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A Comparative Study of Energy Performance of Fumed Silica Vacuum Insulation Panels in an Apartment Building

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Abstract: Building insulation materials has a significant impact on building energy consumptions. However, conventional materials are easily flammable and can cause fire disasters in buildings. Therefore, it is important to select appropriate insulation materials for building energy efficiency and safety and Vacuum Insulation Panels (VIPs) are increasingly applied to building insulation. Considering this, the present study investigates energy performance of VIPs with design alternatives, such as window systems, infiltration rates, etc., by using energy simulation. Among various VIPs, fumes silica VIPs were chosen. In addition, eight combinations were compared to find the best energy efficient design conditions. The results of the present study showed that building energy performance can be improved with an appropriate combination of design options including fumed silica VIPs.

Keywords: fumed silica Vacuum Insulation Panels; energy simulation; heating load; cooling load

1. Introduction

The world is facing global warming, which has a significant impact on our daily lives, as we live through seasonal changes and the increase of CO_2 emissions. In addition, rising concerns over the future availability of energy-producing minerals such as oil and coal have led to increased efforts to minimize the amount of energy consumed by buildings, which consume 40% of the world's total energy for cooling and heating [1]. Thus, reducing the energy for the cooling and heating of buildings would significantly reduce overall energy consumption, leading to a reduction in CO_2 emission [2,3].

One of the ways to achieve energy savings is to install insulation in building envelopes, and many studies have been conducted to investigate the benefits of thermal insulation in relation to energy consumptions in buildings. Jim [4] monitored air-conditioning energy consumption in a building with and without building thermal insulation, and especially green roofs, concluding that buildings with the benefit of thermal insulation can decrease cooling load. Stavrakakis et al. [5] also investigated a cool roof's impact on thermal performance of educational buildings. They concluded that thermal comfort was improved and energy consumptions for cooling was decreased. According to the study by Zagorskas et al. [6], replacement of internal insulation with materials such as Eco-wool and Vacuum Insulation Panels can improve the energy performance in historic buildings. As can be seen, heat flow into and out of the building is greatly reduced, thus the need for cooling and heating when building envelopes are well insulated is minimized. Although the implementation of insulation is not the key solution, the use of insulation in building envelopes can be beneficial for the improvement of the overall building energy efficiency [7].

Building benefits from insulation materials can be achieved through the proper installation and selection of insulation materials. The current construction market offers a wide range of building insulation materials, including polystyrene foams, rigid polyurethane foams, rock wool and so forth. In addition, polystyrene and polyurethane foam panels have been noted for their good performance of resisting heat transfers through building envelopes [8–11]. However, these foams and conventional insulation materials are flammable and can cause fire disasters in buildings [12–15]. According to the study of Jiang et al. [12], if these materials cause fire, then it can spread quickly in an entire building and toxic gases can be released [16] In addition, many countries have incorporated into their building standard laws the prohibition of using conventional insulation materials that are inflammable. For instance, the French Standard NF P92-510 as well as the European classification standards EN 13501-1 and EN ISO 1182 all emphasize the dangers of using flammable materials as insulators as well as prohibit their use [17,18]. Moreover, traditional insulation materials increase the thickness of building envelopes, which may cause a significant loss of indoor space area [19]. Therefore, there have been significant attempts to switch from conventional insulation materials to Vacuum Insulation Panels (VIPs) for building envelopes, which are composed of an open porous core of fumed silica enveloped in several metallized polymer laminate layers [20]. Several studies showed that the use of VIPs as thermal insulations in buildings can bring significant energy savings [20–24]. The present study aims to provide designers with useful information by presenting the results of experiments on the energy performance of fumed silica VIPs compared to conventional insulation materials considering building loads. Different types of glazing, building orientations and infiltration rates are also considered. This study then provides an appropriate combination of design options as an analysis of the annual total energy consumptions of an apartment building in South Korea. Energy simulations were carried out to evaluate the energy performance of each design alternatives using IES-VE, a commercial building performance analysis tool developed by IES that uses EnergyPlus as its simulation engine [25].

2. Fumed Silica VIPs

Due to the flammable nature of conventional insulation materials [12], VIPs have been increasingly used in building envelopes, presenting thin and non-flammable characteristics [26,27]. Thermal conductivity of VIPs normally ranges 0.007–0.008 $W/m^{-1}K^{-1}$, which is 10 times higher than the average performance over 25 years of conventional thermal insulation materials [19,28,29]. Current vacuum-based insulations are categorized in three types: vacuum insulation panels (VIPs), which are the central focus of the current study; vacuum insulating glazing (VIG); and Vacuum insulating sandwiches (VISs). VIPs are defined by Baetens et al. [22] as evacuated foil-encapsulated open porous material with high thermal insulating capabilities. VIPs' overall structure is comprised of a porous core enveloped by an air and vapor tight barrier that is sealed to protect it from heat [24]. The air-tightness of the envelope is crucially important, as it prevents the panels from losing their thermal insulating abilities. In regards to the general function of the core of VIPs, it provides the entire VIP element with insulating and mechanical properties. In a review by Baetens et al. [22], the properties of VIP core should have optimum thermal resistance. Several materials, such as polycarbonates, ultrafine glass fibers, phenolic form and fumed silica, are being studied as core materials of VIPs [24,30,31]. Among those materials, the present study focusses on fumed silica as a core material for VIPs.

Fumed silica is composed of silicon carbide normally with fibers for structural stability inside the pores and is the most commonly used core-material for VIPs today [24]. In addition, silica is nontoxic, incombustible, and recyclable and the core of fumed silica has an important role in absorbing water vapor permeating through the envelope [24]. Due to low thermal conductivity of around 0.004 $W/m^{-1}K^{-1}$, fumes silica can reduce the heat transfer by radiation and energy consumptions if they are properly installed [22,24,32]. However, little information is available on building thermal and energy performance of building envelopes with fumed VIPs. Thus, the current paper discusses thermal insulation performance of fumed silica VIPs in combination with other building elements and conditions, namely building orientation, building infiltration rates, building glazing type and insulation thickness.

3. Methodology

The heat gain and loss by buildings should be adequately controlled to ensure thermal comfort of the occupants, minimizing energy consumptions [33,34]. To predict thermal behavior in buildings, several computer aided simulation tools have been used to provide reliable building performance data [35–40]. In addition, the results of simulations can be applied to the conceptual stage of building design to ensure energy efficient buildings. The current paper utilized IES-VE to assess building loads with fumed silica VIPs. IES-VE tool generally offers a thorough analysis on diverse aspects regarding performance of buildings such as daylight performance, thermal performance, bulk flow and so on [41–43]. Moreover, this software provides user-friendly interface and produces output in tabular form or graph to interpret and analyze data easily in the form of ASCII files [44]. Regarding the features, the IES-VE tool was the ideal candidate for use in the study. The reference building used for the study was a typical apartment building in South Korea.

3.1. Building Descriptions

Most residential buildings in South Korea are apartment buildings [45,46]. The reference apartment building, which is located in Seoul, South Korea, consists of 20 floors, and each floor contains four apartments. Other building elements such as walls, windows, etc. are presented in Table 1.

Table 1. Building material characteristics.

Element	Constructions	U-Factor (W/m^{2}K)
Wall	Dense concrete + Insulation	0.39
Internal partition	Concrete (200 mm)	2.48
Glass (including frame)	6 mm + 6 mm (low-e) (Total shading coefficient: 0.7467) (Visible light transmittance: 0.76)	1.97
Slab	Sandy soil + Polystyrene + Concrete	0.41
Ceiling	Sandy soil + Polystyrene + Concrete	0.95

3.2. IES-VE Modeling Process

For the modeling process by IES-VE, an apartment building was created using ModelIT. Solar radiation was calculated through a year by ApacheCalc. Moreover, thermal behaviors were analyzed to calculate cooling loads from May to October 2014 in the building using ApacheSim. As shown in Figure 1, it is suggested that the simulation results in the middle of the floors of the reference building are analyzed to avoid the influence from the sol-air temperature in the roof and heat from the ground. Table 2 presents the boundary conditions to investigate the heating and cooling loads in an apartment building. With regard to indoor comfort temperatures, the Korean government insists the set point temperatures be 26 °C for cooling and 20 °C for heating in the software as an energy consumption reduction policy. The set point temperatures utilized in the study were chosen to match the Korean government recommendations. In addition, the mechanical system was not considered to investigate changes in building loads solely using fumed silica VIPs in the building envelope, since energy consumptions in buildings have been significantly influenced by mechanical systems [47–49]. Contrary to office buildings, the operating schedule of the reference building were not considered in the present study due to uncertainty in occupants' schedules. In addition, the principal purpose of the study was to compare the performance of two types of insulation materials, fumed silica VIPs and expanded polystyrene, which is a conventional insulation material. As shown in Table 3, window glazing types, building orientations, air change rates, and a shading device were also simulated in combination with the insulation materials. Table 4 also presents the details of wall constructions with insulation materials and window systems, which were also used in the reference apartment building. Figure 2 presents setup of design alternatives and shows how these alternatives were investigated to determine the efficiency of fumed silica VIPs that would offer optimum building energy performance.

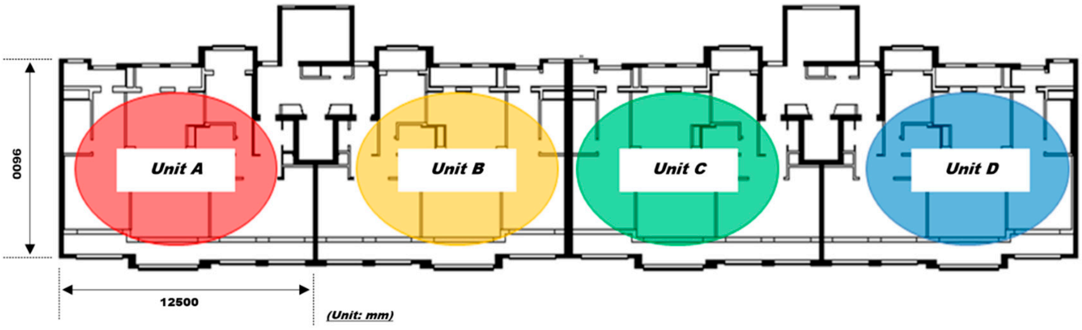


Figure 1. Four units in the middle floor.

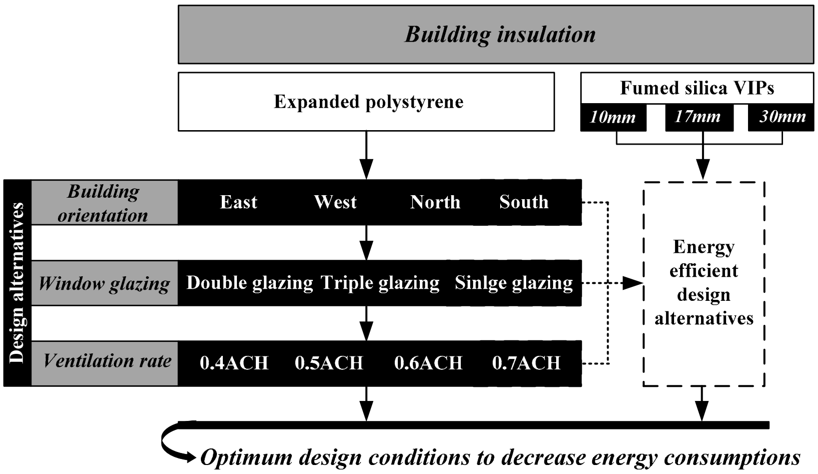


Figure 2. Setup of design alternatives.

Table 2. Boundary conditions for energy simulation.

Part	Values	
Design temperature	cooling set-point	26 °C
	heating set-point	20 °C
Humidity	30–70%	
People	4 persons (sensible gain: 90 W/person, latent heat: 60 W/person)	
Use schedule	all day used	
Infiltration rate [50]	0.7 ACH	
Weather data	Seoul, Korea (latitude: 37°, longitude: 127°)	

Table 3. Design alternatives.

Part	Conditions
Orientation	East West South North
Window system	Single glazing with low-e coating Double glazing with low-e coating Triple glazing with low-e coating
Infiltration ACH	0.7 0.6 0.5 0.4
Insulation	Expanded Polystyrene Fumed Silica VIP—10 mm Fumed Silica VIP—17 mm Fumed Silica VIP—30 mm
Shading device	External shading device

Table 4. Details of external wall and window material composition.

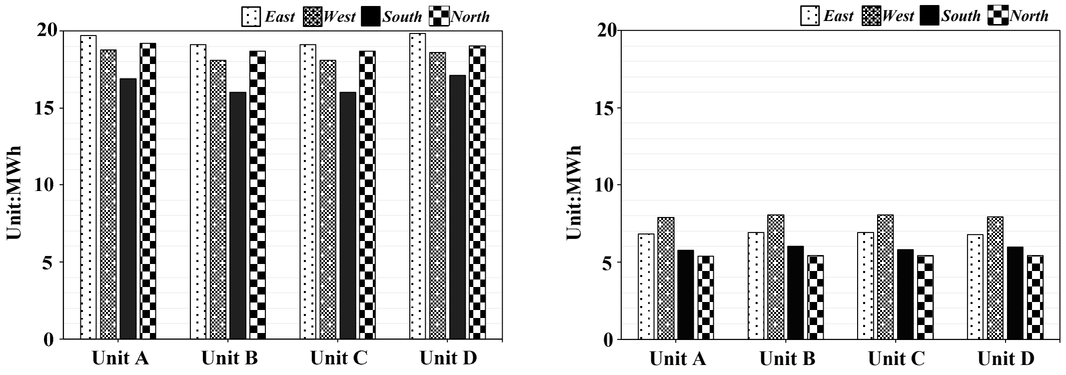
Wall/Window	Type of Insulation	Material Composition	U-Value (W/m^{2}K)
External Wall	Expanded polystyrene	Concrete (200 mm) + Insulation (80 mm)	0.37
	Fumed silica (10 mm)	Concrete (200 mm) + Insulation (10 mm)	0.39
	Fumed silica (17 mm)	Concrete (200 mm) + Insulation (17 mm)	0.24
	Fumed silica (30 mm)	Concrete (200 mm) + Insulation (30 mm)	0.14
External Window	Single glazing Low-e	6 mm clear + 6 mm low-e	1.97
	Double glazing	6 mm clear + 12 mm Air + 6 mm low-e	1.40
	Triple glazing Low-e	6 mm low-e + 12 mm Argon + 6 mm low-e + 12 mm Argon + 6 mm low-e	0.68

4. Results

The heating and cooling loads of design alternatives with fumed silica VIPs obtained by IES-VE simulation were compared to analyze the energy efficiency in a reference building.

4.1. Building Orientations

The building in the current study contains four units in an apartment building: Units A–D. In Units A and D, three facades of their envelopes were exposed to the outdoor weather condition. For Units B and C, only two façades of the building envelopes were in contact with the outdoor environment. Figure 3 shows the heating and cooling loads through four building orientations. For the heating load, the energy usage of Unit D was the biggest and the lowest energy consumption was observed in Unit C. On the other hand, the largest and the lowest cooling loads occurred in Units B and A, respectively. For energy consumed by the orientation, the heating loads were the lowest when the building is oriented to the south. In addition, the lowest cooling loads were observed in the north facing building. The difference between the heating and cooling loads was larger than the difference in energy consumptions among units (18 to 18.7 MWh for heating and 6.4 to 6.6 MWh for cooling). It can be seen that the south orientation is the best option among other orientations.

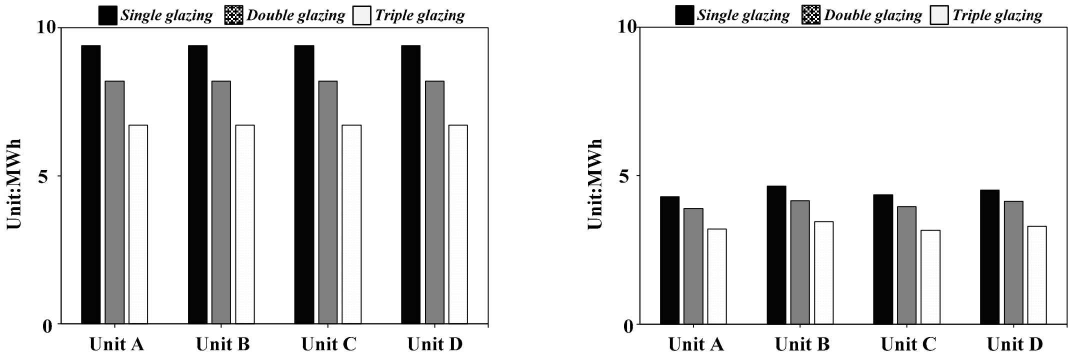


(**a**) (**b**)

Figure 3. The effect of building orientations on building energy consumptions. (**a**) Heating loads; (**b**) Cooling loads.

4.2. Window Glazing Type

The reference building was simulated with the south orientation and the initial window system in the reference building is the single glazed unit consisting of low-emissivity windows of 6 mm + 6 mm dimensions with the total shading coefficient of 0.75. For the study, three types of window glazing types were considered: single pane glazing, double pane glazing and triple pane glazing. Figure 4 shows the results of energy consumptions of the reference building with three window systems.



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

Figure 4. The effect of window glazing on building energy consumptions. (**a**) Heating loads; (**b**) Cooling loads.

As shown in the results, the triple glazing system is the most energy efficient system for both the heating and cooling loads. Although double glazed units have been generally applied to buildings in South Korea, current building trends show that the use of triple glazed units are rapidly increasing. Since triple system allows less heat to escape during cold periods, it is effective at reducing energy consumptions, especially for heating loads. In addition, the results indicate that the use of triple glass is not only beneficial in reducing heating loads but also cooling loads as compared to other types of window glazing systems.

4.3. Air Infiltration Rates

Figure 5 presents the energy consumption with four different infiltration rates from 0.4 ACH to 0.7 ACH. As can be seen, there is little difference in the heating and cooling loads with these infiltration rates, since a large amount of energy was reduced with the use of triple pane windows.

In the case of the cooling loads, the energy use was increased as the infiltration rate was decreased. On the other hand, a decrease in infiltration rates can reduce the heating loads.

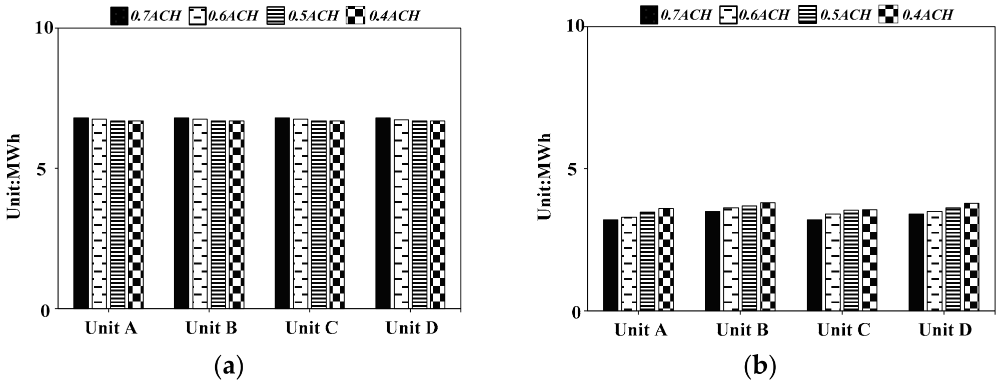


Figure 5. The effect of infiltration rates on building energy consumptions. (**a**) Heating loads; (**b**) Cooling loads.

4.4. Fumed Silica VIPs

Through the Sections 4.1–4.3, the most energy efficient design conditions were chosen. Considering these conditions, energy efficiency of three different thicknesses of fumed silica VIPs and expanded polystyrene were investigated. The insulation thicknesses of fumed silica VIPs for the study were 10 mm, 17 mm, and 30 mm and each of the insulation thickness was simulated with the most energy efficient conditions: triple glazing, 0.4 ACH, and the south orientation.

As indicated in Figure 6, there is little difference in the heating loads between the expanded polystyrene and the fumed silica VIP 10 mm. The heating loads were decreased as the thickness of fumed silica VIPs was increased, whereas the cooling loads were increased with an increase of the fumed silica VIPs' thickness.

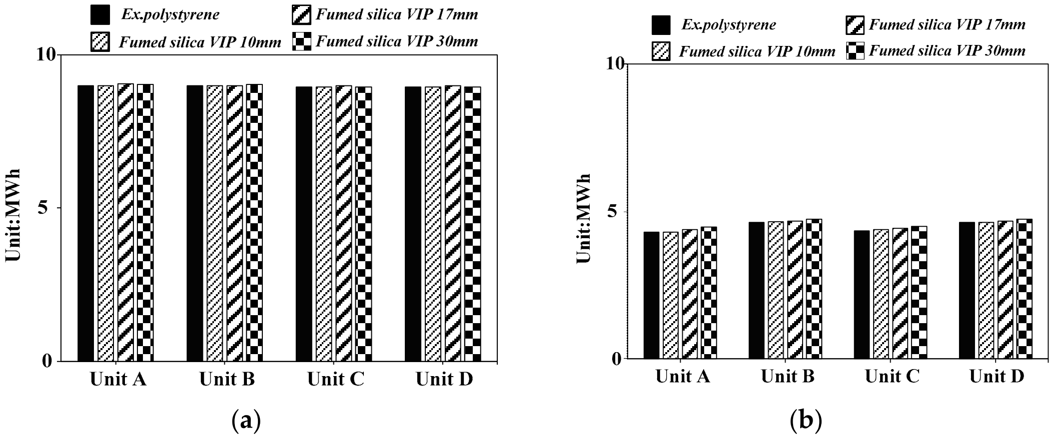
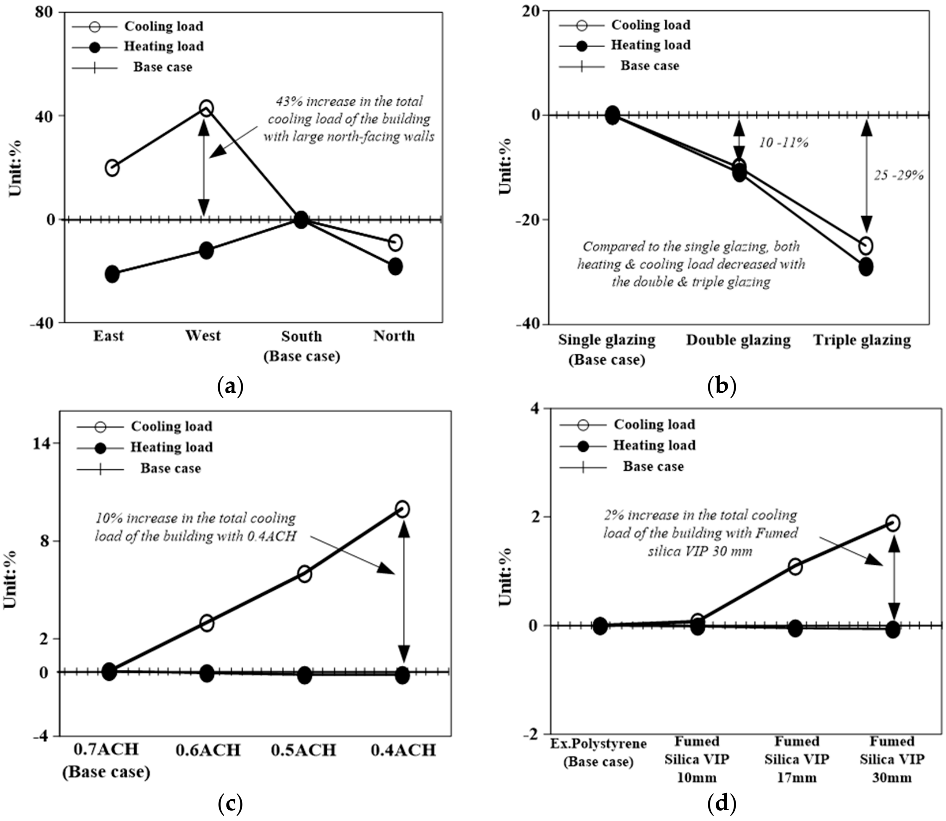


Figure 6. The effect of fumed silica VIPs on building energy consumptions. (**a**) Heating loads; (**b**) Cooling loads.

4.5. Comparisons of the Heating and Cooling Loads in the Unit

Considering the best conditions as indicated above, Figure 7 shows the comparison analyses of the heating and cooling loads in Unit B. As can be seen, 43% of cooling energy was additionally used when the building was oriented to the west. In addition, the largest reduction in the heating and cooling was observed when the triple pane window system was equipped in the building. Unlike Figure 8a,b, Figure 8c,d shows relatively small changes in the heating and cooling loads, where the best conditions were applied. The total energy consumptions can be reduced when the infiltration rates were increased. In addition, the thick fumed silica VIP required more cooling energy than that of other fumed silica VIPs of 10 mm and 17 mm. However, the total energy consumptions among three fumed silica VIPs showed a slight difference and it can be seen that the use of fumed silica VIPs can reduce the energy use for heating and cooling.



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

(**c**) (**d**)

Figure 7. The comparisons of the heating and cooling loads of Unit B with design alternatives. (**a**) Building Orientation; (**b**) Window Glazing; (**c**) Infiltration Rate; (**d**) Building Insulation.

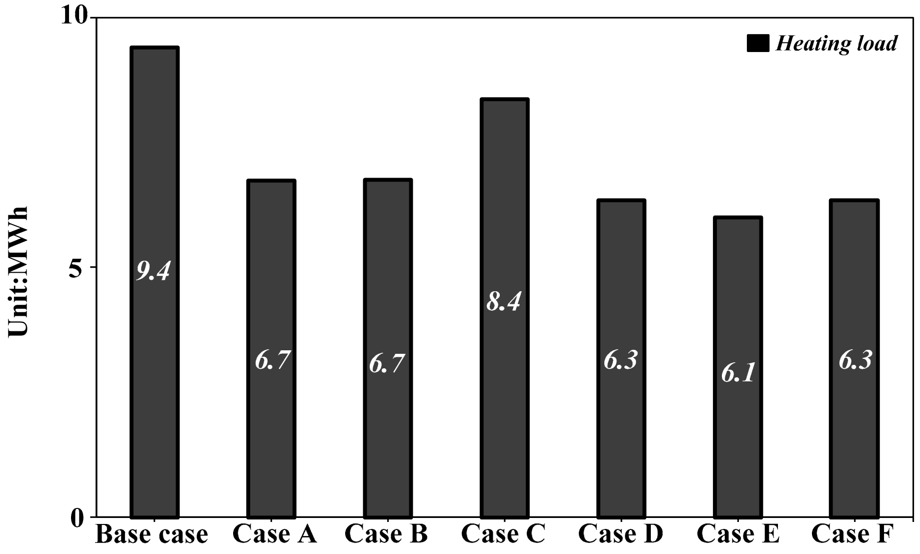


Figure 8. The comparisons of annual heating loads with the combinations of design alternatives.

4.6. Energy Efficient Strategies to Reduce Building Energy Consumptions

Design alternatives were applied to a reference apartment building and the energy consumption of each design variable was investigated using IES-VE. Considering the results of the comparisons in Sections 4.1–4.4, the optimum design condition was explored based on combinations of design options. Eight combinations including the base case are presented in Table 5. Expanded polystyrene insulation material was used for Cases A and B and two different thicknesses of fumed silica VIPs were applied in Cases C–H. In addition, Cases A–F, for annual heating loads, and Cases A–H, for annual cooling loads, were investigated. In addition, an external shading device was applied in Cases G and H.

Table 5. The combinations of design alternatives.

Case	Condition
Base case	Ex. Polystyrene + Single glazing with low-e coating + 0.4 ACH
Case A	Ex. Polystyrene + Triple glazing with low-e coating + 0.4 ACH
Case B	Ex. Polystyrene + Triple glazing with low-e coating + 0.7 ACH
Case C	Fumed silica VIP (17 mm) + Double glazing with low-e coating + 0.4 ACH
Case D	Fumed silica VIP (17 mm) + Triple glazing with low-e coating + 0.7 ACH
Case E	Fumed silica VIP (30 mm) + Triple glazing with low-e coating + 0.4 ACH
Case F	Fumed silica VIP (30 mm) + Triple glazing with low-e coating + 0.7 ACH
Case G	Ex. Polystyrene + Single glazing with low-e coating + 0.4 ACH + External shading device
Case H	Fumed silica VIP (30 mm) + Triple glazing with low-e coating + 0.7 ACH + External shading device

As shown in Figure 8, the annual heating loads in the building equipped with triple pane windows with low-e coating were lower than that with double glazing windows. In addition, the use of fumed silica VIPs can reduce the heating loads more than the use of expanded polystyrene. Among Cases D–F, the lowest annual heating load was observed in the building with 0.4 ACH (Case E).

The annual cooling loads with various combinations of design options are presented in Figure 9. Contrary to the annual heating loads, there was little difference between the base case and Case C. Moreover, an increase of infiltration rates in the building with triple pane window system can reduce the annual cooling loads, as noted previously. The lowest annual cooling loads occurred when the building was insulated with a 30 mm fumed silica VIP, equipped with triple pane windows and an external shading device, and had 0.7 ACH.

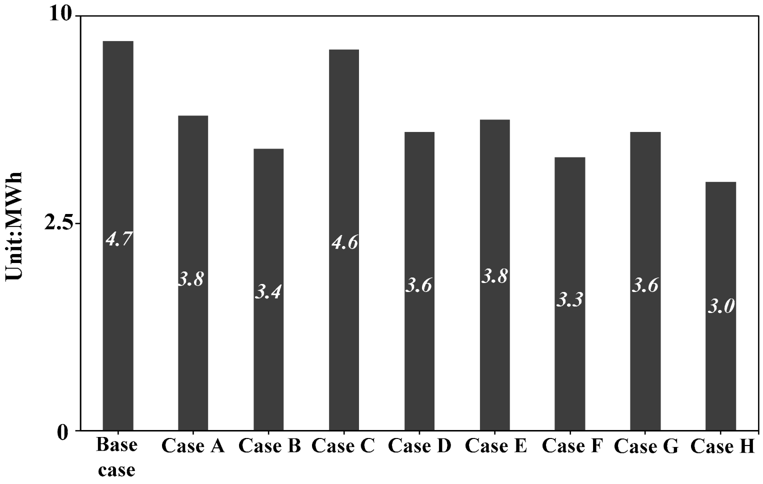


Figure 9. Comparison of annual cooling loads with the combinations of design alternatives.

In sum, in the building with triple pane windows and a 30 mm of fumed silica VIP, a decrease of infiltration rates, such as 0.4 ACH for winter season, and an increase of infiltration rates, such as 0.7 ACH for summer season, can reduce the total annual energy consumption.

5. Conclusions

The building energy consumptions have been highly influenced by various design parameters. Among these parameters, the selection of building insulation materials can have an impact on total energy consumption in the selected building, as shown in the present study. To improve energy efficiency in buildings, fumed silica VIPs were applied to an apartment building in South Korea and the annual heating and cooling loads were estimated using IES-VE energy simulation. In addition, the energy performance of combinations of design options such as window systems, infiltration rates and building orientations were also investigated. The results of this study are summarized as follows.

In energy modeling analyses, four design alternatives, including building orientations, window systems, infiltration rates and insulation materials, were considered. For building orientation, the lowest heating load occurred when the building was oriented to the east, but a significant amount of cooling load also occurred. Considering the visual comfort, a south facing building was a better option than a north facing building. In addition, a building equipped with triple pane windows and 0.4 ACH can reduce the heating loads. Moreover, the use of a 30 mm fumed silica VIP showed better energy performance than the expanded polystyrene.

For the best design conditions to reduce the annual total energy consumption, eight combinations of design options were investigated. The case where the triple pane windows was applied with a 30 mm of fumed silica VIP and 0.7 ACH showed the best performance in the annual heating and cooling loads.

In conclusion, many problems due to insufficient consideration of building design variables have caused excessive energy use in buildings. This can be improved by the proper selection of building insulation materials, such as fumed silica VIPs, during the design process. However, there is still limited use of fumed silica VIPs due to the relatively higher cost compared to that of conventional building materials [51]. For further study, it is required to investigate the cost effectiveness and installation of fumed silica VIPs to improve the building energy efficiency.

Author Contributions: Taesub Lim and Jaewang Seok designed the study and performed the simulation. Daeung Danny Kim wrote the manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

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