C	3	0.192
	D	5	0.321
old-*Hanok*		-	-

Based on the simulation setting, the annual heating and cooling loads were evaluated based on the sum of the load in two seasons; winter and summer. In addition, the reduction ratio, which is expressed as the relationship between the value of the base and target cases was used to compare the energy savings with the base case.

2.3. Material Properties

To select the applicable material properties in a new-*Hanok*, the following three different types were chosen: Case 1, an old traditional *Hanok,* called *Genjaegotaek,* built in 1869 [50] with real data; Case 2, a house that uses materials fulfilling the latest Korean Building Act (revised in 2017); and Case 3, a house that respects the passive house building guideline materials (PHPP 2015 [53]) for nZEB. Table 2 lists the conditional U-value properties of the three cases.

Table 2. Material properties calculated as the U-value (W/m^{2}K).

Types	Wall	Roof	Floor	Window
Old-*Hanok* (Case 1)	3.270	0.788	0.590	5.879
Korean Building Act (Case 2)	0.210	0.150	0.180	1.200
Passive house guideline (Case 3)	0.150	0.150	0.150	0.800

2.4. PCM (Phase Change Material)

Among the many techniques for increasing the thermal comfort, PCM has been used for heating-cooling load reduction and peak load shifting. The thermodynamic features of PCM are known as the absorption and release of the phase change latent heat under isothermal condition [55]. Theoretical and numerical analysis were conducted and the integration of PCM modeling with a building dynamic simulation was performed using ESP-r [44,56].

The most critical properties of a PCM for improving the building thermal performance are the melting point, transition temperature range and latent heat of the phase change. Assuming that the normal temperature distribution in Korea is approximately 0 to 30 °C, three PCMs, which range in ambient temperature were chosen [32,57–59] for the simulation and are listed in Table 3. These three PCMs were tetrabutylammonium bromide, propyl palmitate and paraffin C13–C24, with melting and solidification temperatures of 10–12 °C, 16–18 °C and 22–24 °C, respectively, with a thickness of 25 mm. To reduce the energy load and maintain a uniform indoor temperature, the PCMs were installed in the inner side of the external wall, as shown in Figure 4. In addition, the basic descriptions and abbreviated terms are as follows: T_m, melting temperature; T_s, solidification temperature; latent heat of fusion, which is the heat absorbed as a substance changes phase from liquid to solid; setting temperature; melting and solidification temperatures; and reduction ratio, the energy savings compared to the base case. In terms of thermal conductivity, density and specific heat capacity, the mean or median values based on commercial product details were used [20].

Table 3. Thermophysical properties of the PCMs used in the simulation.

Names	Type	T_m (°C)	T_s (°C)	Latent Heat of Fusion (kJ/kg)	Thermal Conductivity (W/m·K)	Density (kg/m^3)	Specific Heat Capacity (J/kg·K)
Tetrabutylammonium bromide [60]	Organic	10	12	193	0.6	1500	2000
Propyl palmitate [61]	Organic	16	18	186	0.6	1500	2000
Paraffin C13–C24 [62]	Organic	22	24	189	0.6	1500	2000

2.5. Wall Composite with PCM

Three different types of wall configurations were set as the main variables in this experiment, as shown in Figure 4. One common feature of the three cases is that 25 mm PCM-*Hwangtoh* is used as a component of the wall, the main difference being the value of heat transfer (U-value). Case 1 is composed of a wall of old-*Hanok*. This assumes a wall composed of pure *Hwangtoh*. Case 2 assumes a wall that meets the legal standards required by Korean housing. At this time, cellulose which is a pack of cellulose pulp in felt form was used as the thermal insulation material based on the guidelines of the National *Hanok* Center [1] and its thickness was calculated to be 155 mm to meet the current code (Korean Building Act). Finally, in Case 3, the insulation standard was reinforced to a passive house level and an insulation of 260 mm was used with the other materials remaining the same as in Case 2. In Cases 2 and 3, terracotta was applied as an alternative to *Hwangtoh* and waterproofing and steel frames were also used [1].

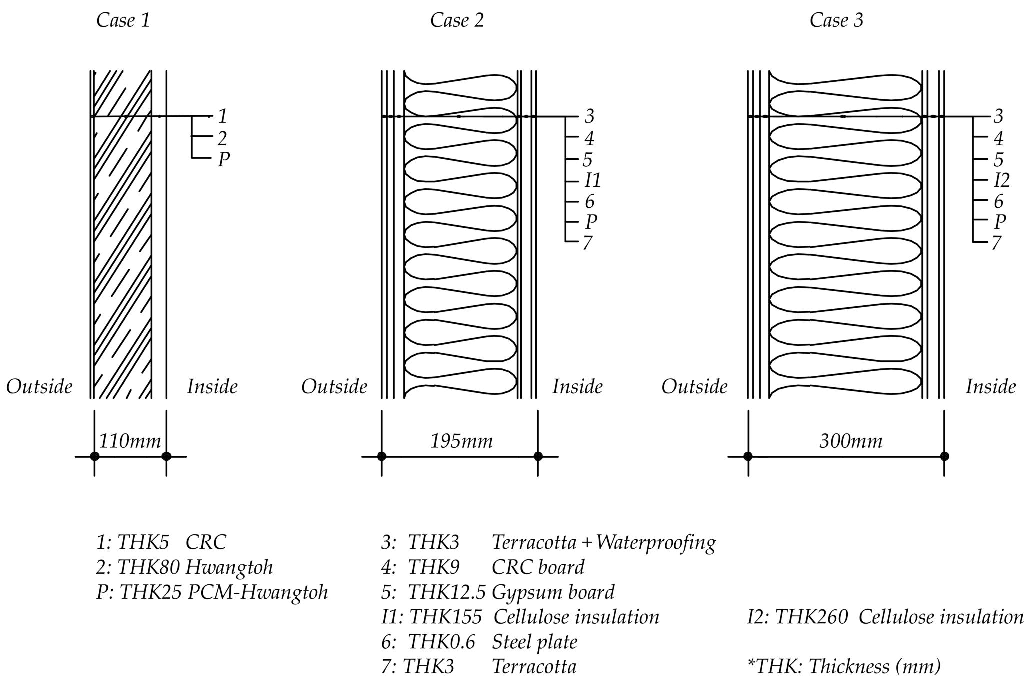


Figure 4. Section drawing detail of PCM-*Hwangtoh* composites installation.

2.6. PMV (Predicted Mean Vote)

Thermal comfort, which is a human's satisfaction with the thermal environment, can be expressed as the PMV, based on Fanger's model [63]. The PMV defines how people would be satisfied in a thermal environment and it is standardized as ASHRAE 55-2004 and used to evaluate the thermal comfort [51,64–66]. The values range from −3 (too cold) to +3 (too warm) and a range from −0.5 to 0.5 is normally recognized as a comfort zone by ASHRAE [51]. In this paper, the number of hours with |PMV| <1, that is, PMV values ranging from −1 to 1, which is the cumulative time comfort over a year, was selected to evaluate the thermal comfort.

3. Results and Discussion

The results can be divided into three parts: energy performance evaluation in terms of the infiltration changes, two simulations with a PCM temperature setting and PMV analysis. In the first part, the simulation was performed to determine how the energy performance changes based on the infiltration uncertainty. Second, two simulations were conducted, which are presented as a process to find the optimal PCM temperature according to various material characteristics through sensitivity analysis. Finally, PMV was applied to determine how thermal comfort is achieved at the junction between the various materials and how much energy reduction and human comfort are similar or different.

3.1. Energy Performance According to the Insulation Material and Infiltration Level Change

The annual heating and cooling loads were drawn by varying the material properties and infiltration without applying a PCM. The three infiltration values were taken from Table 1 and are shown in Figure 5. Considering that the ACH of a typical residential building in Korea is approximately 0.4, 0.321 was selected as the infiltration intermediate value in the simulation [67].

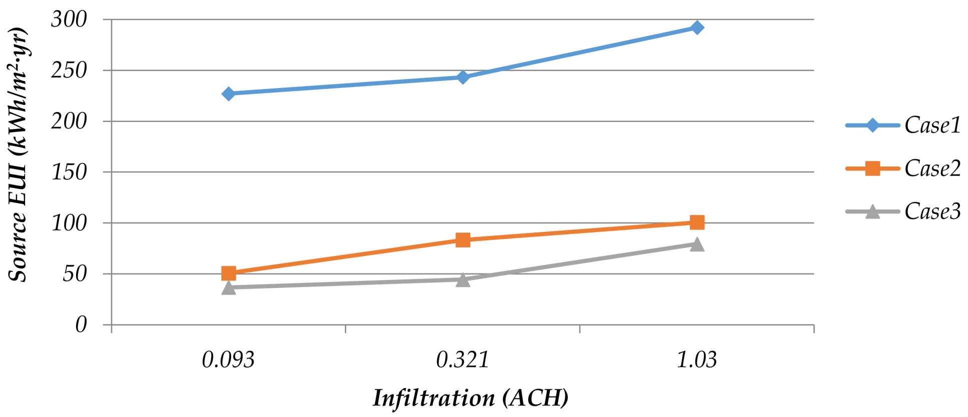


Figure 5. Annual heating and cooling load based on three different cases of insulation.

Figure 5 shows that strengthening of the insulation performance and infiltration in the *Hanok* can reduce the energy load by approximately 66%, 21% and 73% from Case 1 to Case 2, Case 2 to Case 3 and Case 1 to Case 3, respectively. For the material properties for a new-*Hanok*, the addition of thermal insulation materials and strengthening infiltration can improve the energy performance. The next part clarifies how the energy performance (total energy consumption and peak load energy consumption) and thermal human comfort can be improved when a PCM is applied.

3.2. Energy Performance Based on the Variation of the PCM-Hwangtoh Composite

The first simulation was conducted to select the appropriate temperature range in phase change mode. In setting the phase change temperature, three types in the range among the mean ambient temperature 0 to 30 °C were chosen, which are PCMs with a melting and solidification temperature range of 10–12 °C, 16–18 °C and 22–24 °C. A total of 12 simulations were performed based on three types of material properties, Cases 1, 2 and 3, according to the three different types of PCMs and non-PCM. Figure 6 compares the annual heating and cooling loads by applying the three types of PCMs. The reduction ratio is expressed as the relationship between the value of the base case and the target case.

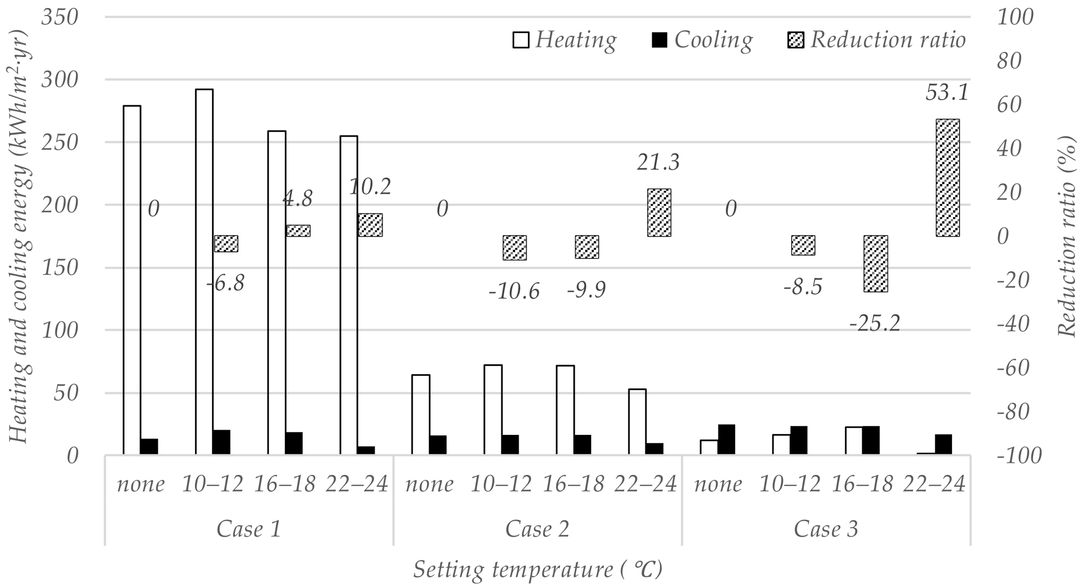


Figure 6. Annual heating and cooling load by the PCMs; 1st simulation.

According to the simulation results, setting the phase change temperature range to 10–12 °C and 16–18 °C increases the total heating and cooling loads slightly compared to the base case. In the case when 22–24 °C was used, the PCM decreased the heating and cooling load reduction ratio by 10.2, 21.3 and 53.1 in Cases 1, 2 and 3, respectively, compared to the non-PCM application. This means that selecting the 22–24 °C PCM temperature range, which is the cooling and heating set point, is efficient.

Based on the first simulation, the next simulation as sensitivity analysis, which ranged from 20–26 °C was conducted and the results are shown in Figure 7. Therefore, the second simulation was performed by further dividing the PCM temperature into six different types: none, 20–22 °C, 21–23 °C, 22–24 °C, 23–25 °C and 24–26 °C. The reduction ratio in the figure was calculated based on the PCM not being included in each case, which is the base case. The simulation results showed that the optimal set points of the PCMs for Cases 1, 2 and 3 are 24–26 °C, 23–25 °C and 24–26 °C respectively. This means that the optimal PCM set point should be applied differently according to the change in material properties. In addition, the heating and cooling load reduction ratio increased when the material properties were upgraded from Case 1 to Case 3. Following these results, for the near future in a passive house, PCM can reduce the heating and cooling loads significantly in a new-*Hanok* by approximately 60% compared to the non PCM applied building.

In terms of the monthly energy reduction, PCM-*Hwangtoh* composites positively affect the condition not only in spring and autumn but also in summer and winter, as listed in Table 4. The monthly heating load reduction ratio in January, which demands the maximum heating loads, was Case 1 at 2.1%, Case 2 at 11.4% and Case 3 at 94% compared to the non-PCM application. This means that the heating load reduction of the PCM can be maximized in a fully insulated situation, so the effect of the PCM and insulation on the heating energy saving is positive.

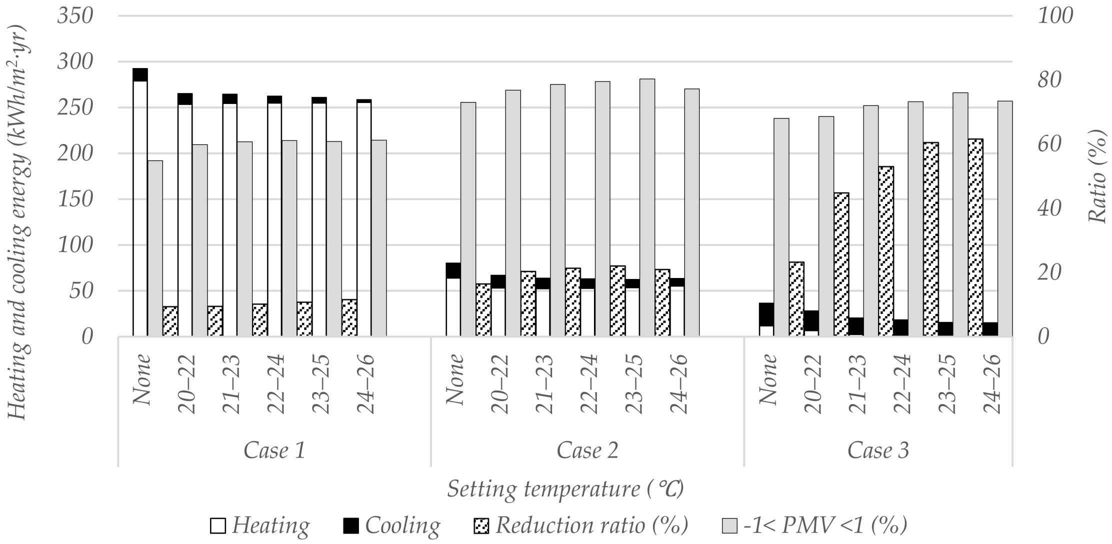


Figure 7. Annual heating and cooling load by the PCMs; 2nd simulation.

Table 4. Monthly heating and cooling load by the PCMs; 2nd simulation.

Types	Heating and Cooling Energy	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Case 1	Heating (kWh)	6511	5328	3604	2018	729	106	2	4	68	1119	3239	5794
	Cooling (kWh)	0	0	0	0	32	157	333	586	198	43	0	0
PCM (24–26)	Heating (kWh)	6370	5163	3247	1468	380	7	0	0	0	768	2948	5783
	Cooling (kWh)	0	0	0	0	1	6	68	200	4	4	0	0
Case 2	Heating (kWh)	1647	1255	785	402	97	8	0	0	1	189	724	1459
	Cooling (kWh)	0	1	26	42	150	234	299	457	257	142	14	0
PCM (21–23)	Heating (kWh)	1459	1106	569	177	47	0	0	0	0	51	542	1328
	Cooling (kWh)	1	2	10	7	31	100	230	442	89	62	14	0
Case 3	Heating (kWh)	382	234	115	37	10	0	0	0	0	9	89	336
	Cooling (kWh)	0	3	65	106	326	384	372	515	423	300	35	0
PCM (24–26)	Heating (kWh)	9	7	7	1	0	0	0	0	0	1	7	9
	Cooling (kWh)	2	5	24	18	77	179	263	454	183	156	35	0

On the other hand, the difference in energy reduction between summer and winter is obvious. In Figures 8 and 9, there are two types of days, the hottest and coldest days of the year and the daily ambient temperature and heating and cooling loads are drawn. The x-axis of the figures represents the time and the y-axis represents the temperature and heating and cooling energy load. In addition, the dotted line in the graph indicates the temperature, the thick line indicates the PCM (24–26) applied case and the thin line indicates the base case, which is the non-PCM case. Compared to the non-PCM energy loads, in summer, the gap, which is shaded in gray (darkened), between non-PCM and PCM (24–26) is minor. On the other hand, in winter, the gap between the two material composites is extremely large. The reason for this is during the hottest day, two major factors, both temperature and solar radiation increase the indoor temperature. On the other hand, in winter, temperature and solar radiation have an opposite effect on the indoor temperature.

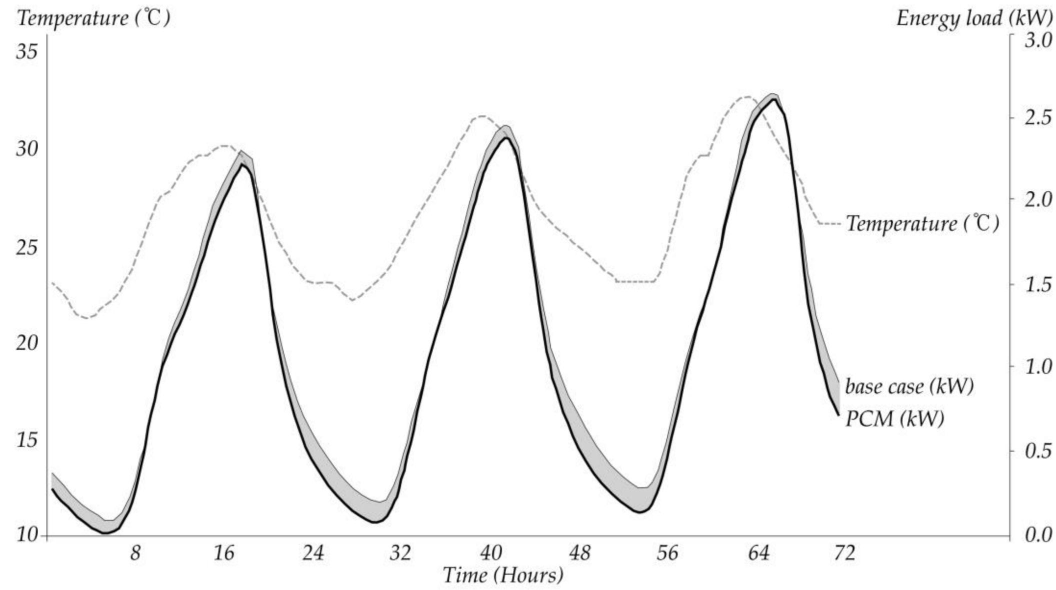


Figure 8. Daily peak load reduction in Case 3 (Hottest days of a year).

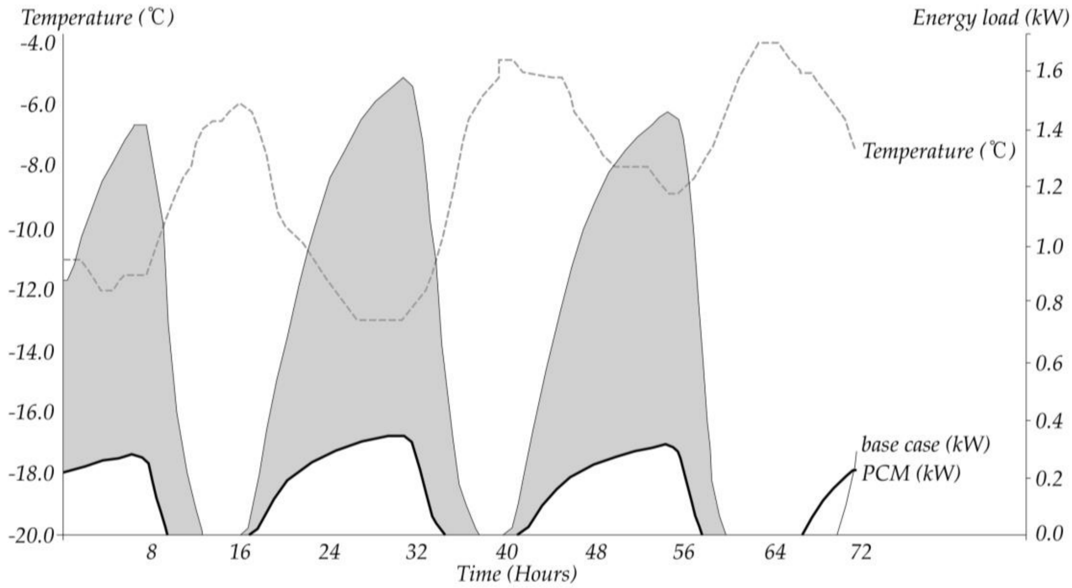


Figure 9. Daily peak load reduction in Case 3 (Coldest days of a year).

3.3. Thermal Performance with PMV Analysis Based on the Variation of the PCM-Hwangtoh Composite

Based on the results of the two energy simulations, PMV analysis was performed and the basic input data is as follows: (1) Clothing level, 0.7 (clo); (2) Activity level, 1.46 (MET) and (3) Air velocity, 0.1 (m/s) [64,68,69].

As shown in Figure 7, when applying different PCMs for each case, the range of the PMV value was 73.0–80.3% for Case 2 and 68.6–76.0% for Case 3. Figure 10 presents the results regarding the three optimal energy cases, Case 1, 2 and 3 with 24–26 °C, 23–25 °C and 24–26 °C, respectively. For thermal comfort, Case 2 showed the highest percentage, which is approximately 80.3% followed by Case 3 with approximately 76%. Therefore, Case 2 is superior to Case 3 in terms of the portion where the PMV falls within the range of −1 to 1. The reason why Case 2 shows a higher percentage of PMV than Case 3 is that winter is the season when a PCM is more effective in the Korean climate. In winter, the PMV is measured based on the operating temperature of the PMV of approximately

20–24 °C, that is, an average of 22 °C [70]. The internal heating temperature is set to operate at 24 °C. The set temperature of the PCM is 24–26 °C, which is also higher than the PMV standard ranges. The winter temperature is often maintained above 24 °C because the internal heating system tends to maintain temperatures greater than or equal to 24 °C and in Case 3, the performance of insulation and infiltration is quite good. Therefore, the PMV is relatively higher than the reference value. In addition, the occupant has the advantage of wearing thinner clothes on the inside in winter and staying in a better thermal condition than usual [71].

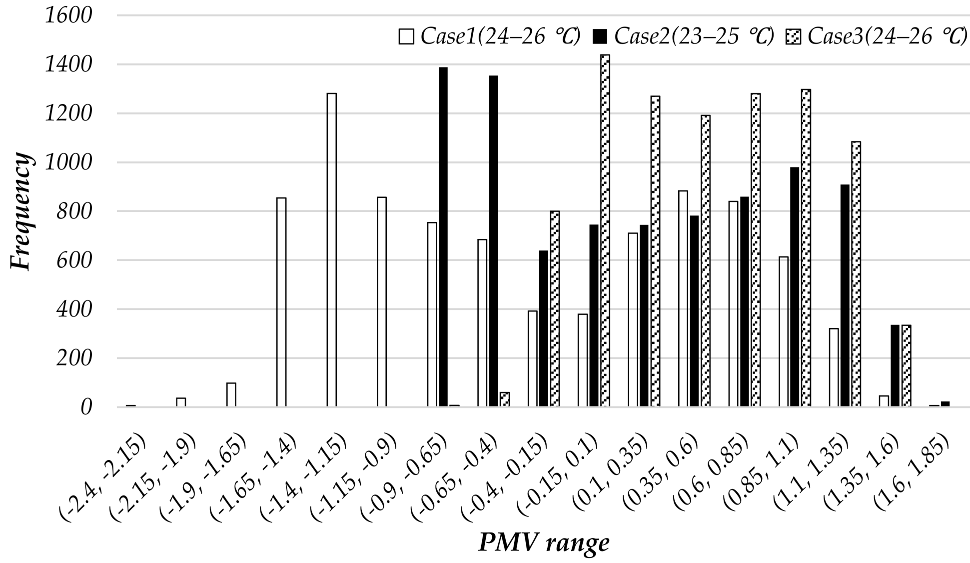


Figure 10. Frequency diagram of PMV in three cases.

When the PMV range was subdivided and its frequency was examined, as shown in Figure 10, the absolute value range of the PMV changes was smaller for Case 3 than for Case 2. In other words, the area in Case 3 is displayed at the frequency of 9 stages in total from (−0.65, −0.4) to (1.35, 1.6) compared to the area in Case 2, which is displayed at a frequency of 11 stages in total from (−0.9, −0.65) to (1.6, 1.85). This suggests that Case 3 can maintain the internal temperature of the room more effectively within the appropriate range, resulting in a "flattening effect" [55] on the internal room temperature.

4. Conclusions

This study examined how a PCM combined with a new-*Hanok* envelope, particularly the wall composite, can affect the building energy and thermal performance. The heating and cooling load reduction and PMV comfort range were measured and evaluated with the variation of infiltration, insulation and PCM properties. The optimal phase change temperature was also investigated in variable types of PCM applications with sensitivity analysis. The results for the design and material guidelines are as follows.

- Infiltration revealed a significant effect on the energy consumed. In particular, *Hanok*, which is constructed by mixing various materials, has considerably low infiltration, so it is important to strengthen it.
- Compared to traditional *Hanok* materials, strengthening insulation based on passive house regulation for nZEB can reduce the heating and cooling energy by approximately 73%.
- The PCM helps reduce the energy consumption when it approaches the passive house regulation material property. The heating and cooling load reduction ratio compared to the non-PCM

application are as follows: Case 1 (old-*Hanok*), 10.2%; Case 2 (Korean Building Act), 21.3%; and Case 3 (passive house regulation), 53.1%.

- The optimal set point of the PCM for energy saving has a different value depending on the material properties. The optimal phase change temperature of a PCM for a new-*Hanok* is as follows: Case 1, 24–26 °C; Case 2, 23–25 °C; and Case 3, 24–26 °C.
- In PMV analysis, the use of a PCM can narrow the comfort range and centralize the optimal point, which is 0 point. The results confirm that a PCM has a "flattening" influence inside the zone temperature.

This paper examined the feasibility of applying a PCM to *Hanok* through the sensitivity survey method. Nevertheless, more advanced research will be needed to address the weak points.

- PMV is affected significantly by the operation schedule and occupant behavior. Dividing the basic types of the occupant schedule can allow the PMV effect to be measured more accurately by applying a PCM.
- Studies of the life cycle cost and life cycle CO_2 analysis are the major points for economic analysis. The price of the PCM will need to be in the acceptable range and a long-term heating and cooling load calculation will be needed.

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