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TECHNICAL ARTICLE

Thermal Transmittance (U-value) Evaluation of Innovative Window Technologies

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Calculation of heat transfer in windows has a direct impact on the thermal transmittance on highly insulated glazing components. A series of experimental tests were carried out in order to calculate the U-value of active insulated windows using the Heat Flux Meter method (ISO 9869-1); this to compare the insulation properties of traditional single glass, double glazing with different aerogel fillings and vacuum glazing windows.

The use of this heat flux method utilised an environmental chamber to provide a temperature difference of 15 °C reporting the U-values as follows: traditional double glazing 3.09 W/m²·K, vacuum glazing 1.12 W/m²·K, and double glazing with aerogel pillars 2.52 W/m²·K. On the other hand, double glazing with KGM wheat starch reported 3.40 W/m²·K, double glazing with granulated aerogel 2.07 W/m²·K and heat insulation solar glass 1.84 W/m²·K.

Vacuum glazing recorded optimal results under these experimental conditions, describing a U-value 78 % lower when compared to traditional single glazing window units (5.15 W/m²·K). Installation of windows with lower thermal transmittance are expected to increase in the global market to meet the current construction codes, aimed for achieving net zero carbon buildings.

Keywords: aerogel window; net zero carbon buildings; thermal transmittance; U-value; vacuum glazing

Introduction

Energy consumption in the construction sector has increased in recent years, as buildings account for more than 40 % of the energy consumption for most countries (IEA, 2013). In order to reduce this impact, it is relevant to promote stricter regulations focused on the developing of novel technologies on the building's envelope. Fenestration elements play a particular role in this interaction, since they are the weakest point to uphold insulation in buildings. Windows allow bringing solar heat gain, natural light, ventilation and sound vibrations to interior spaces, and similarly they are a barrier to inclement weather conditions. These elements are extremely important to estimate the building energy performance since they act as an envelope for thermal comfort in spaces. In general, the assessment of the window's thermal and optical properties utilises three parameters: visible transmittance, solar heat gain coefficient (SHGC), and thermal transmittance (or U-value) (Aguilar-Santana et al., 2020). Thermal transmittance is relevant for the analysis of insulating properties of glazing materials as per the main objective of this paper, and **Figure 1** presents examples of their conventional values.

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An important part of the energy consumption is associated to the heating and cooling demands from buildings, especially those related to transparent surfaces (windows, skylights and roof lights). These elements contribute significantly to the energy losses in colder climates (Jelle, Kalnæs and Gao, 2015; Velasco-Carrasco *et al.*, 2020). An inverse relation occurs in warmer climates, where these glazing elements contribute significantly to the cooling demand of HVAC systems due to the heat gains through poor insulating materials displayed by traditional glazing systems. Windows with materials of higher heat transfer rate report the highest U-values regardless of the window assembly; this as a result of the environment's interaction through the building envelope in the building's energy losses (Aguilar-Santana et al., 2020).

U-value

Thermal transmittance also known as U-value, is the heat flow rate divided by the area and temperature difference in the surroundings of both sides of a system at a steady state (BSI, 2014); and is a concept utilised to define the insulation properties for building materials. Construction elements with lower U-values are more effective to reduce the energy consumption in buildings due to its capacity to insulate from external weather conditions (usually utilised for colder climates).

U-value rates in windows are comparatively high when compared to other building elements such as floors (0.25

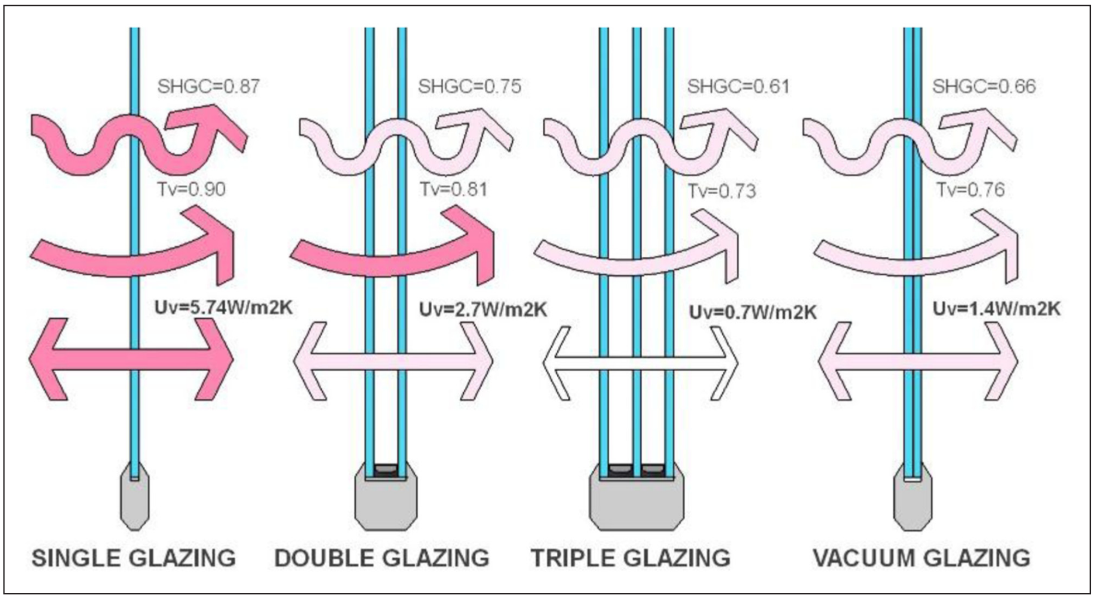

Figure 1: Thermal and optical properties of static windows (Aguilar-Santana, et al., 2020).

W/m²·K), roofs (0.16 W/m²·K) and walls (0.30 W/m²·K) (Jelle et al., 2012). Likewise, traditional window technologies such as single glazing windows have a U-value comparatively high (5.8 W/m²·K), when analysed against double glazing windows (1.2 W/m²·K), and their impact on the energy consumption of the latter is relatively low (Aguilar-Santana et al., 2020). This contrast makes traditional static glazing technologies a conspicuous element of improvement aiming to reduce housing energy consumption, and therefore a challenge for modern building codes worldwide.

Purpose of experimentation

This paper evaluates a series of static windows that utilise passive technologies to improve heat and optical performance in buildings. This would be achieved by calculating their thermal transmittance coefficients via experimental process, using the heat flux meter method described in the international standard ISO 9869-1:2014. The paper objective includes analysing the significance and implications for testing windows under standardised conditions, as well as providing experimental results on the application of this code. The analysis aims to report the heat flow and temperatures on the glazing surface, as well as the assessment of thermal imagery and the formulae applied to the experimental setup.

Methodology

The analysis of building elements in-situ, helps to evaluate their thermophysical properties, their performance for building design, construction and refurbishment. This is applicable in the implementation of thermal comfort and insulation strategies to minimise energy consumption in buildings (Gori et al., 2017). There are several methods for calculating the thermal transmittance in building elements and a summary of the norms for their calculation is listed in **Table 1**, using the codes for the International Organisation for Standardisation.

Calculation of thermal transmittance

For the calculation of U-values in windows and particularly for commercial products, ISO 10077-1:2017 and ISO 10077-2:2017 are a recommended method to utilise since it combines the geometry of the window and their thermal interactions among components (BSI Standards, 2017b, 2017a). Using this method guarantees the consideration of most elements in a traditional window assembly, these including: glazing(s), frames, shutters and blinds. These methods are particularly helpful when comparing rating reports in commercial window products defined as "declared values" by manufacturers, also denoted as "U_w".

For the purpose of this research, the U-value calculations will focus on the thermal transmittance of glazing "U_g" or "glazing U-value"; this is to promote an equilibrated comparison of insulating capacities among prototypes. Moreover, the selection of this methodology presents a baseline for comparison given the novel characteristics of the glazing technologies involved, where the heat transfer focuses mainly in the central area of glazing.

For the focus of this experimental process, the selected code was the heat flow meter method (average process) due to its scalability, accuracy and adaptability. Since it is a non-invasive method, it could be adjusted to different glass sizes and save the experimentation process from the use of duplicate specimens. Contrastingly, the size restrictions and measurement periods linked to this standard make this method challenging for achieving a calculation balance. However, the use of infrared thermography helps in the validation of results, comparing the collected data throughout the experimental process (**Figure 5**).

Heat flow meter method (ISO 9869–1:2014)

Considering that a steady state plausible for on-site experimentations, the ISO standards recommends the average method to estimate the thermal transmittance. Their calculation are based on recording the heat flow rate, ambient and interior temperatures for relatively long periods (at least 72 hours). This method is valid only if the heat

Table 1: Comparability of application of ISO standards in the calculation of thermal transmittances (BSI, 2014) (International Organization for Standardization, 1994) (International Organization for Standardization, 2010) (BSI, 2018).

Standard code	Advantages	Disadvantages
HFM ISO 9869-1:2014 Heat flow meter method	· Portable and versatile test. · Reduced calibration times of HFM (every two years). · Not limited to specimen size. · Not an invasive method.	· Requires a flow rate constant for a considerable amount of time (72 hours as a minimum). · Requires direct thermal contact. · The specimen should not be exposed to solar radiation. · Total uncertainty from 14 to 20 %.
GHP ISO 10291–1994 Guarded hot plate	· It can be applied to multiple glazing. · Medium-scale equipment outline. · Relatively inexpensive compared to other methods. · Method approached to simulated steady-state.	· Requires two nearly identical specimens. · Size dependant (ideally a square specimen fitted to 800 × 800 mm). · Requires cooling units. · Not suitable under solar radiation.
CHB ISO 12567–1:2010 Calibrated hot box	· Imposes steady-state conditions on specimens. · Considered as a high-precision method. · 95 % of confidence level in results. · Scalability of specimen size.	· Requires initial calibration panels. · Specimen size restricted (to fit the hot-box size). · Aperture size greater than 0.8 m^2. · Minimum of nine temperature positions required.
IRT ISO 9869–2:2018 Infrared thermography	· It does not require direct thermal contact to surfaces. · Can be used in specimens with larger study areas. · Allows measurements on site (with temperature differences >10 °C interior-to-exterior).	· Requires no incidence of solar radiation. · Only for specimens with small heat capacity per unit area 30 kJ/m^2·K or less. · At least 6 hours of night data as measurement period (3 days is recommended). · Standard uncertainty of 13.8 %.

transfer coefficients are constant during the entire testing period (BSI, 2014).

Using the average method allows a more robust validation of data, being that it assumes the glass transmittance as a quotient of the mean density of heat flow rate, by the mean temperature difference between the interior and exterior sides of the specimen (defined in equation 1). This assumption is only valid however, when the experimentation occurs isolated from direct solar radiation and is carried out at intervals of 0.5 hours for longer periods (BSI, 2014). Calculations of the thermal resistance and conductance of materials are included in equation 2 and 3, accordingly.

$$U = \frac{\sum_{j=1}^{n} q_j}{\sum_{j=1}^{n}\left(T_{sij} - T_{sej}\right)} [W/(m^2 \cdot K)] \quad (1)$$

$$R = \frac{\sum_{j=1}^{n}\left(T_{sij} - T_{sej}\right)}{\sum_{j=1}^{n} q_j} [m^2 \cdot K/W] \quad (2)$$

$$\Lambda = \frac{\sum_{j=1}^{n} q_j}{\sum_{j=1}^{n}\left(T_{ij} - T_{ej}\right)} [W/(m \cdot K)] \quad (3)$$

where,
U = thermal transmittance (W/m^2·K).
R = thermal resistance (m^2·K/W).
Λ = thermal conductance (W/m·K).
Φ = heat flow rate (W).
q = density of heat flow rate (W/m^2).
T_{sij} = interior surface temperature or φ_i (°C).
T_{sej} = exterior surface temperature or ϕ_e (°C).

By using this method, it is endorsed an accuracy rate in the limits of 14 to 28 %; this as a result of the data acquisition system, operational errors and its variation over the sampling period. A thermal network model is presented in **Figure 2** detailing the resistances involved for the analysis of windows. In this particular case, it is described for the utilisation of vacuum glazing with aerogel pillars and the resistance model is included for both the window centre of pane (U_g) as well as for the window edge or frame. This model is particularly useful to detail the temperature points for the glass panes (θ_{im}–θ_{em}), including the heat flux monitoring points (ϕ_i–ϕ_e) and the flux of heat (q) through the window. The particular resistances for every window depend on various characteristics: the number of panes, material composition and gas encapsulation (air, argon or vacuum). Additionally, materials utilised in the construction of windows present different thermal conductivities that are directly associated to the heat flux through glazing units, therefore these factors are investigated and listed in **Table 2**.

Experimental setup

An experimental rig was set at the University of Nottingham, analysing the glass samples by using a WIR36-55 environmental chamber (SSJ System Services Ltd, Rhymney, UK), described in **Figure 3**. This chamber was modified to adapt the glazing samples on a wooden frame with thermawall insulated boards (described in **Figure 4a** and

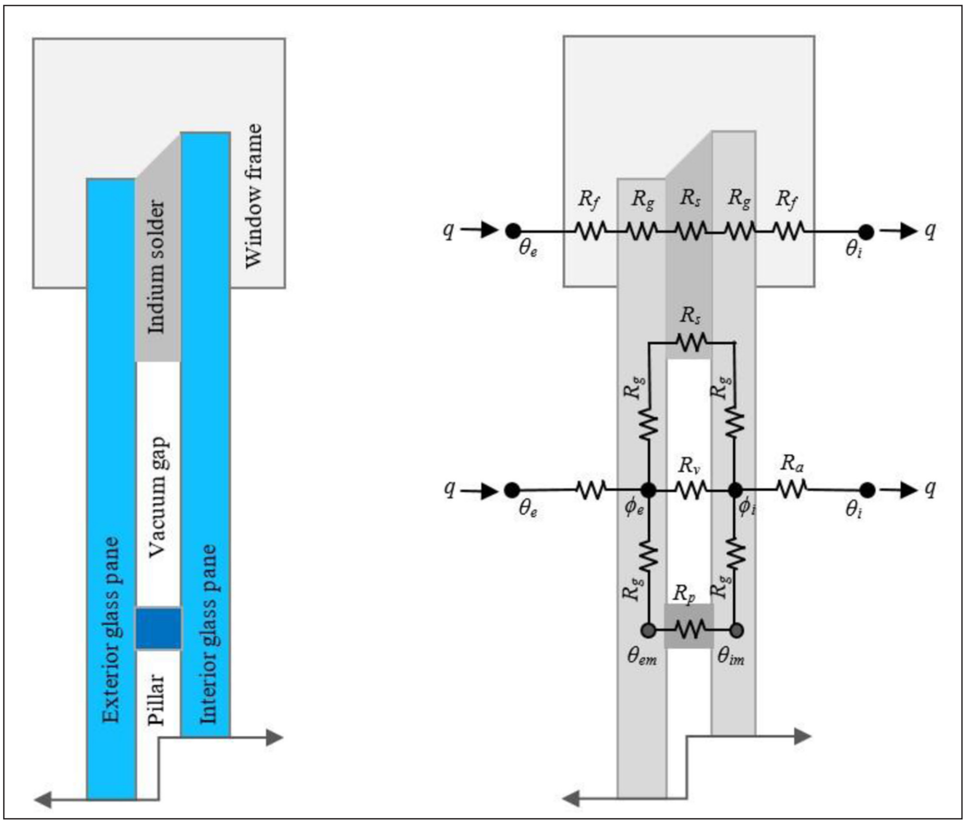

Figure 2: Layer composition and thermal circuit model for testing vacuum windows using the HFM method.

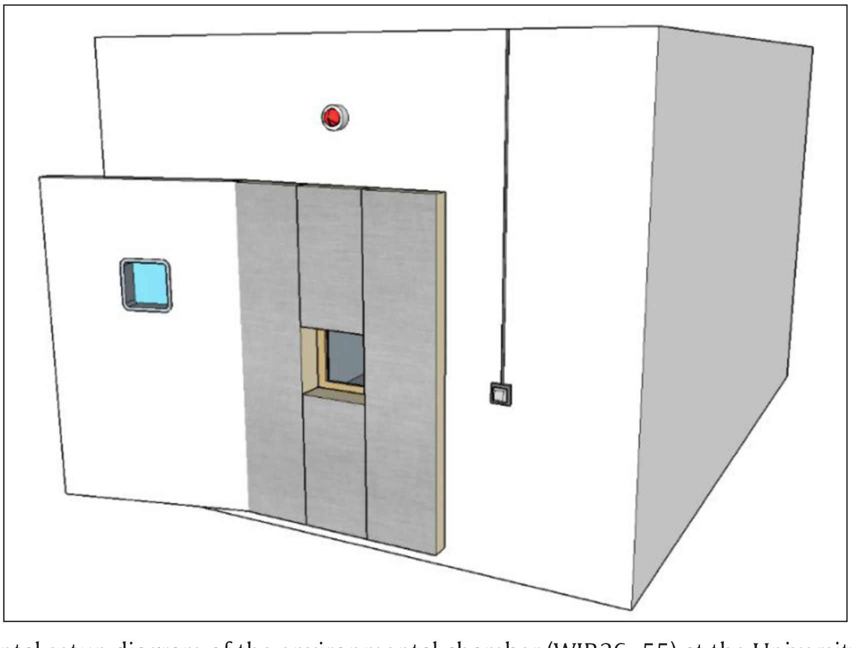

Figure 3: Experimental setup diagram of the environmental chamber (WIR36–55) at the University of Nottingham.

4c), this to allow the controlled temperature at the interior of the chamber (0.0 °C) while promoting a contact with the exterior ambient temperatures (~12.0 °C). Eight k-type thermocouples were installed away from thermal bridges and heat sources. Additionally, two heat flux meters HFP01 (Hukseflux Thermal sensors BV, Delft, NL) with sensitivities of $\Phi_i = 61.54$ μV/(W/m^2) and $\Phi_e = 62.77$ μV/(W/m^2) were attached at the centre of the pane to monitor the heat flow rate. The location of these heat sensors is described in **Figure 4b**. This test was continuously reporting results at intervals of 30 minutes for a period of 72 hours in the experimental setup detailed in **Figure 5**.

The data was recorded on a data acquisition system model DT80 (Omni Instruments Ltd, Dundee, UK) and was complemented by radiant energy imagery using an infrared thermal camera FLIR-E6 (FLIR Systems Inc., Wilsonville, US) every 24 hours on the external side of the experimental setup.

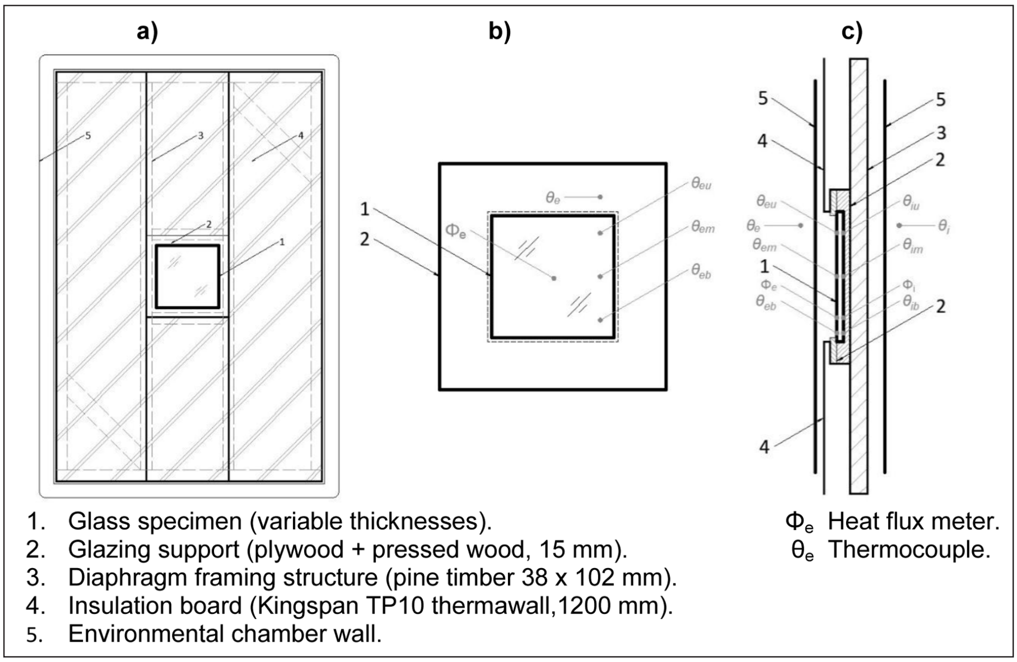

Figure 4: Details on the setup construction: **a)** environmental chamber testing plane, **b)** glazing support assembly, **c)** section of experimental wall.

Table 2: Materials, configuration and properties of the window samples tested with the average method on ISO 9869-1:2014.

Code and name	Configuration and thickness (mm)	Gases in gap and ratio (%)	Solids in gap and thermal conductivity (W/m·K)	Edge conf. and thermal conductivity (W/m·K).	Additional characteristics
W01 SG Single glazing	4	N/A	N/A	N/A	Low-e soda-lime glass pane
W02 DG + Air	4–15–4 (23)	Air mixture (100 %)	None	Warm edge spacer bar (0.03)	Transparent window
W03 DG Argon	4–15–4 (23)	Argon gas (98 %)	None	Warm edge spacer bar (0.03)	Transparent window
W04 DG KGM + Ar	4–15–4 (23)	Argon gas (98 %)	Konjac-glucomannan poly-saccharide aerogel (0.05)	Warm edge spacer bar (0.03)	Opaque window
W05 DG KGMWS + Ar	4–15–4 (23)	Argon gas (98 %)	Konjac-glucomannan aerogel + wheat straw (0.04)	Warm edge spacer bar (0.03)	Opaque window
W06 DG Aerogel	4–15–4 (23)	Air mixture (100 %)	Granulated aerogel (0.01)	Warm edge spacer bar (0.03)	Translucent window
W07 DG HISG + Ar	4–4–15–4 (27)	Argon gas (98 %)	None	Warm edge spacer bar (0.03)	High insulating glass + semi-transparent PV
W08 VG Manufactured vacuum	4–0.03–4 (8)	Vacuum (2 MPa)	Aerogel pillar array 33 pcs (0.03)	Indium solder (86.00)	Transparent window
W09 VG Commercial vacuum	4–0.03–4 (8)	Vacuum (2 MPa)	Steel pillar array 33 pcs (50.20)	Indium solder (86.00)	Transparent window

Windows tested

A series of fenestrations that do not include movable or switchable components (static windows) were tested in the laboratory (**Table 2**). All specimens were manufactured in a 300 × 300 mm size, utilising a soda-lime glass (4 mm thickness) in combination to a light grey tinted low-e coating (except for sample W07, high-insulated glass). This metal oxide low emissivity coating reduced the glass surfaces emissivity while allowing visible light to pass through the glass samples.

The gap filling and insulation technology were used as a criteria for testing these novel windows. Initially, the single glass sample (SG) was utilised as a control sample, making apparent to compare the thermal transmittance of this fundamental window against other specimens. Secondly, a double glazing sample with air filling was tested to compare the impact of encapsulating air in windows. Lastly, the novel window samples were experimentally tested: argon filling, bio aerogels, aerogel and vacuum glazing; making possible to compare their thermal transmittances against each other. Furthermore, the array of solid materials in this gap could have a great impact on their insulating capacity, being an example the starch-based organic aerogel polysaccharides, granulated aerogel mixtures and supporting pillars. Supporting arrays in this test include the use of steel and aerogel pillars that compare the heat transfer properties on vacuum glazing prototypes.

It is expected for these window samples to describe a contrast in their U-value coefficients at the centre of glazing "U_g", depending on the pane configuration (single glazing, double glazing and vacuum glazing). The low-e coating and colour tinting for example, is expected to influence significantly the results for single glazing windows, while double glazing windows are determined by the thermal conductivity of the materials contained in the glass gap. Alternatively, U-value on vacuum glass could be altered by its contained vacuum quality, edge soldering and the pillar materials in the supporting array (Aguilar-Santana, et al., 2020).

Results

A summary of the outcomes derived from the experimental procedure is presented in **Figures 6** and **7**, along with the interior and exterior temperatures on the surface of the glass specimen (T_{sij}&T_{sej}); additional parameters analysed included the density heat flow rate (q) and the calculated thermal transmittance (U-value) during the 72 hour period. **Figure 6** is presented as a control sam-

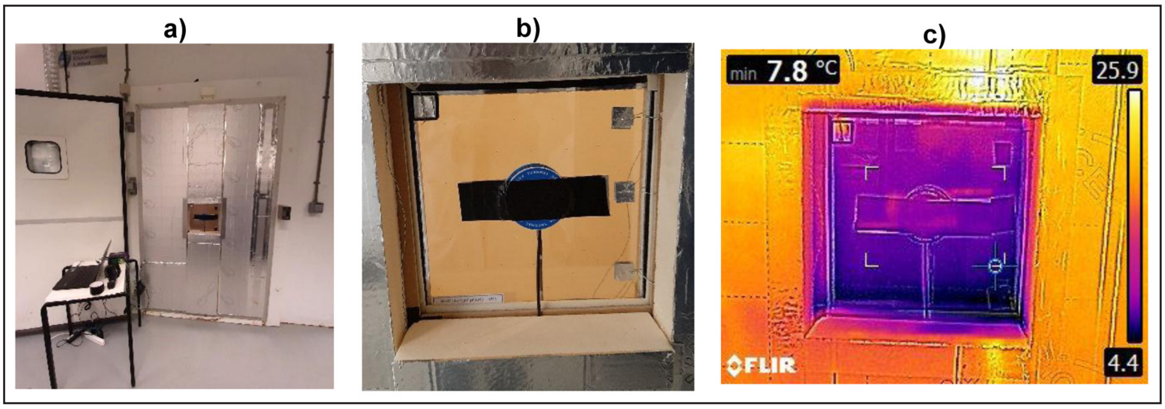

Figure 5: Experimental rig **(a)**, manufactured vacuum glazing sample in test **(b)** and its infrared thermography **(c)**.

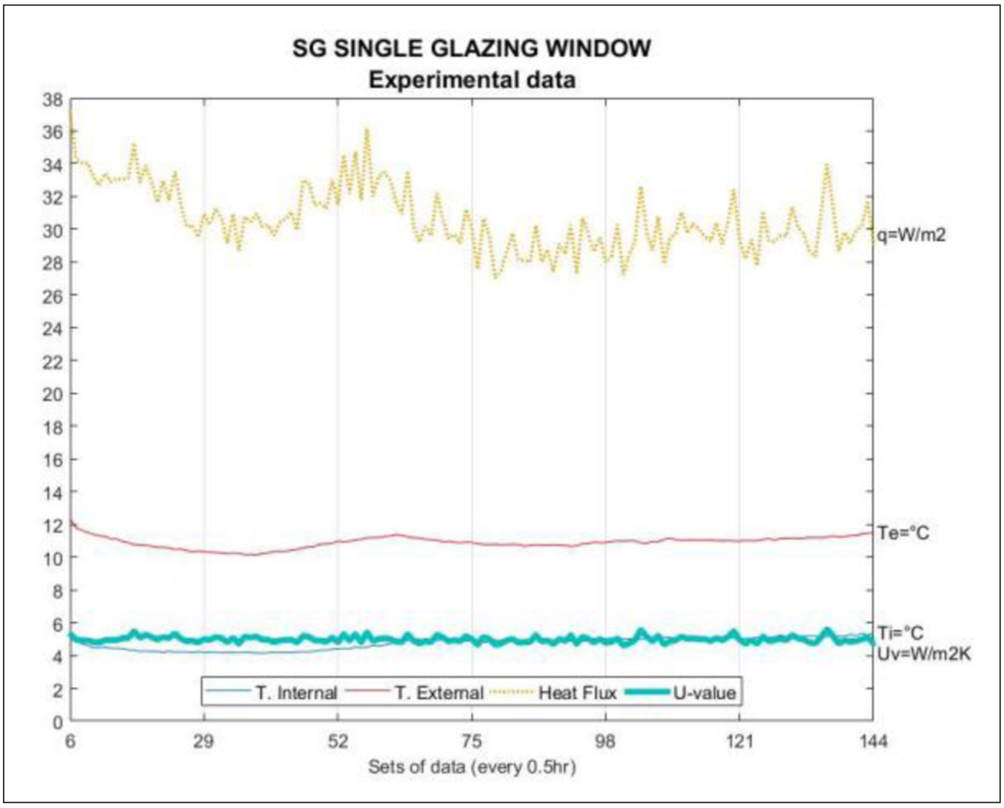

Figure 6: Experimental data of thermal transmittance for the single glazing window.

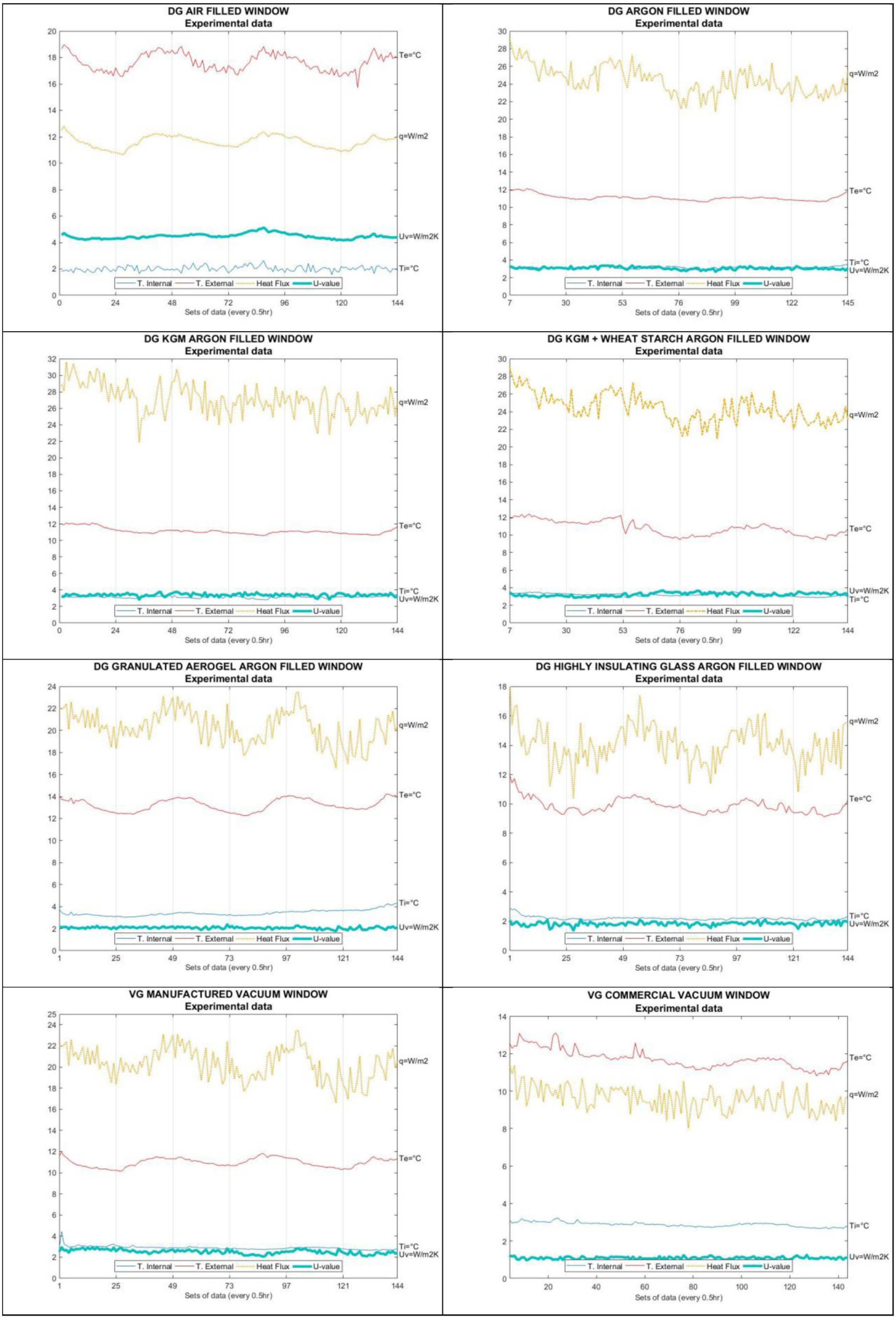

Figure 7: Experimental data of thermal transmittance for novel window technologies.

Table 3: Summary of results of the "heat flux meter method" for novel window prototypes.

Name of window and code	U-value Thermal transmittance (W/m²·K)	R-value Thermal resistance (m²·K/W)	Λ-value Thermal conductance (W/m·K)
01 SG Single glazing WS00-SG-NOM-NOM	5.15	0.20	2.04
02 DG Double gl. + Air WS01-DG-NOM-AIR	5.52	0.18	2.3
03 DG Argon WS13-DG-NOM-ARG	3.09	0.32	1.41
04 DG KGM + Ar WS02-DG-KGM-ARG	3.40	0.29	2.34
05 DG KGMWS + Ar WS04-DG-KGW-ARG	3.30	0.30	1.60
06 DG Aerogel WS05-DG-GRA-AIR	2.07	0.48	1.16
07 DG HISG + Ar WS11-DG-HIG-ARG	1.84	0.54	1.05
08 VG Manuf. vacuum WS10-VG-STP-VAC	2.52	0.40	1.59
09 VG Comm. vacuum WS12-VG-STP-VAC	1.12	0.90	0.95

ple with a predicted behaviour for a static single glazing unit, whereas **Figure 7** summarises the experimental data obtained by the novel window technologies. These sets of data are presented at intervals of 0.5 hours while the summary of calculations (considering thermal resistance and conductance) and their thermography images are presented in **Table 3**.

Thermal transmittance (U-value) analysis

The results condensed in **Table 3** summarise the thermal transmittance calculations for the nine novel windows samples utilised in this research. The single glazing unit (W01 in **Figure 6**) and double glazing air filled (W02 in **Figure 7**) recorded U-values of 5.15 W/m²·K and 5.52 W/m²·K, respectively. These values show a contrast to previously described values of 5.80 W/m²·K and 3.0 W/m²·K presented by (Leung et al., 2020) and (Schultz and Jensen, 2008).

Double glazing window with argon filling (W03) recorded a U-value of 3.09 W/m²·K, comparably higher to 2.0 W/m²·K usually reported for similar glazing structures (Cuce, Young and Riffat, 2014). The utilisation of triple glazing units with a double argon gap filling have demonstrated their capacity to reduce the U-factor to coefficients as low as 0.79 W/m²·K (Lolli and Andresen, 2016), representing a promising assembly for insulating purposes when its overall thickness and window mass (which is usually +30 % heavier) are not a restriction for building implementation.

Novel applications of polysaccharide-based aerogels Konjac-glucomannan (W04) and Konjac-glucomannan strengthened with wheat starch (W05) showed U-values of 3.30 W/m²·K and 3.40 W/m²·K, respectively. The reduction of thermal conductivity by using KGCWS described thermal conductivities of 0.046 W/m·K by previous researchers, using the technology for building applications (Wang et al., 2019). KGCWS relies on its porous structure, insulating ability and sustainable manufacturing process for becoming an alternative that could match the insulating capabilities of argon-based double glazing windows.

Within this experimental range, double glazed windows with aerogel granules filling (W06) reported a U-value of 2.07 W/m²·K; other researchers have found that a similar structure could reduce insulating capacity to further 1.00 W/m²·K or to 0.60 W/m²·K using a monolithic aerogel composite contained in gaps of 14 mm (Buratti and Moretti, 2012). Adopting a similar structure can generate a reduction of up to 19 % in energy savings using aerogel solutions; this when compared to triple glazing units with low-e coatings and argon fillings (Schultz and Jensen, 2008). However, the fragility of pure aerogel material applications requires the silicon aerogel to be contained in a consolidated (and usually with a higher thermal conductivity) container. This without taking into account the visual impact it has in the scattering of light, demonstrated by its traditional translucent appearance. Moreover, applications of aerogel in the glazing industry are very promising, especially when privacy and insulating capabilities are required; this demonstrates an optimal performance on this window for providing indirect natural lighting; especially in clerestories, skylights and greenhouse applications.

Results for the heat insulation solar glass window (W07) showed a U-value of 1.84 W/m²·K that is well below their argon-based counterparts. Similar studies on thermal transmittance on HISG have shown U-values in the range of 1.30 to 1.70 W/m²·K, for low and high transmittances (Li et al., 2019). Alternatively, PV-integrated solutions provide an new approach to insulation characterisation, reporting U-values as low as 1.10 W/m²·K and marking a record for energy production of 40 W in panels with area of coverage of 0.66 m² (Cuce, Young and Riffat, 2014).

Thermal transmittance for manufactured vacuum (W08) and commercial vacuum (W09) are summarised in **Figure 7** and **Table 3**. Experimental values of 2.52 W/m²·K and 1.12 W/m²·K respectively, are in agreement with the manufacturers' data that described U-values of 0.7 to 1.4 W/m²·K (Aguilar-Santana et al., 2020). Finally, it was found that the experimental procedure could be optimised by testing larger samples of vacuum glass and the use of additional temperature sensors. Limiting the effect of thermal conduction through the window and the addition of more thermocouples on the glass panes would present a more detailed spectrum of the surface temperatures.

Thermal insulance (R-value) analysis

The specific thermal resistance of the glazing technologies tested defined how efficient are windows to resist the heat flow. This parameter is a reciprocal value of the thermal conductance and it measures the transversal resistance of heat flow of a given window based on its temperature difference (θ_e-θ_i in Formula 2). A detailed outline of the estimated R-values is registered in **Table 3**. Windows with fewer layers of glass, especially single glazing unit (W01) presented a lower thermal insulance (0.20 m²·K/W) attributable to the soda-lime glass resistance which could be strengthen by the use of additional insulation layers. The use of argon filled solutions on this test reported (0.29 and 0.30) m²·K/W for the bio-aerogels solutions, in samples W04 and W05 respectively.

The comparably higher R-value of the granulated aerogel window (0.48 m²·K/W) when contrasted to argon-based filling solutions, demonstrates the insulating capability of the aerogel material itself. The addition of argon to the filling mixture could significantly increase the overall thermal resistance on this window for future analysis. A similar performace was illustrated by the window W07 (heat insulation solar glass) with 0.54 m²·K/W, demonstrating the insulating properties of this technology in comparison to traditional argon gas double glazing units (0.32 m²·K/W).

Commercial vacuum glazing sample W09 showed a proficient thermal resistance (0.90 m²·K/W), in relation to all the tested window solutions detailed in this paper; a higher vacuum pressure in the gap layer and the use of fewer supporting pillars could have helped for decreasing this coefficient. Alternatively, the sample manufactured at The University of Nottingham (W08), reported a lower thermal resistance (0.4 m²·K/W) due probably to a lower vacuum pressure and sample ageing, illustrating the importance of vacuum quality in evacuated windows.

Thermal conductance (Λ-value) analysis

Thermal conductivity in windows respond to several factors such as the material thicknesses, metal coatings and the interior-to-exterior conditions of testing. The calculations for this value are usually made using Fourier's law of heat conduction, finding that larger differences in temperature are desirable to reduce the uncertainty during experimentation (Zhao et al., 2019). In this regard, the samples analysed demonstrated a proportional relation from thermal conductance to the thermal transmittance values, varying the temperature difference from 6.0 °C in the single glass sample, to 9.8 °C for the commercial vacuum glazing sample. Larger temperature differences can also be tested using the hot-box method, obtaining more reliable estimations using customisable temperature settings. The use of a laser flash apparatus could show a significant reduction the testing period, this being further detailed in Zhao's research.

Other factor that significantly affects the overall thermal conduction of samples is the particular thermal conductance of the elements composing the prototypes. The glass utilised in the samples manufactured for this experiment have a thermal conductivity of 1.0 W/m·K and reported thermal conductivities of 0.025 W/m·K in double glazing units filled with air, while 0.016 W/m·K was reported in the samples filled with argon gas. Materials utilised for the edge configuration, such as the warm edge space bars (0.03 W/m·K) and metallic edge soldering materials (86.00 W/m·K) have demonstrated to have a direct impact on the overall thermal conductance of windows.

Impact of gas molecules in the gap filling

The number of panes and the gas gap had an important effect in the thermal performance of novel glazing windows. Some researchers have pointed out that smaller gaps between panes filled with argon gas result in heat loss by diffusion between panes, while larger gaps promote internal heat convection (Cuce, 2018). In this regard, samples filled with an air mixture (with a thermal conductivity of 0.026 W/m·K) have higher U-values in general; especially when compared to samples filled with argon gas mixture with 98 % in concentration (Λ = 0.018 W/m·K). This is especially noticeable between the sample W02 and W03, where a difference in the gas filling had a reduction of -44 % in the U-value for the argon-filled sample alone. Furthermore, the thermal conductivity of an air mixture reduced the insulation properties of aerogel in prototype W06, where the integration of an argon gas filling is then advised. A comparison of the impact of the gas molecules on the U-value of windows during the 72 hour testing period is illustrated in **Figure 8**.

Alternatively, the reduction of gas molecules in the gap (vacuum) has demonstrated to have a considerable impact on the thermal transmittance of manufactured and commercial vacuum samples. These results demonstrate the high potential for vacuum glazing windows for the reduction on the heat transfer in window technologies, decreasing the overall glass thickness (to less than 8.1 mm), and additionally improving the thermal transmittance of the window prototypes. These characteristics made possible to reduce the U-values to 2.52 and 1.12 W/m²·K in the manufactured and commercial vacuum glazing, respectively.

Impact of heat transfer through the window contour

Within the experimental range of the thermal transmittance calculation previously presented, three temperature stations were located in all glazing samples during for the 72 hour procedure. This in order to report the U-value of the windows in their weakest point (usually close to the edge of samples). The summary of the average temperatures reported is included in **Table 4**.

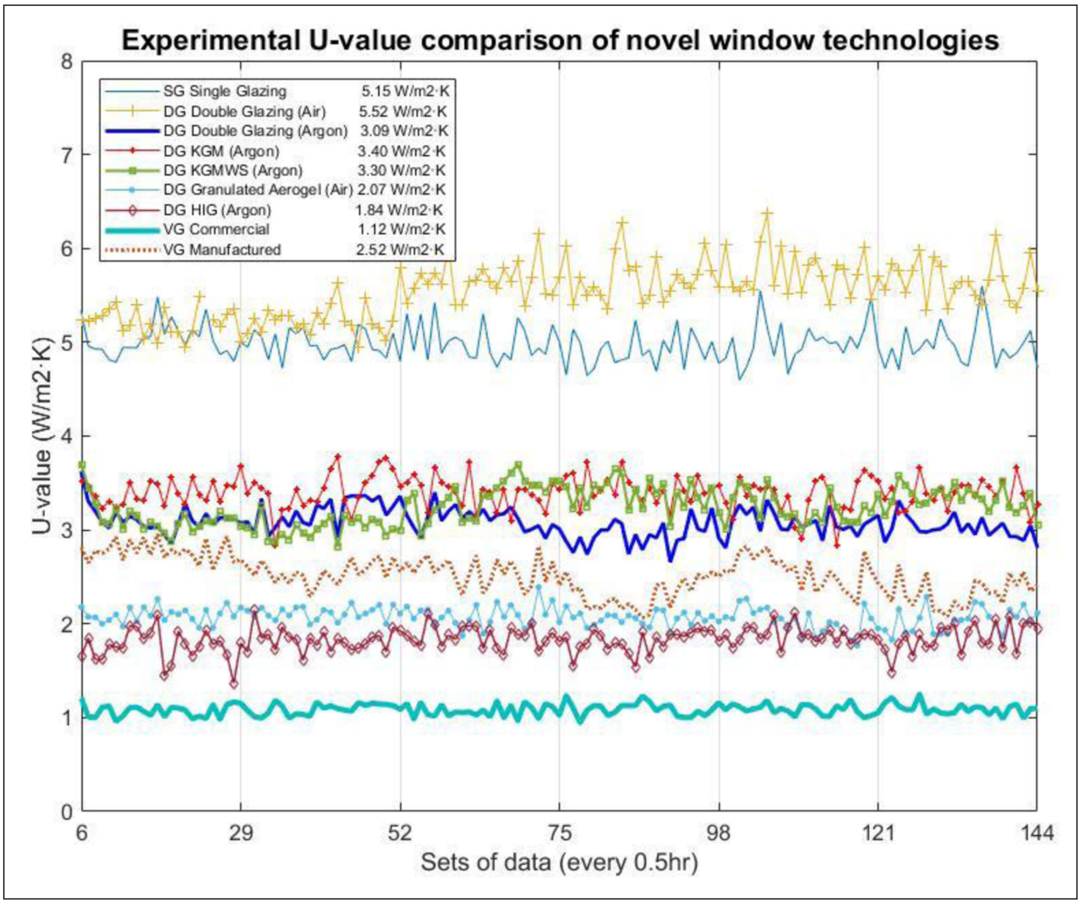

Figure 8: Thermal transmittance comparison of window samples over a 72-hours period.

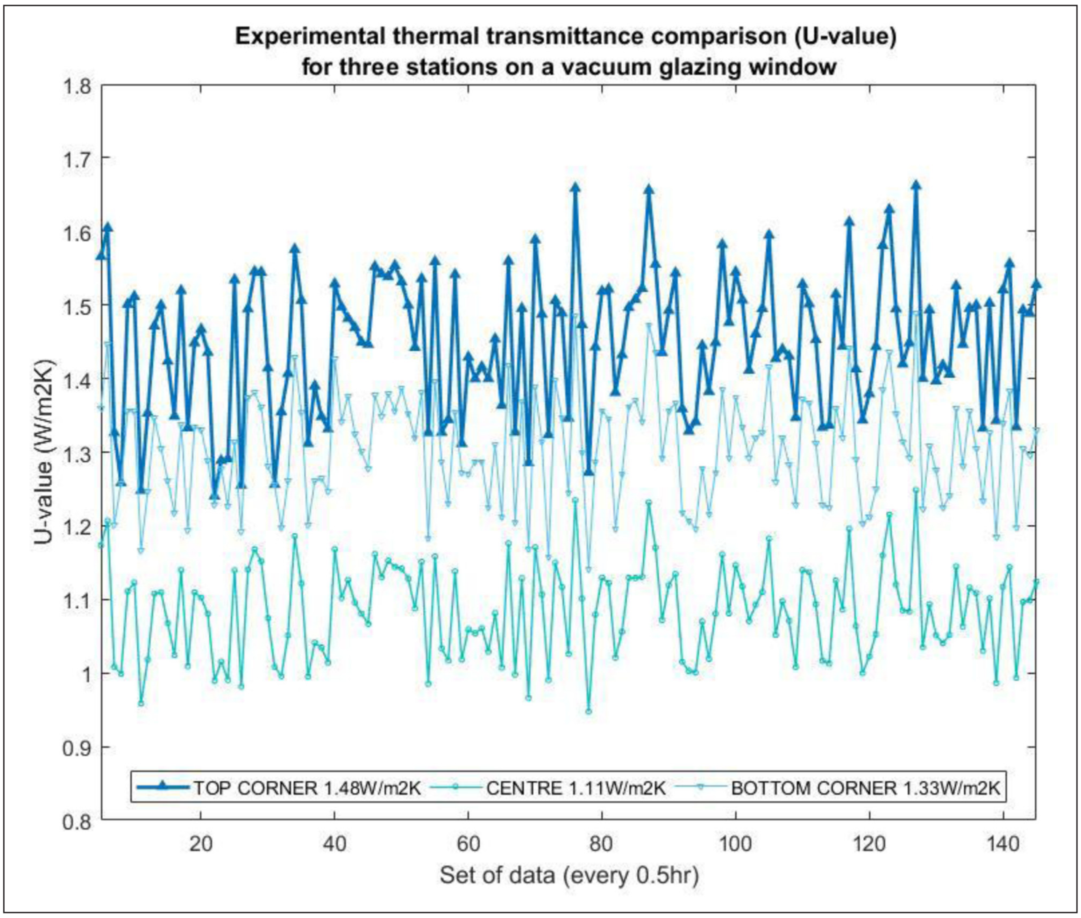

Figure 9: U-value comparison for the top, centre and bottom section of a commercial vacuum window.

According to the experimental data presented in **Table 3**, results confirmed that the thermal transmittance of glazing units is higher at the borderline areas. An example of this behaviour is given for the test on the commercial vacuum window in **Figure 9**, where the top corner station recorded the highest U-value (1.48 W/m^2·K), whilst the bottom corner observed 1.33 W/m^2·K; this is comparably 32 % and 19 % higher in contrast to the centre U-value (1.12 W/m^2·K). Cuce reported a similar trend on the edge insulation, finding 4 % and 11 % increase on top and bottom corner for an argon filled double glazing unit (Cuce, 2018). This results indicate that vicinity of other materials near the window rim (frame, soldering material, sashes), contribute to an increase in the heat transfer rate due to conduction of the composing materials; similarly as for the occurrence of convection motion in those samples that contain a gas mixture in the internal gaps. However, air leakage from the cooling chamber and diaphragm framing structure (see **Figure 5**) may have contributed to irregular measurements and abnormalities on the rates described.

Discussion and conclusions

This study presents the application of the heat flux meter method defined in ISO 9869-1:2014 to calculate the thermal transmittance (U-value) of eight novel window technologies. This contrasted against argon filling windows, novel aerogel, bio aerogel solutions, heat insulation solar glass and vacuum glass samples. An environmental chamber at The University of Nottingham was modified to analyse the thermal transmittance of windows using the heat flux meter method. The thermal transmittance of nine samples has been determined and their results are condensed and presented in **Figure 10**.

In terms of their U-value rate and thermal resistance, the windows tested are classified into three groups: the low efficiency solutions represented by the single glazing (W01) and double glazing air filled windows (W02),

Table 4: Average temperatures of window samples, for the stations defined in Figure 6 and Figure 7.

Code and window	Av. air Temp. ambient θe (°C)	Av. air Temp. chamber θi (°C)	T. diff. θe-θi (°C)	Av. Surf. Tem. θe-top (°C)	Av. Sur. Tem. θi-top (°C)	Av. Sur. Tem. θe-centre (°C)	Av. Sur. Tem. θi-centre (°C)	T. diff. θe-θi (°C)	Av. Sur. Tem. θe-bottom (°C)	Av. Sur. Temp. θi-bottom (°C)
W01 SG Single glazing	19.85	2.35	17.50	12.56	5.34	11.05	5.24	5.81	8.96	3.48
W02 DG + Air	17.64	2.02	15.63	11.63	4.92	10.97	4.47	6.50	8.68	2.89
W03 DG Argon	19.11	1.59	17.52	12.42	5.79	11.09	5.06	6.03	8.91	3.65
W04 DG KGM + Ar	12.96	1.37	11.58	11.74	3.15	11.13	3.15	7.98	8.27	2.48
W05 DG KGMWS + Ar	17.52	2.09	15.43	13.08	4.35	11.05	3.58	7.47	6.84	2.41
W06 DG Aerogel	18.52	1.08	17.44	13.60	4.44	13.18	3.46	9.72	10.82	2.62
W07 DG HISG + Ar	14.19	0.74	13.45	10.92	3.28	9.86	2.20	7.66	7.30	1.86
W08 VG Man. vacuum	12.53	1.23	11.30	11.08	5.05	10.97	2.88	8.09	11.31	3.09
W09 VG Com. vacuum	11.10	0.72	10.38	10.08	3.46	11.73	2.89	8.84	10.33	2.97

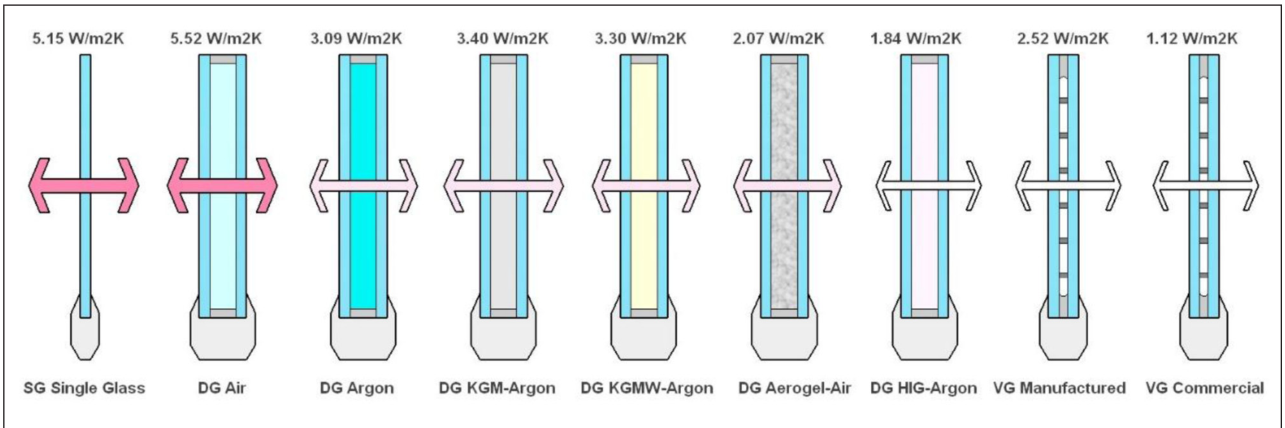

Figure 10: Thermal transmittance (U-value) of the nine novel window prototypes tested.

whereas the medium-efficiency solutions comprise the rates obtained by traditional double glazing window (W03) and novel bio aerogel solutions (W04 and W05). Finally, the most advantageous rating level range was achieved by the granulated aerogel glazing (W06) with the possibility to further enhance their U-value with an integrated argon gas filling is included. Heat insulation solar glass (W07) and the vacuum solution (W08 and W09, explicitly). The optimised U-value of the commercial vacuum glazing 1.12 $W/m^2 \cdot K$ was defined for several factors like vacuum pressure, thermal conductivity, pillar array and a reported low heat transfer at the centre of the pane (listed in **Figure 9**).

This experimental analysis presents a detailed comparison of thermal transmittance in novel window glazing based on their multi-layered composition, gas cavity and utilisation of novel materials towards a higher insulating capacity. From this testing the following conclusions are presented:

- Window elements play a key role in reducing the energy consumption in buildings since they are usually the weakest point in the thermal transmittance capacity of buildings.
- An experimental method utilising the ISO 9869-1:2014 heat flow meter method, along with radiant energy imagery as a non-invasive approach to calculate the thermal transmittance at the centre of glazing (U_g) on novel window technologies.
- Low efficiency solutions included single glazing unit (W01, 5.15 $W/m^2 \cdot K$) and double glazing air filled window (W02, 5.52 $W/m^2 \cdot K$).
- Medium efficiency solutions integrated by argon filled double-glazing (W03, 3.09 $W/m^2 \cdot K$), KGM aerogel (W04, 3.40 $W/m^2 \cdot K$) and KGM aerogel with wheat starch (W05, 3.30 $W/m^2 \cdot K$).
- A high efficiency tier that comprise granulated aerogel glazing (W06, 2.07 $W/m^2 \cdot K$), heat insulation solar glass (W07, 1.84 $W/m^2 \cdot K$) manufactured (W08, 2.52$W/m^2 \cdot K$) and commercial vacuum glazing windows (W09, 1.12$W/m^2 \cdot K$).
- Insulating capabilities of granulated aerogel were demonstrated by the R-value of this window (0.48 $m^2 \cdot K/W$), when contrasted to argon-based gap fillings.
- An argon-filled gap (W03, with 98% in concentration) reported a reduction of –44 % in the thermal transmittance coefficient when compared to a sample filled with air mixture (W02).
- A variable thermal transmittance was reported for a vacuum glass window on a top (1.48 $W/m^2 \cdot K$), centre (1.12 $W/m^2 \cdot K$) and bottom (1.33 $W/m^2 \cdot K$) station, due primarily to the conduction of materials and convection in the air volumes in contact to the glazing. This represented higher U-values of 32 % and 19 % for the top and bottom corner when compared to the central section of a vacuum glass.

Limitations of the study

Due to the nature of the testing and the conceptualisation of thermal transmittance, this study has potential limitations. The test conducted focused mainly on the thermal transmittance of glazing systems (at the centre of pane), also described as "U_g" or U-value of glazing and it requires to be differentiated from the thermal transmittance of a whole window "U_w" that includes the effects of window framing, spacers and the thermal properties of each component. As a result, it is reasonable to identify the results contained in this paper as a comparable measure against reports including similar methodologies and that may be an interesting approach for future studies using these innovative technologies.

Suggestions for future research

The results presented in this paper complement the thermal transmittance studies on glazing due to the novelty of the prototypes as well as the window's area size. However these outcomes could be further analysed using alternative thermal transmittance calculation approaches, such as the calibrated hot-box method (ISO 12567-1:2010) for comparison purposes. Additionally, the analysis of thermal bridging and air leakage in the samples could lead to improvements in the testing method. The utilisation of alternative window technologies, such as triple glazing with argon filling and triple vacuum glazing are advised for enhancing the insulating capacity of building elements. It is important to highlight that innovative window technologies with low U-value coefficients are often required in building codes as an effective method to reduce the energy consumption in buildings.

This study demonstrate the heat flux meter method as a mechanism to calculate U-value of windows utilising an environmental chamber to induce a temperature difference in window panes with satisfactory results. From this analysis, an estimation of the heat flux and ultimately heat transfer in novel window assemblies is presented.

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Competing Interests

The co-author Saffa Riffat is the Editor in Chief of this journal and was removed from all editorial duties involving the review and processing of the submission.

References

Aguilar-Santana, JL, *et al.* 2020. Review on window-glazing technologies and future prospects. *International Journal of Low-Carbon Technologies. Oxford Academic*, 15(1): 112–120. DOI: https://doi.org/10.1093/ijlct/ctz032

BSI. 2014. ISO 9869-1:2014- Thermal insulation — Building elements — Insitu measurement of thermal resistance and thermal transmittance; Part 1: Heat flow meter method, p. 48.

BSI. 2018. ISO – ISO 9869-2:2018 – Thermal insulation — Building elements — In-situ measurement of thermal resistance and thermal transmittance — Part 2:

Infrared method for frame structure dwelling. Available at: https://www.iso.org/standard/67673.html (Accessed: 21 July 2020).

BSI Standards. 2017a. BS EN ISO 10077-2: 2017 BSI Standards Publication Thermal performance of windows, doors and shutters – Calculation of thermal transmittance.

BSI Standards. 2017b. BSI ISO 10077-1: 2017 BSI Standards Publication Thermal performance of windows, doors and shutters — Calculation of thermal transmittance Part 2: Numerical method for frames, p. 48.

Buratti, C and **Moretti, E.** 2012. Glazing systems with silica aerogel for energy savings in buildings. *Applied Energy*, 98: 396–403. DOI: https://doi.org/10.1016/j.apenergy.2012.03.062

Cuce, E. 2018. Accurate and reliable U-value assessment of argon-filled double glazed windows: A numerical and experimental investigation. *Energy and Buildings*, 171: 100–106. DOI: https://doi.org/10.1016/j.enbuild.2018.04.036

Cuce, E, Young, C-H and **Riffat, SB.** 2014. Performance investigation of heat insulation solar glass for low-carbon buildings. *Energy Conversion and Management*, 88: 834–841. DOI: https://doi.org/10.1016/j.enconman.2014.09.021

Gori, V, *et al.* 2017. Inferring the thermal resistance and effective thermal mass distribution of a wall from in situ measurements to characterise heat transfer at both the interior and exterior surfaces. *Energy and Buildings*, 135: 398–409. DOI: https://doi.org/10.1016/j.enbuild.2016.10.043

IEA. 2013. International Energy Agency: Modernising Building Energy Codes, p. 74. Available at: https://www.iea.org/publications/freepublications/publication/PolicyPathwaysModernisingBuildingEnergyCodes.pdf.%0D.

International Organization for Standardization. 1994. ISO 10292:1994 Glass in building – Calculation of steady-stae U values (thermal transmittance) of multiple glazing, 10292.

International Organization for Standardization. 2010. ISO 12567-1:2010 Thermal performance of windows and doors – Determination of thermal transmittance by the hot-box method – Part 1: Complete windows and doors.

Jelle, BP, *et al.* 2012. Fenestration of today and tomorrow: A state-of-the-art review and future research opportunities. *Solar Energy Materials and Solar Cells*. North-Holland, pp. 1–28. DOI: https://doi.org/10.1016/j.solmat.2011.08.010

Jelle, BP, Kalnæs, SE and **Gao, T.** 2015. Low-emissivity materials for building applications: A state-of-the-art review and future research perspectives. *Energy and Buildings*. Elsevier Ltd, pp. 329–356. DOI: https://doi.org/10.1016/j.enbuild.2015.03.024

Leung, CK, *et al.* (2020) Optical and thermal performance analysis of aerogel glazing technology in a commercial building of Hong Kong. *Energy and Built Environment*, 1(2): 215–223. DOI: https://doi.org/10.1016/j.enbenv.2020.02.001

Li, X, *et al.* 2019. Energetic and economic evaluation of hybrid solar energy systems in a residential net-zero energy building. *Applied Energy*. Elsevier Ltd, 254: p. 113709. DOI: https://doi.org/10.1016/j.apenergy.2019.113709

Lolli, N and **Andresen, I.** 2016. Aerogel vs. argon insulation in windows: A greenhouse gas emissions analysis. *Building and Environment*. Elsevier Ltd, 101: 64–76. DOI: https://doi.org/10.1016/j.buildenv.2016.03.001

Schultz, JM and **Jensen, KI.** 2008. Evacuated aerogel glazings. *Vacuum*. Pergamon, 82(7): 723–729. DOI: https://doi.org/10.1016/j.vacuum.2007.10.019

Velasco-Carrasco, M, *et al.* 2020. Experimental evaluation of phase change material blister panels for building application. *Future Cities and Environment*. Ubiquity Press, 6(1): 1–7. DOI: https://doi.org/10.5334/fce.84

Wang, Y, *et al.* 2019. The advances of polysaccharide-based aerogels: Preparation and potential application. *Carbohydrate Polymers*. Elsevier Ltd, p. 115242. DOI: https://doi.org/10.1016/j.carbpol.2019.115242

Zhao, X, *et al.* 2019. Reduced-scale hot box method for thermal characterization of window insulation materials. *Applied Thermal Engineering*. Elsevier Ltd, 160. DOI: https://doi.org/10.1016/j.applthermaleng.2019.114026

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