THERMAL PERFORMANCE OF WATER-FILLED WINDOW IN TROPICAL CLIMATE, PENANG, MALAYSIA.

Hazril Sherney Basher*, Goh Zhen Yi, Syafizal Shahruddin
School of Housing, Building and Planning, Universiti Sains Malaysia, Penang, Malaysia.
*Corresponding author: hazril@usm.my

Abstract
The Earth's surface temperature continues to rise each year due to various contributing factors such as the sun's increasing intensity, global warming, and the depletion of the ozone layer. One significant cause of ozone depletion is the release of chlorofluorocarbon (CFC) gases from air conditioners (AC) used to cool indoor spaces. The type, thickness, and structure of glass windows play a crucial role in influencing indoor temperatures, as windows not only allow sunlight to enter but also permit heat transfer from the sun. Clear glass, in particular, has limited ability to block solar heat, resulting in temperature differences between indoor and outdoor environments. This study investigates the effects of varying water cavity thicknesses in different window prototypes to assess temperature differences between indoor and outdoor spaces, the construction's ability to block heat, and the duration of heat retention. Findings show that the water-filled window prototype lowered indoor surface temperature by an average of 0.87°C, demonstrating its potential to enhance energy efficiency through the thermal mass properties of water.

Keywords: energy efficiency, glazing, thermal performance, tropical climate, water-filled window.

Article history:
Submitted: 27/10/2025; Revised: 18/11/2025; Accepted: 20/12/2025; Online: 24/12/2025

INTRODUCTION

In tropical countries such as Malaysia, a substantial portion of building energy consumption is attributed to air-conditioning systems. This highlights the urgent need to explore passive cooling strategies that can effectively reduce cooling loads and enhance energy efficiency. Passive cooling techniques, including solar and heat control measures, aim to minimize internal heat gains (GBI Explanatory Booklet, 2012; He & Hoyano, 2010). The implementation of such measures can significantly reduce the capacity requirements of air-conditioning systems and overall energy demand (He & Hoyano, 2010). Among emerging alternatives, water-filled window systems have shown promise as a renewable and sustainable solution for mitigating solar heat gain within buildings. This research seeks to harness the thermal properties of water as a means of enhancing building envelope performance by reducing heat transfer through glazing. Despite its potential, the application of water in window systems specifically for thermal insulation remains relatively underexplored.

While glass panels are fundamental for maximizing natural daylight, they also facilitate considerable solar heat transmission into interior spaces. The design of water-filled windows involves the circulation of water between two glass panes, creating a “water wall” effect that absorbs and dissipates heat accumulated on the glass surfaces (Taleb & H.M., 2013). This dynamic configuration enhances the building's capacity to regulate indoor temperatures through heat exchange and energy absorption (Jim & C.Y., 2014; Coma et al., 2014).

The building envelope plays a critical role in regulating external environmental factors such as heat, light, and airflow. Research suggests that optimizing the performance of the building envelope can account for up to 80% of a building's overall environmental response, thereby strengthening its integration with the surrounding context (Westphalen & Koszalinski, 1999). Office buildings, which are among the highest energy consumers, dedicate approximately 25% of their total energy use to operational demands (Wigginton & Harris). The widespread adoption of glass façades in office architecture, while aesthetically appealing and beneficial for daylighting, poses significant challenges in maintaining indoor thermal comfort. Studies indicate that between 30% and 35% of the total capital cost of well-serviced office buildings is attributed to building services, including environmental systems, maintenance, and energy expenditures throughout the building's lifecycle (Wigginton & Harris).

LITERATURE STUDIES

Water-Filled Window

Water-filled windows constitute a central element of the Water Wall System (WWS), described by Wu and Lei (2016) as a façade-integrated Thermal Energy Storage (TES) system capable of absorbing heat for a specific duration and subsequently releasing it. This technology has demonstrated significant potential in reducing building energy consumption. TES technologies are generally categorized according to the type of heat storage medium into sensible heat storage and latent heat storage systems. Kuznik et al. (2011) explained that latent TES systems store and release substantial amounts of energy through the phase change of the storage medium. In contrast, sensible TES systems, as outlined by Tamme et al. (2013), store or release heat through temperature variations within the storage material. Materials with high thermal capacity such as concrete, brick, or water are commonly utilized in sensible TES applications to stabilize temperature fluctuations, with water being particularly advantageous due to its high specific heat capacity. Sensible TES can be further classified into short-term and long-term storage systems, where short-term TES accumulates heat during the day and releases it at night, while long-term TES operates over seasonal cycles (Tamme et al., 2013). The WWS is categorized as a short-term TES system.

Historically, the Water Wall System has evolved considerably in building facade design. Its early form consisted of simple water-filled drums or containers embedded within facades, serving as thermal mass elements known as solar barrel walls. With technological advancement and growing sustainability demands, WWS designs have become increasingly sophisticated. Modern configurations typically feature a water layer enclosed between two glazing panels composed of construction-grade materials carefully selected for durability and performance. Depending on its integration within the building, the WWS can generally be divided into two main types; direct gain systems and collaborative systems. In both configurations, water functions as thermal mass, contributing to both heating and cooling processes.

In direct gain systems, the water wall is positioned adjacent to the building's exterior envelope and oriented towards the sun, allowing continuous solar energy absorption, storage, and redistribution within the same interior zone (Saadatian et al., 2012; Saadatian et al., 2013). In the other hand, Collaborative passive systems, in contrast, combine the water wall with complementary passive design strategies, such as sunspaces, solar chimneys, or greenhouses, sometimes enhanced by clerestory roofs. These systems typically incorporate dampers or vents at the base that draw in cool air, which is subsequently heated within the cavity between the glass and water wall before being circulated back indoors through upper vents (Bevilacqua et al., 2019). During nighttime, the vents are closed, allowing the stored heat in the water wall to radiate into the interior spaces. Integrating WWS with sunspaces or solar chimneys has been shown in prior studies to enhance overall thermal performance and energy efficiency.

Opaque Water Wall

Opaque water walls derive from the form the foundational structure of water wall systems (WWS). In this configuration, WWS is integrated into an opaque building façade, acting as a barrier between the interior living space and the external environment. Examples of such façades include those are made from concrete, metal plates, PVC pipes, and thermal insulating panels (Wu & Lei, 2016). This setup does not allow for outside views.

Semi-Transparent Water Wall

When a WWS is combined with a semi-transparent external façade, such as light-porous plastic or glass, it allows some daylight to penetrate the system from the outside. In these configurations, the interior side of the WWS can be made of either semi-transparent or opaque materials, affecting the amount of daylight that enters the room. A common example of a semi-transparent WWS is the Trans wall consisting of a water layer between two glass panes with a semi-transparent absorption plate in the middle. This design absorbs at least 80% of the incident solar radiation through the semi-transparent plate, while the remaining 20% is being transmitted (Agrawal et al., 2011). This type of wall employs both direct and indirect gain techniques and is particularly suitable for regions with high daytime temperatures (Al-Karaghouli et al., 2011). Baffles are often used to reduce convective heat flow through the walls. To improve water viscosity and prevent microorganism growth, bio-inhibiting agents and gelling additives were use which are necessary (Al-Karaghouli et al., 2011).

Water Wall with Phase Change Materials (PCMs)

Water Wall Systems (WWS) can be further enhanced through the integration of Phase Change Materials (PCMs), leveraging the synergistic benefits of both technologies to improve thermal performance and energy efficiency. PCMs may be incorporated on the exterior, interior, or on both sides of the water wall assembly. During daytime operation, PCMs absorb thermal energy from the surrounding environment and undergo a phase transition from solid to liquid, thereby storing latent heat. At night, the materials solidify and release the stored energy, effectively reducing the demand for active cooling during the day and heating during nighttime hours (McLaggan et al., 2018; Khan et al., 2020).

Building upon the characteristics of the various WWS configurations discussed earlier, semi-transparent WWS variants provide enhanced versatility in achieving energy conservation through thermal energy storage while maintaining optimal daylight transmission. Furthermore, semi-transparent WWS offer greater architectural flexibility, allowing designers to combine functional performance with aesthetic appeal. The fundamental components of a semi-transparent WWS are outlined below.

Components of a Semi-transparent WWS

The main key components of a semi-transparent WWS consist of two glass panes and a water layer, with the heat transfer efficiency primarily dependent on the properties of these elements. Additionally, the materials used to secure the WWS to the façade such as frames, screws, nuts, and bolts must be considered when evaluating the system's exact heat transfer characteristics. This section examines the roles of the glass panes and the water column within a semi-transparent WWS.

Glazing Materials

The efficiency of the WWS is influenced by the characteristics of the glazing, which controls the amount of solar radiation transmitted (Richman et al., 2010). Important considerations in WWS design include the type of material, the number of glass layers, and the thickness of each layer (Stazi & Mastrucci, 2012). Generally, reducing the transmissivity of glass from 0.9 to 0.45 results in a notable decrease in water temperature within the WWS (Wu & Lei, 2016). Moreover, lowering glass transmittance overtime significantly reduces the maximum daily air temperature in the adjacent room, while the minimum daily temperature remains relatively stable. Studies also indicate that reducing glass transmissivity can prevent excessive indoor heating during the day while maintaining thermal comfort levels at night (Kisilewicz, 2019). Therefore, the properties of the glazing directly affect the performance of the WWS and are critical considerations in its design.

Opaque Water Wall

The optimal thickness of the water layer in a WWS depends on the building's location, latitude, and climate (Saadatian et al., 2013). The water layer's thickness directly affects the performance of any WWS. A thicker water layer delays heat energy penetration into the interior, potentially causing thermal discomfort for occupants in cold climates (Yang, 2014). However, a thicker water column can also lead to smaller temperature fluctuations (Wu & Lei, 2016). Conversely, a very thin water column can cause the building's interior to overheat. Therefore, determining the ideal water column thickness is crucial before constructing the façade, as adjusting it post-construction is technically challenging. Base on the materials used in the building façade, WWS is typically categorized into three configurations: opaque WWS, semi-transparent WWS, and WWS incorporating Phase Change Materials (PCMs).

Energy Performance of Water Wall Systems (WWS)

The energy efficiency and thermal performance of glass façades are primarily influenced by their design configuration and the selected glazing materials. An effective facade system should maximize natural daylight penetration while simultaneously minimizing unwanted heat transfer into interior spaces. Achieving an optimal balance between daylighting and thermal control is critical to enhance the overall energy performance of building envelopes. The selection of appropriate glazing systems for green buildings can significantly reduce cooling loads generated by external heat gains and, consequently, lower energy consumption associated with air-conditioning and artificial lighting (Kisilewicz, 2019; Li et al., 2020). Within this context, the Water Wall System (WWS) including both transparent and semi-transparent configurations serves as an energy efficient facade solution that diminishes reliance on mechanical heating, cooling, and lighting by forming a thermally active yet light-transmissive envelope.

The principal objective of WWS implementation is to maintain thermal comfort throughout the year by adapting to seasonal variations in outdoor climatic conditions. This is achieved through the inherent thermal mass of water, which stabilizes indoor temperature fluctuation, absorbing excess heat during warmer periods and reducing heat loss during cooler conditions. Transparent WWS designs further enhance energy efficiency by preserving optical transparency, thereby permitting daylight penetration while moderating solar heat gain. The overall performance of WWS is closely dependent on the thermal and optical properties of its constituent materials. When solar radiation strikes a semi-transparent water wall, a portion of the energy is absorbed by the water layer, while the remainder is transmitted indoors. The absorbed heat gradually contributes to space heating and daylighting benefits during daytime operation, and during nighttime, the retained energy is released back into the interior, providing mild thermal comfort (Wang & Lei, 2018).

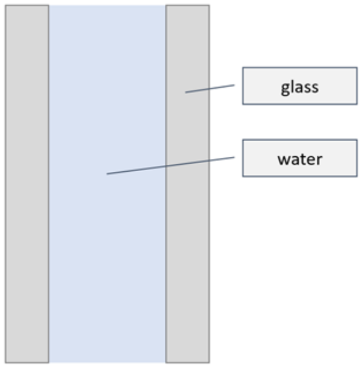

Figure 1: Water-Filled Window Section

Table 1. Summary of Recent Research That Demonstrate the Thermal Performance of A Water-Filled Window

No	Author/Year	Title	Methodology	Findings/Results
1	Lianto, 2018	'Water-filled window' construction to protect sunlight heat propagation into the room	Laboratory Experiment	The "water-filled window" construction with a clear glass thickness of 3 mm, 5 mm water and 3 mm clear glass (window type-2) shows the best result among the other "water-filled window" construction, to maximize temperature decrease when tested using a heat from the sunlight.
2	Chow et al., 2020	Warm climate performance of water-filled double-glazing with submerged heat exchanger	Dynamic Simulation Model	The numerical results show that the 24-h thermal efficiency is in the range of 26%–51% in the selected cities, mainly depending on the seasonal variation in ambient temperature. The degree of electricity saving in air conditioning will depend on the actual site location and the building activity. This innovative technology has wide application potential in zero-energy buildings.
3	Venkiteswaran et al., 2017	A Case Study on the Use of Harvested Rainwater to Operate Passive Cooling Water Wall (PCWW) for SEGi University Tower	numerical simulation (CFD software ANSYS FLUENT)	This case study proves that the PCWW is able to reduce the total heat gain by as much as 7.84kWh (8 hours of working) in a classroom. By incorporating the PCWW system into the building, a total of 658.972kWh could be saved per month, which would translate into in Ringgit Malaysia (RM) 3352.26/ month. The system was seen to produce a drop of almost 1 °C in indoor temperature compared to building setup without the PCWW and 24.6% in terms of power and cost savings.

The literature review from 2014 to 2024 indicates that most studies on water-filled window systems focus on simulations or limited laboratory tests. Lianto (2018) conducted lab experiments on specific glass and water thicknesses but did not explore wider design variations or long-term effects. Chow et al. (2020) used dynamic simulations to study thermal efficiency in warm climates, while Venkiteswaran et al. (2017) applied CFD modelling to evaluate a Passive Cooling Water Wall system using harvested rainwater. Although these studies provide valuable insights, they are mainly theoretical and lack experimental validation under controlled conditions. Therefore, this research adopts an experimental approach using physical models to generate reliable data on the thermal performance of water-filled windows and to support practical design applications for energy-efficient buildings in tropical climates.

METHODOLOGY

Research Method

This study utilizes quantitative approaches through field measurement of physical models to obtain numerical outcomes regarding thermal performance of water-filled window. The experimentation took place in an open area without any external shadings in Penang, Malaysia. The window prototype was constructed using materials including 3mm transparent acrylic sheet, hot glue, cupboard, and room temperature water. Glass was omitted from the experiment due to construction constraints. These scaled window prototypes (figure 2) which have been reduced or rescale measuring area compared to an exact window size were chosen as a pilot study to gather preliminary results before the implementation of an exact 1:1 scale window in high rise condition. The 2 surfaces which involved in the thermal performance evaluation will be the outdoor surface of the window prototype that is expose to direct sunlight and indoor surface which is not exposed to direct sunlight will be used to measure thermal evaluation. The experiment was conducted based on the following parameters:

i. Fixed variables: Thickness, size of acrylic sheet, temperature of water
ii. Manipulated variables: Thickness of water cavity between acrylic sheets
iii. Responding variables: Outdoor and indoor surface temperature

This study examined the potential surface temperature reduction between an outdoor and indoor surface of a water-filled window compared to a conventional window. Measurements were conducted concurrently for direct comparison and enhanced accuracy of the findings.

Phase 1: Prototype Construction Process

The window prototype was assembled using A5-sized 3mm acrylic sheets. The sheets were affixed to another acrylic sheets at the base and the sides of the prototype. It is then sealed with hot glue to prevent any leaks. A cupboard is covered on the top and sides of the prototype to prevent direct sunlight and heat was applied on the indoor surfaces. There are three types of prototypes were utilized for the study: Prototype A; consist of a single layer of acrylic sheet which represent a conventional window, Prototype B includes double layers with a 50mm gap between them and finally Prototype C features double layers with a 100mm gap. Table 2 and table 3 provides a summary of the size and dimensions of these window prototypes. The gap widths between the acrylic sheets (50mm and 100mm) were varied to determine the thermal insulation of water. Subsequently, Window Prototypes B and C were filled with room temperature water at 28.5°C.

Table 2. Types of Window Prototype

Window Prototype	Description	Dimension	Water Cavity Thickness
A	Single Acrylic Sheet	210mm (l) x 50mm (w) x 148 (h)	-
B	Double Acrylic Sheets	210mm (l) x 100mm (w) x 148 (h)	50mm
C	Double Acrylic Sheets	210mm (l) x 150mm (w) x 148 (h)	100mm

Table 3. Materials Representation

Prototype's Material	Real Life Material
Acrylic Sheet	Glass
Cardboard	Walls and Floors

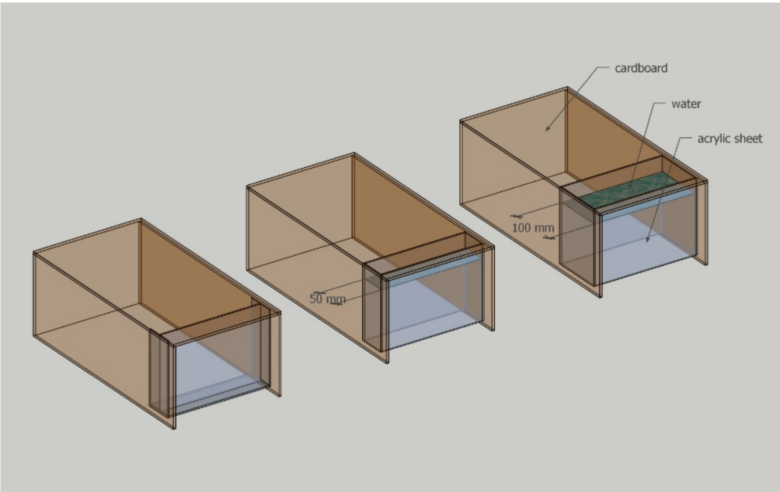

Figure 2: Types and Configuration of Window Prototypes

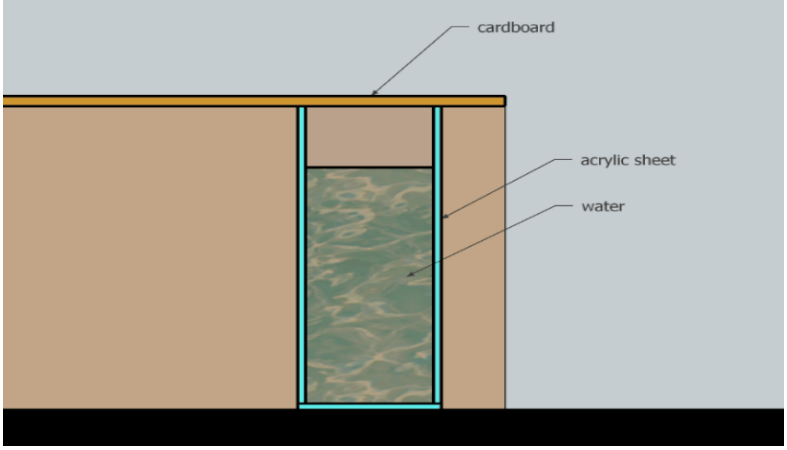

Figure 3: Schematic Section of Window Prototype B & C

Phase 2: Thermal Test

The thermal performance of the window prototypes was assessed by measuring the heat transferred to the window prototypes. An IR400 EXTECH infrared thermometer (Figure 4) was utilized to measure outdoor and indoor surface temperatures, with a temperature range spanning from -20°C to 332°C. According to Awang (2021), the study indicates that the peak heat occurs between 3pm and 5pm due to the Earth's surface absorbing heat faster than can radiate until late afternoon, when the process reverses. Consequently, the thermal tests were conducted during this timeframe, with readings taken every 15 minutes interval for a total duration of 45 minutes. The tests were carried out by placing the window prototypes under direct sunlight, as depicted in Figure 3. The data was collected over a period of 3 clear days to account for variations in local weather conditions, and to ensure precision in the results when exposed to worst case scenarios.

Figure 4: IR400 EXTECH Infrared Thermometer

Figure 5: Window Prototypes

Figure 6: a) Outdoor Surface Temperature Test, b) Indoor Surface Temperature Test

RESULT AND DISCUSSION

Effect of Solar Radiation on the Outdoor Surface of Window Prototypes

Temperature evaluations were conducted over three clear days. The results are shown in Table 4, Table 5, Table 6, and a total average result are presented in Table 7. The window prototype A: representing conventional window shows the highest average outdoor surface temperature at 0-minute, 15 minutes, 30 minutes and 45 minutes compared to window prototype B (with 50mm water cavity) and C (with 100mm water cavity).

Considering prototype A as a conventional window, the following discussion compares the results of prototype B (with a 50mm water cavity) and prototype C (with a 100mm water cavity) to those of prototype A. Prototype B (with 50mm water cavity) and prototype C (with 100mm water cavity) managed to reduce the outdoor surface temperature at least an average drop of 1.88°C and 2.75°C (Table 6). Prototype A (representing conventional window) indicated an average reading of 40.35°C, whereas prototype B (with 50mm water cavity) and prototype C (with 100mm water cavity) recorded at least 38.47°C and 37.60°C. According to figure 7, the maximum outdoor surface temperature drop achieved was 4.0°C between prototype C (with 100mm water cavity) and prototype A (representing conventional window), which occurred on day 1 (4th June 2024) at 3 p.m. (0-minute interval). The minimum outdoor surface temperature drop was at least 0.9°C achieved between prototype B (with 50mm water cavity) and prototype A (representing conventional window), recorded on day 3 (6th June 2024) at 3.15 p.m.

The overall result shows the thermal performance of the window in prototype C is lower than window prototype A and B (Figure 7 and Figure 8). It also shows the higher water cavity width of a window prototype has result in less thermal conductivity. The higher the temperature drops from 3 days' reading with high surface temperature indicates more effective of water cavity in window prototype. Therefore, the water cavity in window prototype shows greatest effect on thermal insulation compared to window prototype A which is without water cavity.

Table 4. Thermal Test Result (Day 1), 4/6/ 2024 (Outdoor Temperature: 32 °C, Ambient Temperature: 37°C, 3pm)

Time	Window Prototype A			Window Prototype B (50mm water cavity)			Window Prototype C (100mm water cavity)		
	Outdoor Surface Temp. (°C)	Indoor Surface Temp. (°C)	Temp. Difference (°C)	Outdoor Surface Temp. (°C)	Indoor Surface Temp. (°C)	Temp Difference (°C)	Outdoor Surface Temp. (°C)	Indoor Surface Temp. (°C)	Temp. Difference (°C)
0 minute	39.0	38.5	0.5	36.3	35.8	0.5	35.0	34.4	0.6
15 minutes	40.8	40.2	0.6	39.2	38.4	0.6	38.3	37.8	0.5
30 minutes	42.0	41.7	0.3	40.2	39.4	0.8	39.6	38.8	0.8
45 minutes	43.0	42.6	0.4	40.5	39.5	1.0	40.2	38.5	1.7
Average Temp.	41.2	40.75	0.45	39.05	38.28	0.73	38.28	37.38	0.90

Table 5. Thermal Test Result (Day 2), 5/6/ 2024 (Outdoor Temperature: 32 °C, Ambient Temperature: 37°C, 3pm)

Time	Window Prototype A			Window Prototype B (50mm water cavity)			Window Prototype C (100mm water cavity)		
	Outdoor Surface Temp. (°C)	Indoor Surface Temp. (°C)	Temp. Difference (°C)	Outdoor Surface Temp. (°C)	Indoor Surface Temp. (°C)	Temp Difference (°C)	Outdoor Surface Temp. (°C)	Indoor Surface Temp. (°C)	Temp. Difference (°C)
0 minute	39.2	38.6	0.6	36.6	36.1	0.5	35.3	34.6	0.7
15 minutes	41.1	40.4	0.7	39.4	38.6	0.8	38.4	38.1	0.3
30 minutes	42.2	42.0	0.2	40.4	39.7	0.7	39.8	39.1	0.7
45 minutes	43.1	42.7	0.4	40.8	39.9	0.9	40.4	38.8	1.6
Average Temp.	41.4	40.90	0.5	39.3	38.58	0.73	38.48	37.65	0.83

Table 6. Thermal Test Result (Day 3), 6/6/ 2024 (Outdoor Temperature: 31 °C, Ambient Temperature: 35°C, 3pm)

Time	Window Prototype A			Window Prototype B (50mm water cavity)			Window Prototype C (100mm water cavity)		
	Outdoor Surface Temp. (°C)	Indoor Surface Temp. (°C)	Temp. Difference (°C)	Outdoor Surface Temp. (°C)	Indoor Surface Temp. (°C)	Temp Difference (°C)	Outdoor Surface Temp. (°C)	Indoor Surface Temp. (°C)	Temp. Difference (°C)
0 minute	36.5	36.1	0.4	34.8	34.4	0.4	34.0	33.5	0.5
15 minutes	37.8	37.2	0.6	36.9	36.3	0.6	36.1	35.5	0.6
30 minutes	38.9	38.4	0.5	37.5	36.8	0.7	36.9	36.0	0.9
45 minutes	40.6	40.3	0.3	39.0	38.1	0.9	37.2	35.8	1.4
Average Temp.	38.45	38.00	0.45	37.05	36.4	0.65	36.05	35.2	0.85

Table 7. Total Average of Thermal Test Results Over Three Days.

	Outdoor Surface Temp. (°C)	Indoor Surface Temp. (°C)	Temp. Difference (°C)	Outdoor Surface Temp. (°C)	Indoor Surface Temp. (°C)	Temp Difference (°C)	Outdoor Surface Temp. (°C)	Indoor Surface Temp. (°C)	Temp. Difference (°C)
0 minute	40.35	39.88	0.47	38.47	37.75	0.70	37.60	36.74	0.86

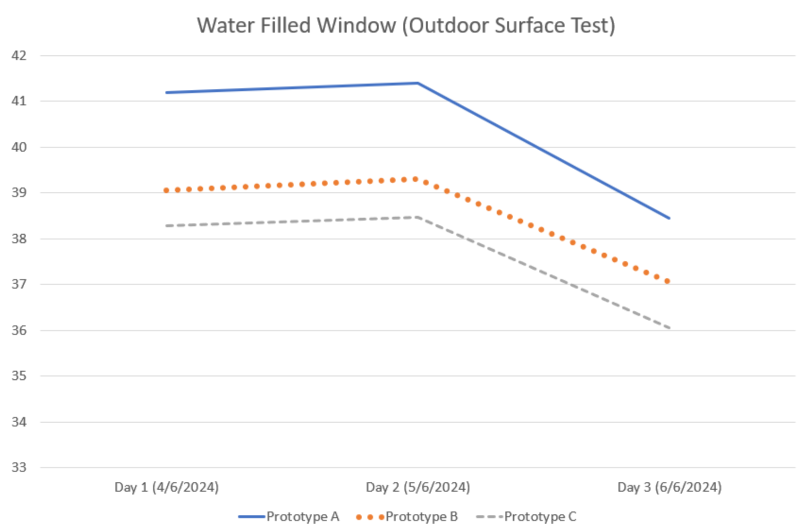

Figure 7: Total Average Outdoor Surface Temperature of Water-Filled Window Prototypes

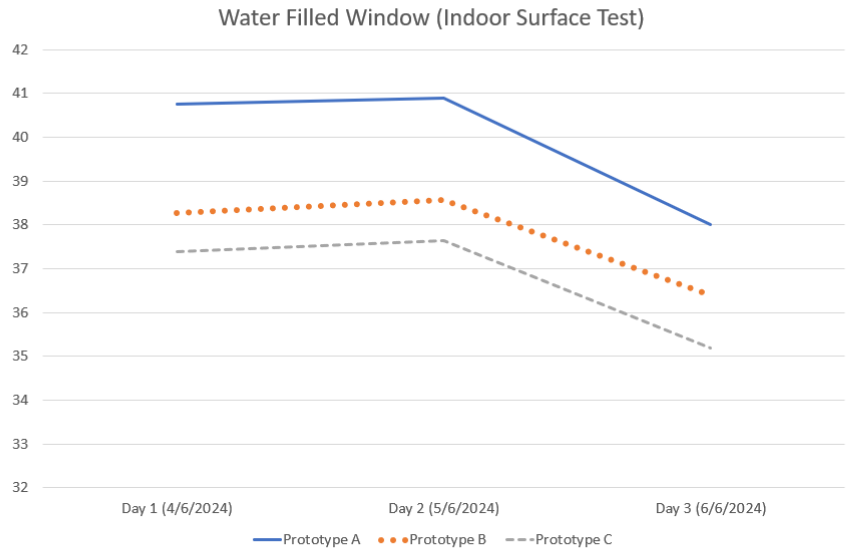

Figure 8: Total Average Indoor Surface Temperature of Water-Filled Window Prototypes

Effect of Solar Radiation on the Indoor Surface of Window Prototypes
The results are shown in Table 4, Table 5, Table 6, and a total average result in Table 7. The window prototype C (with 100mm water cavity) shows the lowest average indoor surface temperature at 0-minute, 15 minutes, 30 minutes and 45 minutes compared to window prototype A (representing conventional window) and B (with 50mm water cavity). Considering prototype A as a conventional window, the following discussion compares the results of prototype B (with a 50mm water cavity) and prototype C (with a 100mm water cavity) to those of prototype A. Prototype B (with 50mm water cavity) and prototype C (with 100mm water cavity) managed to reduce indoor surface temperature at least an average drop of 2.13°C and 3.14°C (Table 6). Prototype A (representing conventional window) indicated an average reading of 39.88°C, whereas prototype B (with 50mm water cavity) and prototype C (with 100mm water cavity) recorded 37.75°C and 36.74°C. The maximum indoor surface temperature drop achieved was 4.5°C between prototype C (with 100mm water cavity) and prototype A (representing conventional window) which occurred on day 3 (6th June 2024) at 3.45 p.m. (45-minute interval). The minimum indoor surface temperature drop was at least 0.9°C achieved between prototype B (with 50mm water cavity) and prototype A (representing conventional window) recorded on day 3 (6th June 2024) at 3.15 p.m. (15-minute interval).

Temperature difference between Outdoor and Indoor Surface of Window Prototypes
Comparing among each prototypes' temperature difference between outdoor and indoor surface temperature, prototype C (with 100mm water cavity) shows the highest average temperature difference compared to window prototype A (representing conventional window) and B (with 50mm water cavity). Prototype A (representing conventional window), prototype B (with 50mm water cavity) and prototype C (with 100mm water cavity) have an average temperature difference of 0.47°C, 0.70°C and 0.86°C. The maximum temperature difference achieved was 1.7°C by prototype C (with 100mm water cavity), which occurred on day 1 (4th June 2024) at 3.45 p.m. (45-minute interval). The minimum temperature difference was at least 0.2°C achieved by prototype A (representing conventional window) recorded on day 2 (5th June 2024) at 3.30 p.m. (30-minute interval).The overall results indicate that the thermal insulation of the water cavity in window prototype C is higher than in prototypes A and B. Prototype C exhibit the greatest temperature difference, demonstrating that the water cavity significantly enhances its thermal performance.

CONCLUSION
The study findings indicate that both prototype B (with a 50mm water cavity) and prototype C (with a 100mm water cavity) effectively reduced surface temperatures through thermal insulation provided by water-filled windows. On average, prototype B achieved a surface temperature decrease of 0.70 °C, while prototype C showed a more significant reduction of 0.86 °C. The maximum temperature difference observed was 1.7°C for prototype C at 3:45 p.m. Prototype C consistently demonstrated superior performance in average surface temperature reduction, achieving 0.86 °C, highlighting its efficiency

even under high ambient temperatures. With this reduction of 1°C, it can achieve 3 - 5% energy savings in the space.

In conclusion, water-filled windows exhibit distinct thermal insulation properties, effectively reducing thermal conductivity during the daytime. This study demonstrates the enhanced thermal performance of windows using sustainable solutions such as water. The findings suggest that water-filled windows are particularly suitable for high-rise buildings, which experience significant direct sunlight and cannot rely on natural ventilation due to strong winds at higher levels. By reducing heat ingress, water-filled windows improve overall thermal efficiency. Additionally, the study shows that as the width of the water cavity increases, the surface temperature of the water-filled window decreases, further enhancing thermal performance compared to conventional windows.

The main contribution of this experiment is the finding that increased usage of water in water-filled windows that lowers thermal conductivity and heat gain while maintaining clear visibility to the exterior spaces. This challenges the perception that a larger window area necessarily leads to higher heat gain. The study highlights potential solutions for improving thermal comfort and reducing high energy usage when expose to over illumination or higher ambient temperatures. It demonstrates the potential of water-filled windows to enhance a building's energy efficiency in the longer run.

However, there are limitations due to the scale of the prototype, which affects the accuracy of measuring of exact thermal performance, especially considering the area exposed to direct sunlight. Therefore, further research should explore water-filled windows on a full-scale (1:1) basis over an extended period, including both day and night-time temperatures. Such studies would improve the accuracy of thermal performance data and help determine the optimal water cavity width to reduce electricity and air-conditioning usage, thereby decreasing overall energy consumption. Further research should also include the manipulation of different alternative mediums such as algae, gel-based substances, phase change materials (PCM), aerogels, etc., as thermal insulation, rather than water, which was used in the current research.

Acknowledgment

This study was funded by the School of Housing, Building, and Planning, Universiti Sains Malaysia.

References

Agrawal, B., & Tiwari, G. N. (2011). Building integrated photovoltaic thermal systems: For sustainable development. Royal Society of Chemistry.

Bevilacqua, P., Benevento, F., Bruno, R., & Arcuri, N. (2019). Are Trombe walls suitable passive systems for the reduction of the yearly building energy requirements? Energy, 185, 554–566.

Coma, J., et al. (2014). New green facades as passive systems for energy savings on buildings. Energy Procedia, 57, 1851-1859.

GBI Explanatory Booklet. (2012). GreenbuildingindexSdnBhd, 2–5.

He, J., & Hoyano, A. (2010). Experimental study of cooling effects of a passive evaporative cooling wall. Building and Environment, 45, 461–472.

Jim, C. Y. (2014). Air-conditioning energy consumption due to green roofs with different building thermal insulation. Applied Energy, 128, 49–59.

Khan, R. J., Bhuiyan, M. Z. H., & Ahmed, D. H. (2020). Investigation of heat transfer of a building wall in the presence of phase change material (PCM). Energy Built Environment, 1, 199–206.

Kisilewicz, T. (2019). On the role of external walls in the reduction of energy demand and the mitigation of human thermal discomfort. Sustainability, 11, 61.

Kuznik, F., David, D., Johannes, K., & Roux, J. J. (2011). A review on phase change materials integrated in building walls. Renewable and Sustainable Energy Reviews, 15, 379–391.

Li, D., Wu, Y., Wang, B., Liu, C., & Arıcı, M. (2020). Optical and thermal performance of glazing units containing PCM in buildings: A review. Construction and Building Materials, 233, 117327.

McLaggan, M. S., Hadden, R. M., & Gillie, M. (2018). Fire performance of phase change material enhanced plasterboard. Fire Technology, 54, 117–134.

Richman, R. C., Cianfrone, C., & Pressnail, K. D. (2010). More sustainable masonry facades: Preheating ventilation air using a dynamic buffer zone. Journal of Building Physics, 34, 27–41.

Saadatian, O., Sopian, K., Lim, C. H., Asim, N., & Sulaiman, M. Y. (2012). Trombe walls: A review of opportunities and challenges in research and development. Renewable and Sustainable Energy Reviews, 16, 6340–6351.

Saadatian, O., Sopian, K., Salleh, E., Lim, C. H., Riffat, S., Saadatian, E., Toudeshki, A., & Sulaiman, M. Y. (2013). A review of energy aspects of green roofs. Renewable and Sustainable Energy Reviews, 23, 155–168.

Stazi, F., Mastrucci, A., & Munafò, P. (2012). Life cycle assessment approach for the optimization of sustainable building envelopes: An application on solar wall systems. Building and Environment, 58, 278–288.

Taleb, H. M. (2013). Using passive cooling strategies to improve thermal performance and reduce energy consumption of residential buildings in U.A.E. Frontiers of Architectural Research, 3, 154–165.

Tamme, R., Laing, D., Steinmann, W. D., & Bauer, T. (2013). Thermal energy storage. Solar Energy, 688–714.

Wang, H., & Lei, C. (2018). Combined solar chimney and water wall for ventilation and thermal comfort. In Proceedings of the 4th International Conference on Building Energy, Environment, Melbourne, Australia, 5–9 February 2018 (pp. 705–710).

Westphalen, D., & Koszalinski, S. (1999). Energy consumption characteristics of commercial building HVAC systems (Vol. 2: Thermal distribution, auxiliary equipment, and ventilation, p. 128).

Wigginton, M., & Harris, J. (2013). *Intelligent skins*. Routledge.

Wu, T., & Lei, C. (2016). Thermal modelling and experimental validation of a semi-transparent water wall system for Sydney climate. Solar Energy, 136, 533–546.

Yang, L., Yan, H., & Lam, J. C. (2014). Thermal comfort and building energy consumption implications - A review. Applied Energy, 115, 164–173.