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# Numerical Study on the Thermal Insulation of Smart Windows Embedded with Low Thermal Conductivity Materials to Improve the Energy Efficiency of Buildings

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**ABSTRACT**

The building industry accounts for almost 40% of the world's energy consumption. To reduce the global heat transfer coefficient, sustainable buildings should use highly insulated enclosures. As the building envelope serves as a barrier between the exterior and interior of the building, integration of passive solar design principles in its construction, such as smart windows with low thermal conductivity materials are essential. Smart windows may assist to reduce energy consumption by minimizing heat gain by the building, which able reduce the cooling loads while maintaining the thermal comfort for the building users. This study features smart double-glazed windows filled with low thermal conductive materials which are argon and aerogel to improve window insulation in pursuit of energy efficiency improvement. A numerical model is developed in ANSYS Workbench to evaluate thermal insulation performance of argon-filled and aerogel-filled windows by measuring the indoor surface temperature of the building at three critical times of the day. Newton's Law of Cooling is used to compute the empirical value of the heat transfer across the window to compare and validate the numerical data. This study shows that argon-filled and aerogel-filled window able to reduce the heat transfer across the building up 21% and 59% respectively. Aerogel is proven to resist more heat transfer as compared to argon.

## 1. Introduction

The buildings sector is considered as the biggest consumers of energy, responsible for 40% of overall energy consumption worldwide, which also the utmost contributor of the accelerating global warming and climate change. The global warming is predicted to raise the average of earth’s surface temperature from 1.1° to 6.4° by the year 2100 and threaten the survival of peoples, animals and plants [1]. Meanwhile, the global warming and extreme climate has also caused thermal discomfort that necessitate for heating, ventilating and air-conditioning (HVAC) systems to ensure the thermal comfort inside the buildings [2], which demand up to the 60% of the overall building energy consumption [3]. Reducing the energy demand by improving the building designs and the usage of

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renewable energy to reduce the dependency on fossil fuels are required to enhance the energy efficiency of the buildings.

Heat transfer in the building envelopes accounts for 70-80% of the energy consumed. A proper design and materials of the building envelopes especially walls and windows play a vital role in controlling the heat transfer in and out the building while maintaining the interior thermal comfort [4]. The usage of highly thermal insulated materials as the building envelope is one of the sustainable strategies to reduce the overall heat transfer coefficient and concurrently reduce the heating and cooling load of the building. This means that thermal comfort can always be maintained while reducing dependence on HVAC systems. Even though it preserves more energy, it is also economically and ecologically sustainable. Innovation and the development of sustainable insulating materials with the capability of reducing environmental emissions are rapidly entering the market as the world moves toward sustainable design strategies [1].

Windows functionality is difficult and vital since it is designed to let natural sunlight into the structure while minimising glare for the comfort of the residents [5]. Currently, double glazing units with a spacer in between dominate the window market. Due to their endurance, traditional spacers are generally made of metal and fibre. It does, however, cause significant heat loss and condensation [6]. Solar adaptive glazing, such as reflective, insulative, and multiplane windows, has been proposed in recent technologies to reduce heat transfer. The U-value, which reflects heat loss by conduction, convection, and radiation, is an important factor to consider window performance. Advanced glazing technology has been developed to lower heating and cooling loads by minimising U-values [7].

The performance of the thermal insulation of the window is determined by the number of glazing layers, the size of the space between the panes, and the materials used to fill the gap between the panes, such as gases and aerogel. Inert gases such as argon, krypton, and xenon are commonly utilised by window manufacturers to fill the gap between the two panes of glass. Xenon has the strongest heat resistance, but it is the most expensive to produce, followed by krypton and argon, making argon the best option among all inert gases. Previous study has shown that argon-filled glass can lower window conductivity by 67% when compared to air-filled glazing [8]. Aerogel, on the other hand, is known as one of the most promising thermal superinsulation materials due to its porous structure with nanometre pore size, which permits the material to have thermal conductivity lower than that of still air [9]. According to Lolli and Andresen [10], aerogel glazing can cut 9% of greenhouse gas emissions. The designed aerogel glass is thought to have a heat loss coefficient comparable to triple layer gas-filled glazing [11].

In terms of heat transfer resistance, the window is the most vulnerable component of the building envelope. To reduce heat transfer through the window, insulating materials with the lowest thermal conductivity, such as vacuum glazing, gas filled glazing, aerogel, and phase change materials (PCM), are used [1]. Depending on the temperature and location of the building, each material has advantages and disadvantages. The objective of this study is to determine the improvements of the argon-filled glazing (U-value of 0.79W/m$^2$K) and the aerogel glazing (U-value of 0.65 W/m$^2$K) compared to the conventional air-filled double glaze pane [10]. A numerical method used to determine the interior building temperature as well as the average heat transfer across the building to evaluate the effectiveness of this thermal insulation materials on the thermal performance of the building. This study is essential in determining the best insulating materials to use as glazing for buildings in Malaysia, which has a hot and humid climate all year.

## 2. Related Work

Several research on this topic have determined that insulating materials with the lowest thermal conductivity of the window play a crucial role in reducing energy consumption while preserving thermal comfort in the building. For instance, Javad and Navid [3] investigated the temperature distribution and air age for two heat source and smart window situations with two ventilation apertures. The simulation is done utilising a 3D steady-state RANS CFD simulation and an SST k-turbulence model. Their findings demonstrated that electrochromic windows could reduce the temperature difference between the floor and ceiling by 50%. Moreover, windows with or without electrochromic glazing reduced the highest relative air temperature between the floor and ceiling by 87 percent and 30 percent, respectively, compared to standard windows.

Cuce [6] examined the U-value performance of commercial argon-filled double-glazed windows using theoretical, computational, and experimental techniques. The author emphasised that thermal bridges and edge effects play a crucial role in the actual U-value performance of glazing products with U-values of 1.23, 1.18, and 1.31W/m$^2$K, respectively. He discovered that experimental performance numbers are advised for use in energy demand estimates of building.

Ahmed *et al.,* [12] evaluated four cutting-edge designs of sliding smart windows which integrates air-gap (AG), phase change material (PCM), photovoltaic (PV), and vacuum glazing (VG) technologies. It is claimed that these electric-generating sliding windows also provide superior thermal insulation and heat storage. Total solar thermal energy gain was calculated to be 2.6 kWh for the double AG, 0.02 kWh for the AG + PV + PCM + VG, 0.22 kWh for the PV + PCM + VG, 1.48 kWh for the AG + PV + PCM, and 0.2 kWh for the ventilated AG + PV + PCM + VG. PV electrical energy generated daily in these systems is approximately 1.3 kWh for the standard scenario with double AG, 1.43 kWh for the PV + PCM + VG, and 1.38 kWh for the ventilated AG + PV + PCM + VG.

Rabie *et al.,* [13] analysed a cooling photovoltaic using different phase change material configurations. They utilised Rubitherm GmbH's Paraffin wax (RT25) PCM. This Paraffin wax (RT25). The model was solved using ANSYS where a simple algorithm was employed in solving the coupling between pressure and velocity. Their finding revealed a 9°C gap between the hottest possible wall temperature in a regular design and a parallelogram. Maximum hot wall temperatures are measured at an average of 70.3 and 63.7 degrees Celsius. They arrived at the conclusion that the PCM tank's cooling performance was improved by a parallelogram layout.

According to the aforementioned literature, window insulation materials with the lowest thermal conductivity are capable of reducing energy consumption while maintaining thermal comfort. Thus, the purpose of this study is to identify the most effective insulating materials to utilise window glazing in Malaysia by utilising smart double-glazed windows packed with low thermal conductivity materials.

## 3. Study Area

Malaysia is considered a maritime country. It is located near the equator, specifically at the northern latitude of 2°30’ and 112°30’ in the East longitude. The South China Sea separates the eastern and western regions of Malaysia. As Malaysia is a tropical country, it has high average temperatures, 6 hours of daylight with little shade, and high levels of sunlight and relative humidity. Malaysia's daily temperature fluctuates from 24°C to 38°C. The climate in the country is pleasant, with long days of sunshine and mild breeze [14–16]. In this study, the ambient outdoor temperature data were collected at Wilayah Persekutuan Putrajaya, Malaysia

## 4. Methodology

### *4.1 Physical Model*

A double glaze window design with 1m$^2$ area, the glass thickness of 6mm each and a gap size of 10mm is created using Design Modeller, a software embedded in ANSYS. The design used is similar with the variation of insulation materials filled in the gap, which is air, argon gas and aerogel. The graphic design of window is display in Figure 1.

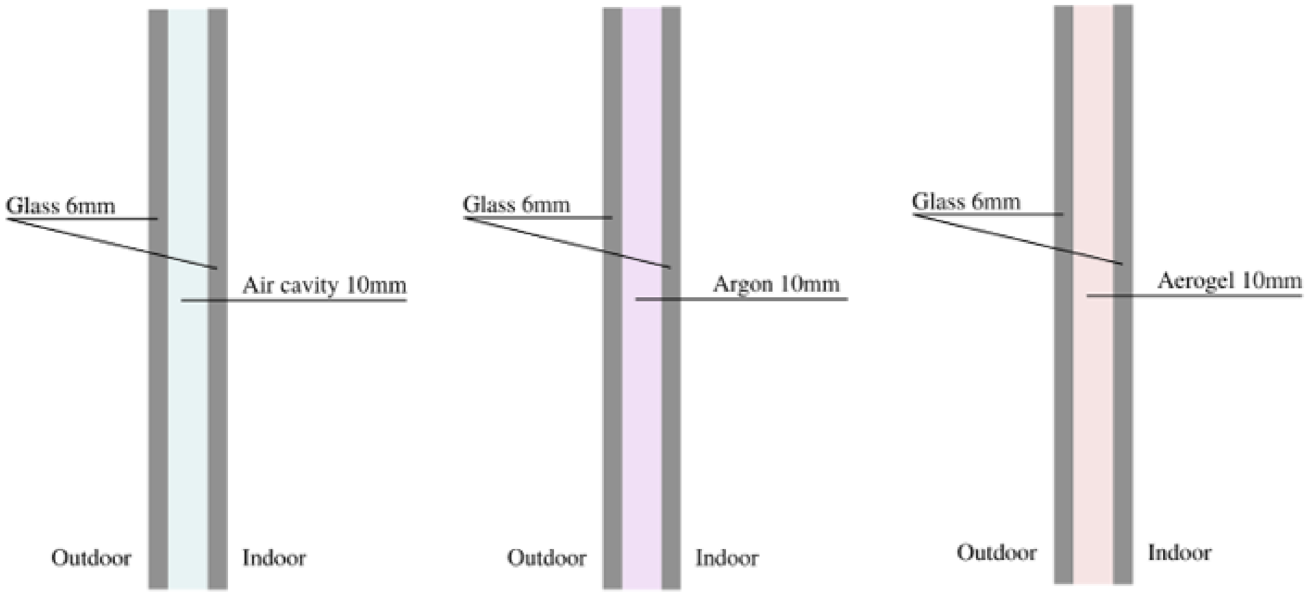


**Fig. 1.** The side view of the window design with three different insulation materials

A steady-state heat transfer analysis of the window's thermal insulation was performed using ANSYS Workbench with the purpose of determining the external and internal surface temperatures of the window and the value of heat flux. In this study, the effective temperature and corresponding thermal expansion for a double-glazed window geometry with heat generation and the average outdoor ambient temperature on the surface of the double glazing are to be estimated. Each model has undergone meshing using the Sweep Method and Body Sizing with element sizes of 0.01 depending on the design sizes (see Figure 2). The mesh's element quality is 1 and the other mesh quality details is as stated in the Table 1. The quality indices of meshing models are within the recommended range (i.e., maximum skewness $< 0.95$; average skewness $< 0.33$; aspect ratio $< 5$; mesh orthogonality $\approx 1.0$). The recommended mesh metric spectrums for skewness and orthogonal quality [17–20] are described in Tables 2 and 3.

**Table 1**
Mesh quality

| Materials | Value |
|---|---|
| Elements | 66146 |
| Nodes | 467386 |
| Aspect Ratio | 1.0037 |
| Skewness | $1.3071^{-10}$ |
| Orthogonal Quality | 1 |

**Table 2**
The spectrum of skewness metrics

| Excellent | Very Good | Good | Acceptable | Silver | Degenerate |
|---|---|---|---|---|---|
| 0-0.24 | 0.25-0.50 | 0.50-0.80 | 0.80-0.94 | 0.95-0.97 | 0.98-1.00 |

**Table 3**
The spectrum of mesh orthogonality metrics

| Unacceptable | Bad | Acceptable | Good | Very Good | Excellent |
|---|---|---|---|---|---|
| 0-0.001 | 0.002-0.14 | 0.15-0.20 | 0.21-0.69 | 0.70-0.95 | 0.95-1.00 |

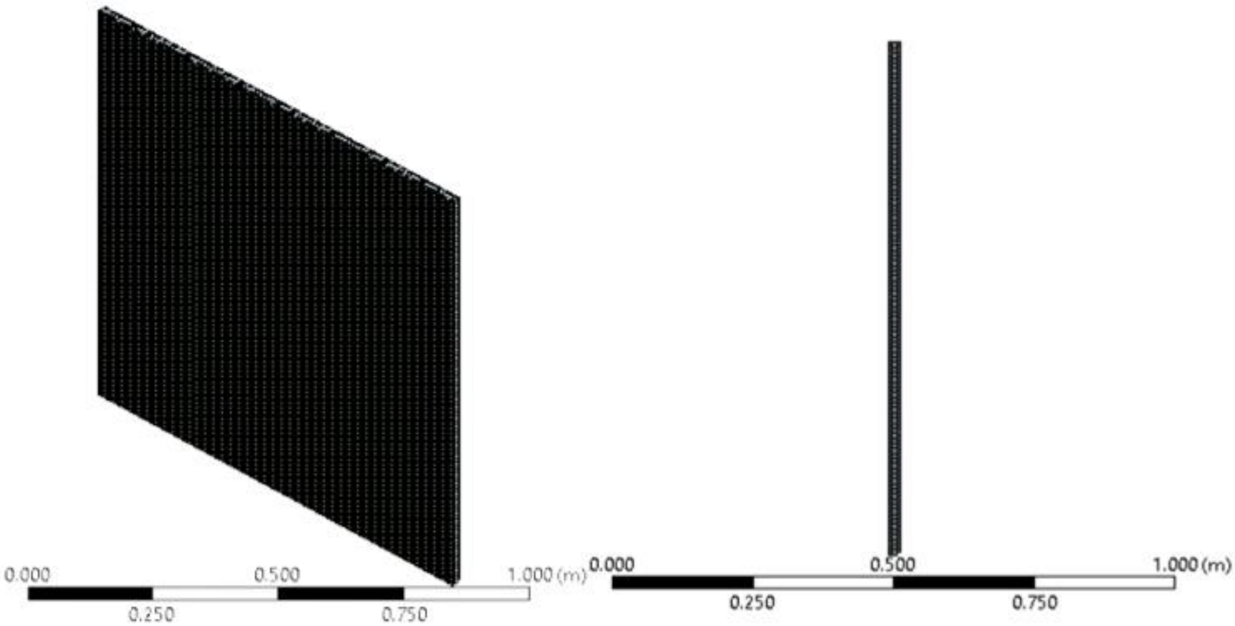


**Fig. 2.** The graphic of the mesh generation

## *4.2 Governing Equations*

The Newton's cooling law governs the heat transfer between a solid surface and a moving fluid: $q = hA (T_s-T_{amb})$ [21], where Ts is the surface temperature and T is the fluid temperature. As a result, lowering the temperature difference ($T_s$-$T_{amb}$) between the surface and the fluid, lowering the convection coefficient h, or lowering the contact surface area A can all help to reduce convective heat transfer. The governing equation used to solve the convective heat transfer into the building is stated as follows.

$$q = hA\,(\mathrm{Ts} - \mathrm{Tamb}) \tag{1}$$

where $q$ is the heat flux, $h$ is convective coefficient, $T_s$ is the surface temperature of the solid and the $T_{amb}$ is the ambient temperature of the surrounding.

For the thermal analysis of the finite volume, the energy equation to solve the problem is [22],

$$\rho . cp . \frac{\partial T}{\partial t} - \lambda \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) = q \tag{2}$$

where $\rho$ is density, $c_p$ is the pressure coefficient, $\lambda$ is the thermal conductivity and the q is the heat flux. The thermal conductivity data of each material are shown in Table 4.

**Table 4**
Thermal properties of insulation materials at 31°C

| Materials | U-value ($W/m^2$. K) | Thermal Conductivity (W/m. K) |
| --- | --- | --- |
| Glass | 58.33 | 0.7000 |
| Air | 2.017 | 0.0242 |
| Argon | 0.790 | 0.0170 |
| Aerogel | 0.650 | 0.0140 |

*4.3 Computational Method and Boundary Conditions*

To simulate the proposed design, a few assumptions are made.

i. The outdoor ambient temperature is taken on 3 different time of the day in Wilayah Persekutuan Putrajaya, Malaysia. The temperature variations are detailed in Table 5.
ii. Natural heat convection on the outdoor with the convective heat transfer coefficient of $5W/m^2°C$.
iii. The indoor ambient temperature is constant at room temperature, 25°C with natural heat convection of $8.1W/m^2°C$.

**Table 5**
Outdoor ambient temperature

| Hours | Temperature (°C) |
| --- | --- |
| 0900 | 27 |
| 1200 | 32 |
| 1500 | 34 |

To solve the problem successfully, the boundary conditions on each surface are adequately defined. The solution is then solved, and the surface temperature and heat flux are evaluated and analysed. The simulation's data is verified using theoretical calculations based on Newton's Law of Cooling. Consequently, the validity and reliability of the study results are demonstrated, with a small percentage variation from the theoretical value. The comparison of the numerical value with the theoretical value is illustrated in Table 6.

**Table 6**
Comparison between the theoretical and numerical value of all three materials at 1500 hours (34°C)

| Materials | Heat Flux | Theoretical Inner Surface Temperature(°C) | Numerical Inner Surface Temperature (°C) | Percentage Difference between theoretical and numerical value (%) |
| --- | --- | --- | --- | --- |
| Airgap | 11.995 | 26.481 | 26.473 | 0.030 |
| Argon | 9.376 | 26.158 | 26.150 | 0.031 |
| Aerogel | 4.930 | 25.607 | 25.975 | 1.417 |

## 5. Result and Discussion

*5.1 Temperature Contour Across the Thickness of the Window*

As shown in Figure 3, it shows the temperature contour of the windows filled with air, argon and aerogel, resulting from the numerical simulation. The temperature drop through the window is noticeable along the gap between the glass. It proves that the gap between the windows offers invaluable insulation to the window. The differences of the temperature drop between the three materials filling the gap can be observed in the following subsections.

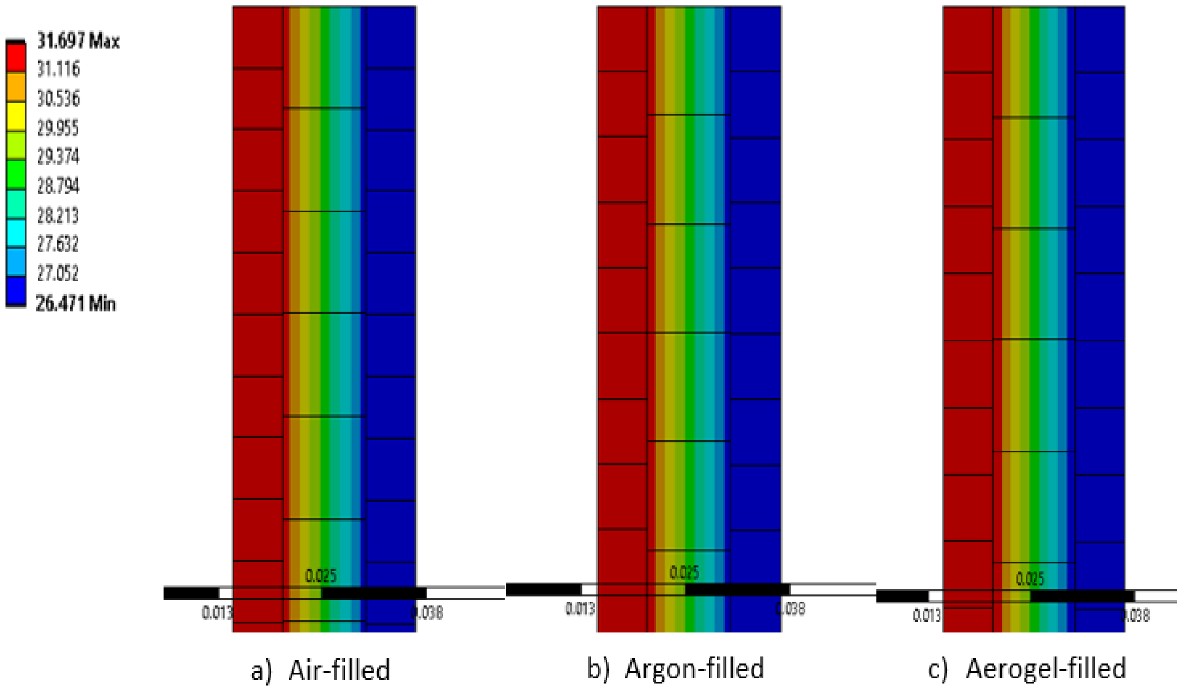


**Fig. 3.** Temperature contour across the thickness of the window at 1500 hours

*5.2 Temperature Variation Across the Thickness of the Window*

The simulation result helps to plot the temperature variation across the window thickness. The temperature reduction along the gap filled with air, argon gas and aerogel are clearly visible and shown in Figure 4 to 6.

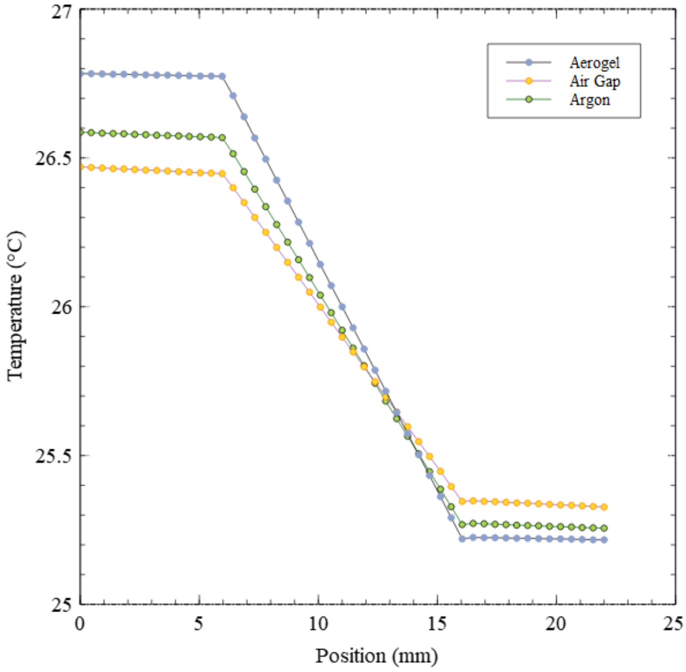


**Fig. 4.** Temperature versus position along the thickness of the window at 0900 hours

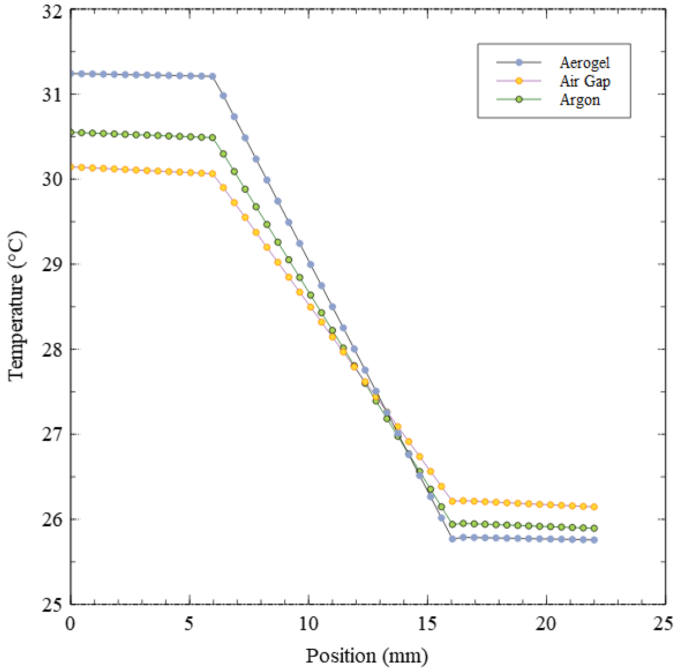


**Fig. 5.** Temperature versus position along the thickness of the window at 1200 hours

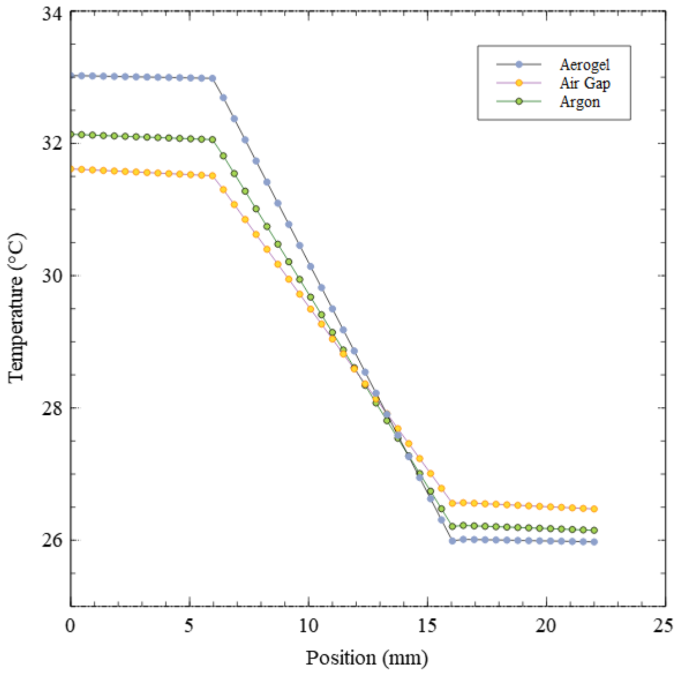


**Fig. 6.** Temperature versus position along the thickness of the window at 1500 hours

From the above figures, it is obvious that the temperature drop of aerogel-filled glazing is the highest among the three materials and it gives the lowest value of the inner surface temperature of the window, followed by argon and airgap. It shows that aerogel has the highest thermal insulation performance and proves that the lower the value of thermal conductivity, the lower the inner surface temperature of the window. Also, the results indicate that the aerogel could absorb the solar heat and maintain the indoor air temperature at comfort level. Thus, it will be easier to achieve thermal comfort.

### *5.3 Inner Surface Temperature of the Window*

The bar graph in Figure 7 can assist in clearly observing the comparison of inner surface temperature between all insulation materials.

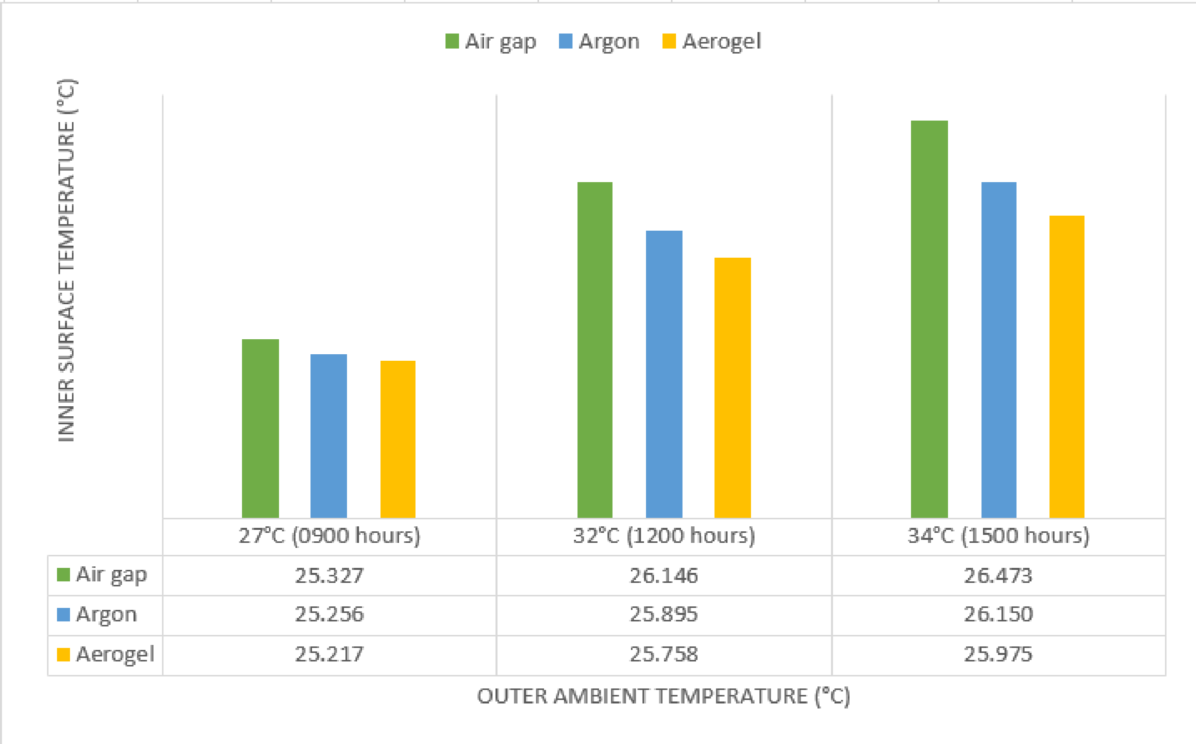


**Fig. 7.** The inner surface temperature versus outer ambient temperature

It is found that the inner surface temperature is reduced up to 1.2% by using argon-filled window and up to 1.9% by aerogel-filled window if compared to the normal double glass window with airgap. This is due to the lower conductivity of argon and aerogel to air. As we observe, the aerogel-filled window helps to maintain the inner surface temperature below 26°C even though the outdoor ambient temperature is at the highest at 34°C. It provides the best thermal comfort to the inner building.

### *5.4 Reduction of Heat Transfer Rate*

Although the inner surface temperature of the window shows only a slight difference between all the materials, the heat flux on the other hand shows a huge reduction. The argon-filled and aerogel-filled window can reduce up to 21.8% and 59% of the heat flux relative to the air-filled window respectively. Even though the thermal conductivity of argon (λ=0.017) and aerogel (λ=0.014) is not much different, it results in a lot of improvement towards the average heat transfer into the building. Details of the heat flux value and the percentage reduction in heat flux are presented in Table 7.

**Table 7**
Heat Flux value and percentage reduction of heat flux

| Hours | Heat flux (W/m²) | | | Percentage reduction of heat flux compared to airgap (%) | |
|---|---|---|---|---|---|
| | Airgap | Argon | Aerogel | Argon | Aerogel |
| 0900 | 2.666 | 2.084 | 1.093 | 21.830 | 59.002 |
| 1200 | 9.329 | 7.292 | 3.826 | 21.835 | 58.988 |
| 1500 | 11.995 | 9.376 | 4.920 | 21.834 | 58.983 |

The results show that the lower the material's thermal conductivity, the greater the capacity to reduce heat transfer in the building. Also, the results indicate that aerogel glazing is useful for indoor air temperature control (passive cooling operation) during daytime. These findings are consistent with those reported in the previous research works. Consequently, thermal comfort is easier to achieve with the necessary lower cooling loads, and then improve the energy efficiency of the building.

## 6. Conclusions

In this study, the performances of windows filled with argon and aerogel are compared to those of double-glazed windows with airgap. Argon and aerogel are considered among the best insulation materials to be used as building envelope materials especially for glazing to retard the heat transfer from the outside of the building and block the cool air from the conditioned space. Windows filled with argon and aerogel have the capacity to reduce heat transfer across the building by 21% and 59% respectively. In the future, the cost reduction of energy can be detailed, and the production and installation cost and life duration of each window can be considered to determine the most cost-effective materials. In addition, the optical properties of the materials can be studied as it will affect visual comfort as well as energy consumption for building lighting.

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