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In Situ Experimental Investigation of Slim Curtain Wall Spandrel Integrated with Vacuum Insulation Panel

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Abstract: Almost every major city's skyline is known for high-rise iconic buildings with some level of curtain wall system (CWS) installed. Although complex, a CWS can be designed for energy efficiency by integrating insulated spandrel components in space-constrained areas, such as slabs/plenums. The main aim of this study was to experimentally examine the thermal performance of an optimized curtain wall spandrel system integrated with vacuum insulation panel (VIP) as spandrel insulation. The study is based on robust experimental evaluations, augmented with appropriate numerical computations. The main study is constituted of six parts: (1) evaluation of VIP specifications and thermal properties; (2) analysis of VIP spandrel configuration, fabrication, and installation in a test building facility; (3) thermal bridge characterization of VIP spandrels; (4) monitoring and assessment of VIP durability within the spandrel cavities; (5) thermal performance analysis; and (6) assessment of related limitations and challenges, along with some further reflections. In all, 22 VIPs (each of size 600 mm²) were used. The effective thermal conductivity of VIPs ranged from 5.1–5.4 (10^{−3} W/mK) and the average value for initial inner pressure was approximately 4.3–5.9 mbar. Three VIP spandrel cases were fabricated and tested. The results proved that the Case 3 VIP spandrel configuration (composed of a double-layer VIP) was the most improved alternative for integrating VIPs.

Keywords: vacuum insulation panel (VIP); curtain wall system (CWS); slim façade; spandrel component; experimental assessment; thermal performance

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1. Introduction

According to the International Energy Agency (IEA), final energy use in buildings grew from 118 EJ in 2010 to around 128 EJ in 2019 [1]. Factors contributing to this rise were particularly due to energy demand for cooling, to power appliances and devices, as well as extreme weather events. Energy-related direct emissions from buildings were about 3 GtCO₂ in 2019, a 5% increase since 2010. Considering indirect emissions from upstream power generation, buildings were responsible for 28% of global energy-related CO₂ emissions in 2019. In absolute terms, buildings-related CO₂ emissions rose and reached an all-time high of 10 GtCO₂ in 2019 [1]. For maintaining a comfortable indoor environment, energy-efficient building envelopes are essential, as the building envelope dominates other sections of a building system regarding the long-term impact on the ultimate energy performance throughout the lifecycle of a building [2].

At present, almost every major city's skyline is known for high-rise iconic buildings with some level of curtain wall system (CWS) installed. Curtain walled buildings appear as glistening and sleek glass façades with narrowly spaced vertical and horizontal mullions (metallic structures) overlapping with glass and spandrel panels. In the case of point-loaded

structural glazing curtain wall systems, there are no narrow spaces between the glazing due to the absence of a metal framework. Although a curtain wall forms a barrier for a building against weather, the curtain wall itself is non-load bearing [3,4]. It is anchored from a supporting structure of a building and so hangs like a curtain [5]. Therefore, it is technically called a “curtain” wall system. Breakthroughs in the metal and glass industry, efficient prefabrication techniques, as well as advancement in curtain wall technologies, have altogether enabled construction of some of the high-rise buildings of today. Some notable advantages of curtain wall façades include daylighting improvement, smaller wall footprint and a lighter structure, faster construction time, elegant aesthetics, among others [6]. Throughout the literature, various studies have been conducted covering different aspects of curtain walls. For instance, design strategies and requirements for frameless structural glazing systems under seismic loads have been scrutinized [7]. Similarly, code provisions for seismic demands and seismic experimental tests have been reviewed [8]. Some researchers focused on delamination and failure detection in curtain wall glazing [9,10]. Additionally, existing safety appraisal methods for hidden-frame glass curtain walls have been evaluated and characterized into a clear five-level appraisal hierarchy system [11]. Based on numerical computations, a dynamic scheduling model for the curtain wall construction process towards improved project planning and reliability has been proposed and validated [12]. The case of fire incidents, extreme climatic conditions, and accidental or human-induced explosions in curtain walled buildings have been comprehensively assessed as well [13–15]. Concerning building energy, a sensitivity analysis on critical design parameters for CWS towards improved energy performance has been conducted [16]. Studies have claimed that curtain walls could even be a better option than masonry walls in terms of space conditioning in a Mediterranean climate, if only they were properly designed [17]. For if not carefully designed, curtain walled buildings could have higher energy requirements for space conditioning when compared to traditional concrete walls, the reasons being the high thermal conductivity difference between glass and metal components of a CWS, as well as lower thermal resistance compared to opaque walls. Consequently, converting curtain walls into plus-energy façades by integrating photovoltaic panels has been proposed and studied [18]. To improve their thermal and energy performance, curtain wall systems are integrated with insulated spandrel sections connected to glazed sections by sharing a metal frame (see Figure 1).

Figure 1. Curtain wall with insulated spandrel component (reabeled from Ref. [19]).

Insulated spandrel helps to curtail convective heat fluxes. The insulation also acts as a fire-stopping material at the edge of the floor slab [20]. However, topics on insulated spandrel sections are marginally considered in the literature [21,22]. Extensive studies have focused on glazing components. For instance, different modeling approaches for the glazing of curtain wall systems have been evaluated [23]. A daylighting performance analysis of glass layers for curtain walls has been investigated as well [24]. Further studies have examined an optimized approach for designing thermochromic glazing for curtain wall buildings [25]. The search for an optimal window-to-wall ratio for office buildings, considering different European climates has been studied [26]. Similarly, the impact of various ratios of glazing-to-external wall areas on energy use in office buildings has been evaluated [27]. Towards controlling solar gains and assessing visual comfort, a sensitivity analysis was performed considering single office units fitted with metal mesh as shading devices [28]. Due to safety concerns, a robot prototype with dual suction cups for cleaning the glazing of high-rise glass curtain walls has been developed and tested [29]. A state-of-the-art review and assessment of future possibilities for fenestration products have been conducted [30]. Likewise, some researchers have carried out a systematic review on the balance between the thermal and daylighting performance of glazing systems and related effects on indoor comfort and energy use [31], and developments in glazing technologies and applications have been comprehensively studied [32]. In addition, a review on aerogel glazing systems for building applications focusing on the fabrication process, thermal, optical, and acoustic properties, quality of lighting, and energy savings compared to conventional glazing systems have been investigated [33]. Even so, there are some challenges to adequately insulating spandrel sections of such slim curtain wall façades to satisfy building energy codes.

Firstly, depending on the configuration of a spandrel, about 15–25 cm of traditional insulation material may be required to fulfill prevailing building energy regulations [34]. For instance, the typical curtain wall shown in Figure 1 utilized 100 mm thick mineral wool insulation. Even with a thermally broken aluminum frame and a triple glazing system, center-of-glazing and spandrel U -values of $1 \text{ W/m}^2\text{K}$ and $0.89 \text{ W/m}^2\text{K}$ were estimated

for the system, respectively [20], which were very far from the requirements defined in energy codes like ASHRAE 90.1. Generally, most opaque insulated spandrels do not satisfy the prescriptive insulation values or effective U -values for cold climates [35]. Secondly, to maintain aesthetics, insulated spandrels are commonly installed as separation elements between floors (at slab/plenum areas) only. This restriction has a direct consequence on the window-to-wall ratio, as well as design flexibility. It is worth noting that besides visible protrusions, usable indoor space is significantly reduced when a thick insulated spandrel section is extended beyond slab and plenum areas. Additionally, to make space for such thick traditional insulation materials, longer inner length and thicker back panels are used. Specifically, the inner length of curtain wall frame relates to its structural performance. Based on structural specifications, the inner length can be shortened. In that case, there may not be enough space to install the required thickness of insulation. Due to this space limitation, even when high structural performance is not needed, the inner length is still enlarged to accommodate the required thickness of insulation. Owing to the aforementioned challenges, a thin and super-insulating material solution is crucially needed. Alternatively, vacuum insulation panels (VIP) are a viable means of insulation for curtain wall spandrels due to VIPs' high thermal resistance per unit thickness compared to any other kind of insulation currently available [36–43]. Basically, VIP is composed of a micro-/nano-porous core material seal under vacuum in a gas-tight laminate envelope. Consequently, to achieve the same U -value, the equivalent thickness of VIP required is extremely reduced as compared to other traditional insulation materials. This makes VIP exceptionally useful for space-tight applications. Figure 2 compares details for a curtain wall insulated with a spandrel section with traditional insulation material and a VIP. It can be seen from Figure 2 (left) that an enlarged inner length is indeed needed to accommodate traditional insulation. Conversely, Figure 2 (right) depicts a plausible shorter inner length for the spandrel insulated with VIP. Particularly for curtain wall applications, one of the relatively overlooked but significantly important characteristics of VIP is its non-flammability according to European standards [44].

Figure 2. Schematic of curtain wall spandrel insulated with traditional insulation (left) and VIP (right).

Based on numerical computations, annual energy use for a five-story curtain walled building has been investigated [19]. Three spandrel insulation alternatives (VIP alone, mineral wool alone, and VIP coupled with mineral wool) and four representative locations in the USA (Detroit, St Louis, Phoenix) and Canada (Winnipeg) were considered in the study. The results showed that VIP spandrel types had the least total energy (heating and cooling) usage. Particularly for colder climates (except for Phoenix), a CWS composed of a VIP spandrel coupled with a double-glazing system used less energy (about 17,877–43,668 kWh/yr) for space conditioning compared to a mineral wool spandrel coupled with a triple glazing system. Using an accelerated aging approach, thermal conductivity evolution of VIPs integrated in the cavity of an insulation glass unit (IGU) were monitored [45]. The VIP-IGU assembly was referred to as an architectural insulation module (AIM). The principal use for the AIM assembly was for curtain wall applications either as insulated spandrels (as separation elements between floors) or as non-vision panels (due to inherent slimness) to be used alongside vision panels. VIPs 20 mm in thickness were used for AIMs made of fumed silica core material enclosed in a metalized envelope. The dimensions of the VIP and AIM were 250 mm × 250 mm and 300 mm × 300 mm, respectively. AIMs were monitored for more than 20 weeks under severe cycling temperature (−20 °C to 80 °C) and humidity (10% to 90%) conditions in a climatic chamber. The results proved that the protection factor for the VIP used within the AIM was more than ten times that of the unprotected VIP. The AIM concept is a strategy to guarantee the durability of VIPs as well as extend VIPs' service life in curtain walled buildings. Realistically, except for some peculiar cases, VIPs are not expected to encounter such harsh aging conditions in real building applications. A comprehensive review covering the thermal and energy performance of curtain walls, the development and building applications of VIPs, and opaque curtain wall spandrels insulated with VIPs has been conducted recently [46]. Researchers concluded that VIP technology is a leap forward in thermal insulation for building applications, especially slim façades, such as curtain walls. Some specific suggestions were that VIP spandrels could be designed such that non-destructive examinations like infrared thermography can be conducted on-site. In addition, the need for commercialization efforts for some VIP technological developments to end up in off-the-shelf standardized VIPs and curtain wall components was highlighted. Nevertheless, it was found that proper long-term monitored assessments of curtain wall installations with VIP spandrels are lacking in the literature. To that end, then, this study was designed.

This study is part of a project that was commissioned to propose, develop, and examine the thermo-energy performance of curtain wall spandrels insulated with vacuum insulation panels (CWS-VIP sp.). Based on numerical and analytical procedures, Part 1 of the project focused on the concept and governing heat transfer equations, initial VIP spandrel models and validation, the curtain wall vision-spandrel ratio effect on building energy, the effect of 2D/3D thermal bridges, and overall thermal performance for curtain walls with and without insulated spandrels (already published in Ref. [34]). The aim of Part 2 was to experimentally examine the dynamic thermal performance of an optimized curtain wall spandrel system integrated with a VIP as spandrel insulation. This paper focusses on Part 2. To that effect, this study is based on robust experimental evaluations carried out over 1.5 years, augmented with appropriate numerical computations. Specifically, three alternative VIP spandrel configurations geared towards minimizing thermal bridges and improving insulation performance while safeguarding the durability of VIPs were critically examined. Infra-red thermography assessments and temperature monitoring campaigns showed that VIPs had been properly integrated in the system, with no defects or failure. Overall, the results proved that the Case 3 VIP spandrel configuration (which was composed of a double-layer VIP structure) was the most improved alternative for integrating VIPs, despite complexities related to its fabrication. Finally, noteworthy limitations of experimental methods employed and future perspectives are duly discussed.

2. Materials and Methods

In this section, detailed experimental procedures and the numerical evaluations used in this study are presented. The section commences by reporting material specifications and in lab assessments of individual VIPs. Then, numerical simulations (using experimental data from in lab tests as inputs) towards evaluating thermal characteristics of VIP spandrels are explained. Afterwards, procedures for the fabrication of VIP spandrel components and installation of the spandrel units in a real-scale mockup building facility are described. Lastly, monitoring methods are reported.

2.1. Specifications and in Lab Assessment of VIP Properties

All VIPs used in this study are commercial grade materials provided by a leading Korean VIP manufacturer. The VIPs were made of fumed silica core material encapsulated in a metalized laminate envelope material. The laminate was composed of three metalized polyethylene terephthalate (PET) films with low-density polyethylene (LDPE) as a sealing layer, laminated together using polyurethane (PU) glue. PET serves as an excellent flat substrate for the metalized aluminum (AL) barrier. Thin Al barrier layers restrict gas and moisture permeation into the core material. LDPE is used for sealing at the weld seam joints of the panel. A schematic representation and SEM of the laminate's structure are shown in Figure ??a,b, respectively. In addition, specifications of the metalized laminate material provided by the envelope manufacturer are listed in Table 1.

PET	Polyethylene terephthalate (12 μm)
AL	Aluminum (0.1 μm)
PU	Polyurethane glue (2 μm)
PET	Polyethylene terephthalate (12 μm)
AL	Aluminum (0.1 μm)
PU	Polyurethane glue (2 μm)
PET	Polyethylene terephthalate (12 μm)
AL	Aluminum (0.1 μm)
PU	Polyurethane glue (2 μm)
LDPE	Low density polyethylene (50 μm)

(a)

Figure 3. Cont.

Figure 3. Details of tri-metalized laminate envelope. (a) Structure of laminate; (b) SEM micrograph [47].

Table 1. Properties of metalized envelope material [48].

Property	Test Method/Condition	Index
Total thickness		92 (μm)
Heat seal strength (HSS)	165 °C, 4 kg/cm ² , 2 s	>3.5 (N/mm)
Puncture resistance (PR)	FTMS 101C 2065	130 (N)
Moisture vapor transmission rate (MVTR)	ASTM F-1249-90, 38 °C 90% RH	<0.015 (gr/m ² day)
Gas Transmission Rate (GTR)	22 °C 50% RH	<9 (cc (STP)/m ² /year)

The inner pressure state of the VIPs was evaluated using a custom-made apparatus which operates based on pressure compensation (also called the envelope foil lift-off method). The apparatus was developed in accordance with IEA EBC Annex 39 guidelines [36]. The foil lift-off method operates on a pressure equilibrium between the internal and external environment of a panel. Figure 4 depicts details of the inner pressure measuring equipment. For the custom-made apparatus, the vacuum chamber can accommodate a maximum sample size of 1 m × 1 m and has a minimum degree-of-vacuum up to 0.001 Torr (0.13 Pa). The vacuum chamber, with an error rate of 0.1%, was equipped with a high-precision laser sensor capable of detecting changes on a millimeter scale. In the vacuum chamber, the laser sensor had a measuring distance of 130 mm, a range of ±15 mm to ±12 mm, and an accuracy of ±0.1% to ±0.25% [49].

(a)

(b)

(c)

Figure 4. VIP inner pressure measurement apparatus: (a) concept, (b) laser component, and (c) vacuum chamber [49].

Thermal conductivity measurements were carried out using heat flow meter instrumentation (EKO HC-074) at a hot plate temperature of 38 °C and a cold plate temperature of 10 °C, under room conditions (temperature of 21–23 °C and relative humidity of 50–55%). The heat flow meter is accurate with a manufacturer's specified repeatability of 0.2% and reproducibility of 0.5%.

2.2. Initial Numerical Computations

Based on Physibel BISCO/TRISCO computations, Part 1 of this project mainly investigated overall thermal performance for curtain walls with and without insulated spandrels, considering different levels of thermal bridges [34]. Thus, these subjects are not considered in the present study. However, models developed in Part 1 were fine-tuned according to the actual components and material specifications of VIP spandrels to be used for mockup tests later in this study. For instance, experimental data for VIPs and extruded polystyrene (XPS)

obtained from laboratory tests were used as inputs for computations. In addition, structural features of a thermally broken aluminum frame system to be used for mockup experiments was modeled. BISCO and TRISCO are thermal analysis programs developed by Physibel for steady state heat transfer with 2D and 3D objects consisting of different materials and submitted to different boundary conditions, using the finite difference method [50,51]. Numerous researchers [37,52–58] have employed BISCO and TRISCO to investigate various thermal performance aspects of VIP components and building systems with VIP, proving that BISCO and TRISCO are sufficiently reliable tools for the analysis of VIP components and constructions with VIP. Prior to experimental assessments, alternative VIP spandrel configurations aimed at: (i) reducing thermal bridges of the overall spandrel system, (ii) protecting the durability of VIPs integrated in the spandrel system, (iii) enhancing the ease of fabrication, and (iv) using readily available materials that were proposed, the thermal performance of which was scrutinized. Since the aim of this study concerns the spandrel section of curtain wall systems, the modeling decoupled (separated) the vision section from the spandrel section. In this study, the VIP was modeled with the effective thermal conductivity value. The effective thermal conductivity accounts for thermal bridging due to the multilayered laminate envelope and core material, panel size, linear thermal transmittance, and VIP weld seam design at the edge of the panel. This approach was already used in other studies [53,59,60]. To model very thin laminate layers with thicknesses in the range of 0.1µm–50µm (for the case of the VIPs used in this study) is very difficult and even requires more sophisticated numerical software. In addition, modeling all envelope material layers separately would require very dense grids [58], and the spandrel scenarios in this study were modeled under the same conditions, so no significant variation in results is attributed to using the effective thermal conductivity value. In all, three VIP spandrel configurations were considered, and their details will be presented in the following Section 2.3. The thermophysical properties of material components of the spandrel system and boundary conditions for numerical simulations, in compliance with the Korean Building Energy Code [61], are summarized in Tables 2 and 3, respectively.

Table 2. Thermal and physical properties of material components for VIP spandrels.

Material	Function	Thermal Conductivity, W/mK	Density, kg/m ³	Specific Heat, J/(kgK)
Aluminum ¹	Frame	160	2800	880
Glass ¹	Structural panel	1	2500	750
Reinforced polyamide ¹	Primary seal	0.3	1450	1600
Silicone ¹	Secondary seal	0.35	1200	1000
EPDM ¹	Gasket	0.25	1150	1000
Silica gel ¹	Desiccant	0.13	720	1000
XPS ²	Thermal breaker	0.028	30	1000
VIP (10mm) ^{2,3}	Spandrel insulation	0.0051	200	800
VIP (15mm) ^{2,3}	Spandrel insulation	0.0051	200	800
VIP (25mm) ^{2,3}	Spandrel insulation	0.0054	200	800

¹ ISO 10456 [62]. ² Based on in lab experimental tests. ³ Effective thermal conductivity values.

Table 3. Boundary conditions.

Environment	Temperature (°C)	Surface Heat Transfer Coefficient (W/m ² K)
Exterior	−11.3	23.25
Interior	20	9.09

2.3. Outdoor Mock-Up Experimental Assessments

2.3.1. VIP Spandrel Configurations

The baseline model (Case 1) was composed of single-layer 25 mm thick VIP integrated between two 6 mm glass panes, as depicted in Figure 5a. The total thickness of the baseline case was 37 mm. Details of Case 2 are shown in Figure 5b. The main difference between Case 2 and Case 1 was the use of a 5 mm layer of XPS between the outer glass pane and the exterior face of the one-layer 25 mm thick VIP. The total thickness of Case 2 was 42 mm. It is worth noting that both Case 1 and Case 2 have a single-layer VIP. Application of single-layer VIP is quite common in building constructions [53,60,63–66]. Finally, Case 3 was made up of a double-layer VIP of thickness 10 mm (towards outdoors) and 15 mm (towards indoors), with a 5 mm layer of XPS between the adjacent surfaces of the VIPs. Case 3 is represented by Figure 5c. The total thickness of Case 3 was 47 mm. Case 3 was designed in this particular manner to evaluate the effect of utilizing two staggered VIPs of equivalent total thickness of 25 mm (the same as the VIP thickness for Case 1 and Case 2) as compared to using a one-layer VIP. Double-layer VIP design has been applied in such applications as precast concrete integrated with VIPs [67] and low-sloped commercial roofing systems [68]. Since the study concerned the spandrels of a curtain wall, experiments were carried out on spandrel specimens only, to better understand their thermal behavior. A typical thermally broken aluminum framing system (U -value of $2.7 \text{ W/m}^2\text{K}$) was used to support the spandrel components, which was suitable for the purpose of the study. It is worth noting that the configurations of VIP spandrels in Figure 5 are the same for the VIP spandrels modeled under Section 2.2, except for the inclusion of an ultraviolet (UV) control film. This is to protect the surface of a VIP facing outdoors from direct solar radiation. Table 4 summarizes the properties of the UV film.

Figure 5. Cont.

Figure 5. Cross-sectional details of VIP spandrel cases. (a) Case 1; (b) Case 2; (c) Case 3.

Table 4. Properties of UV control film [69].

Property	Index
Solar heat gain coefficient (SHGC)	0.23
U value	0.93
Total solar energy rejected	77%

2.3.2. Overview of Real-Scale Mockup Building Facility

Details of the mockup test building facility used for experimental investigations are shown in Figure 6.

Figure 6. Photographs of the mockup test building facility.

The test facility, measuring 6m (length) by 4m (width) by 2.7 m (height), is located at the College of Engineering Campus of Kongju National University, in Cheonan. To avoid shade and to be exposed to solar radiation, the mockup facility was mounted on the rooftop of a four-story educational building. The exterior walls of the test facility, from outdoors to indoors, were composed of a sandwich panel (painted metal sheet, 100 mm EPS insulation and painted metal sheet), 50 mm glass wool insulation, and a 19 mm two-ply gypsum board. The south-facing façade of the facility was designed with openings measuring 1360 mm × 1360 mm (with tolerance of ± 5 mm) into which VIP spandrel components could be installed. The floor plan of the test building is shown in Figure 7.

Figure 7. Plan of test building facility (units: mm).

Interior partitions of the test facility consisted of 19 mm two-ply gypsum board, 90 mm glass wool insulation and 19mm two-ply gypsum board. The indoor temperatures in both test and service rooms were controlled by an electric heat pump (EHP) air conditioning system. The system can operate in cooling mode only. The facility was designed to have three test rooms and was fabricated in a manner to ensure that the test rooms were exposed to the same outdoor and indoor environmental conditions.

2.3.3. Spandrel Fabrication, Installation, and Monitoring Systems

All materials used for the mockup tests are commercially available products. The VIP spandrel fabrication was carried out in coordinated sequences on site. Depending on the configuration of the spandrel, the sandwich panels were duly constructed. Spandrel integrated VIP components were then installed in the test building facility. The internal and external surface temperatures of the spandrel specimens, as well as VIP surface temperatures inside the spandrel cavity, were monitored using K-Type thermocouples. The tips of the thermocouples' wire legs were spot welded with a thermocouple welder prior to setting up in the test building. This was to create a junction where temperature could be measured and to prevent short circuiting. To avoid measurement errors, thermocouples were calibrated and tested before installation in the mockup facility. Global solar radiation incident on the vertical surface was measured using a pyranometer, and outdoor temperature and humidity profiles were measured with a temperature and relative humidity transmitter. The inductive head of the humidity transmitter was shielded from solar radiation to reduce the influence of direct solar radiation on measurements. The indoor climatic environment for individual tests and service rooms were monitored as well. Data was recorded at intervals of 5 min. The durability of VIPs and the thermal bridge of the overall system were examined by infra-red thermography. Details and technical and uncertainty specifications of test equipment used for monitoring are listed in Table 5. Actual images of the experimental apparatus are shown in Figure 8. In all, 26 temperature sensors were used to measure surface and cavity temperatures. Table 6 summarizes the number of sensors used per case. Figure 9 shows thermocouple positions for the interior and exterior surfaces of spandrels, while Figure 10 displays thermocouple positions at the VIP surfaces inside the spandrel cavity. The final building with the spandrel specimens installed is presented in Figure 11.

Table 5. Specification and measurement accuracy of measuring equipment.

Equipment Type (Model)	Specifications
K-Type thermocouple (KX-F-0.32)	Measurement range: $-200\text{ }^{\circ}\text{C}$ to $1372\text{ }^{\circ}\text{C}$ Accuracy: ± 0.50 (at $-200\text{ }^{\circ}\text{C}$ to $-50\text{ }^{\circ}\text{C}$), ± 0.25 (at $-50\text{ }^{\circ}\text{C}$ to $1372\text{ }^{\circ}\text{C}$)
Data logger for thermocouple calibration (Graphtec GL800)	Clock accuracy: $\pm 0.002\%$ (ambient temperature $23\text{ }^{\circ}\text{C}$) Operating environment: $0\text{ }^{\circ}\text{C}$ to $45\text{ }^{\circ}\text{C}/5\%$ RH to 85% RH Measurement range and accuracy: $\pm(0.05\%$ of reading $+ 2\text{ }^{\circ}\text{C})$ at $-200\text{ }^{\circ}\text{C}$ to $-100\text{ }^{\circ}\text{C}$; $\pm(0.05\%$ of reading $+ 1\text{ }^{\circ}\text{C})$ at $-100\text{ }^{\circ}\text{C}$ to $1370\text{ }^{\circ}\text{C}$.
Thermocouple welder (DK-50)	Input voltage: $220\text{ V AC } 1\text{ A } 60\text{ Hz}$ Output voltage: $24\text{--}48\text{ VDC } (20,000\text{ }\mu\text{F})$
Pyranometer (EKO MS-402)	Operating temperature: $-40\text{ }^{\circ}\text{C}$ to $80\text{ }^{\circ}\text{C}$ Irradiance range: 0 to 4000 Wm^{-2} Wavelength range: $285\text{--}3000\text{ nm}$ Response time 95%: $<8\text{ s}$ Sensitivity: $7\text{ }\mu\text{V/Wm}^{-2}$ Temperature response $-10\text{ }^{\circ}\text{C}$ to 40 : $\pm 1\%$ Accuracy: first class pyranometer according to ISO 9060
Indoor air temperature and relative humidity transmitter (EE160)	Operating temperature: $-40\text{ }^{\circ}\text{C}$ to $60\text{ }^{\circ}\text{C}$ Measurement range: $-40\text{ }^{\circ}\text{C}$ to $60\text{ }^{\circ}\text{C}/10\%$ RH to 95% RH Accuracy at $20\text{ }^{\circ}\text{C}$: $\pm 0.3\text{ }^{\circ}\text{C}/\pm 2.5\%$ RH
Outdoor temperature and relative humidity transmitter (HygroFlex HF535)	Operating temperature: $-40\text{ }^{\circ}\text{C}$ to $60\text{ }^{\circ}\text{C}$ Measurement range: $-40\text{ }^{\circ}\text{C}$ to $60\text{ }^{\circ}\text{C}/0\%$ RH to 100% RH Accuracy at $23\text{ }^{\circ}\text{C}$: $\pm 0.1\text{ }^{\circ}\text{C}/\pm 0.8\%$ RH
Data logger for monitoring (Yokogawa WE7241)	Measurement accuracy: $\pm(0.1\%$ of reading $+ 1\text{ }^{\circ}\text{C})$, except $-200\text{ }^{\circ}\text{C}$ to $0\text{ }^{\circ}\text{C}$, $\pm(0.6\%$ of reading $+ 1\text{ }^{\circ}\text{C})$ for thermocouple; $\pm(0.07\%$ of reading $+ 40\text{ mV})$ for pyranometer; $\pm(0.2\%$ of reading $+ 3\text{ mV})$ for air temperature/relative humidity transmitter
Infrared thermal camera (Fluke Ti32)	Operating temperature: $-10\text{ }^{\circ}\text{C}$ to $50\text{ }^{\circ}\text{C}$ Infrared spectral band: $7.5\text{ }\mu\text{m}$ to $14\text{ }\mu\text{m}$ Measurement range: $-20\text{ }^{\circ}\text{C}$ to $600\text{ }^{\circ}\text{C}$ Thermal sensitivity: $\leq 0.05\text{ }^{\circ}\text{C}$ Accuracy: $\pm 2\text{ }^{\circ}\text{C}$ or $\pm 2\%$

Figure 8. Mockup measurement apparatus.

Figure 9. Schematic of thermocouple positions for: (a) interior and (b) exterior surfaces of spandrels.

Table 6. Summary of number of thermocouples.

Sensor Locations	Case 1	Case 2	Case 3
Interior surface (indoor)	4	4	4
Exterior surface (outdoor)	2	2	2
Surface of VIP (inside spandrel cavity)	2	2	4

Figure 10. Thermocouple positions at VIP surfaces inside the spandrel cavity. **Figure 11.** Mockup test facility with installed VIP spandrels.

3. Results and Discussion

In this section, the key results obtained from in lab assessments, numerical evaluations, and outdoor monitoring investigations are reported chronologically. Detailed discussions are also presented. Final reflections, limitations and challenges of the study are clearly stated as well to clearly define the repeatability, scope, and possibilities for further study.

3.1. Thermal Characteristics of VIPs

VIP samples were kept at room conditions for 60 days to observe and discard faulty panels emanating from manufacturing defects. At the end of the 60 days, all VIPs showed no anomalies or vacuum loss and were in good physical condition. Thereafter, the experimental evaluations commenced. In all, 22 VIPs were tested and used in this study. Table 7

summarizes the dimensions, center-of-panel thermal conductivity, and inner pressure of the VIPs. Figure 12 shows a graphical analysis for a VIP (sample No. 1), used to determine internal pressure for the panel.

Table 7. Summary of VIP properties.

Sample No.	Dimension, mm × mm × mm	Center-of-Panel Thermal Conductivity (λ_{cop}), W/mK	Inner Pressure (p), mbar
1	600 × 600 × 25	0.00430	4.0
2	600 × 600 × 25	0.00428	4.0
3	600 × 600 × 25	0.00379	4.5
4	600 × 600 × 25	0.00392	4.0
5	600 × 600 × 25	0.00395	5.5
6	600 × 600 × 25	0.00382	5.0
7	600 × 600 × 25	0.00382	4.0
8	600 × 600 × 25	0.00386	4.0
9	600 × 600 × 25	0.00456	4.0
10	600 × 600 × 25	0.00438	4.0
11	600 × 600 × 15	0.00397	5.0
12	600 × 600 × 15	0.00396	5.5
13	600 × 600 × 15	0.00396	5.5
14	600 × 600 × 15	0.00400	5.0
15	600 × 600 × 15	0.00402	6.0
16	600 × 600 × 15	0.00405	5.0
17	600 × 600 × 10	0.00420	5.5
18	600 × 600 × 10	0.00412	4.5
19	600 × 600 × 10	0.00426	6.0
20	600 × 600 × 10	0.00424	7.0
21	600 × 600 × 10	0.00426	6.0
22	600 × 600 × 10	0.00437	6.5

Figure 12. Determination of inner pressure for VIP (sample No. 1).

All other VIP samples showed similar graphical trends. The pressure in the vacuum chamber of the test apparatus equaled atmospheric pressure at the beginning of the inner pressure measurement. As pressure reduced inside the vacuum chamber (due to the working action of vacuum pumps), the pressure inside the vacuum chamber dropped continuously until a point where the envelope of the VIP lifted from the core momentarily. This was the critical pressure where the two extrapolated curves met. This critical point gave an indication of the inner pressure of each VIP. On the one hand, the mean center-of-panel thermal conductivity and mean inner pressure for VIPs with dimensions

600 mm × 600 mm × 25 mm, 600 mm × 600 mm × 15 mm, and 600 mm × 600 mm × 10 mm was about 0.0041 W/mK, 0.0040 W/mK, and 0.0042 W/mK, respectively. On the other hand, the mean inner pressure for VIPs with dimensions 600 mm × 600 mm × 25 mm, 600 mm × 600 mm × 15 mm, and 600 mm × 600 mm × 10 mm was estimated to be 4.3 mbar, 5.3 mbar, and 5.9 mbar, correspondingly. The linear thermal bridge (Figure 13) at one edge of the panel was estimated to be 0.008 W/mK for the 25 mm VIP, 0.011 W/mK for the 15 mm VIP, and 0.013 W/mK for the 10 mm VIP.

Figure 13. Schematic showing thermal bridge (marked in red) between VIPs.

The edge effect (Δ_{edge}) and effective thermal conductivity (λ_{eff}) were computed based on Equations (1) and (2):

$$\Delta_{edge} = \psi(d) \times d \times p / A \quad (1)$$

$$\lambda_{eff} = \lambda_{cop} + \Delta_{edge} \quad (2)$$

where $\psi(d)$ is linear thermal transmittance at the edge of the panel (W/mK) and d , p , and A are the thickness (m), perimeter (m), and area (m²) of the panel, respectively. Thermal characterization results for VIPs are summarized in Table 8.

Table 8. Summary of VIP thermal conductivity characterization.

Description	25 mm VIP	15 mm VIP	10 mm VIP
Mean center-of-panel thermal conductivity, W/mK	0.0041	0.0040	0.0042
Linear thermal transmittance, W/mK	0.008	0.011	0.013
Effective thermal conductivity (including thermal bridge), W/mK	0.0054	0.0051	0.0051

3.2. Numerical Evaluations of Insulation Performance for VIP Spandrels

Table 9 summarizes the simulation results at steady state conditions. Figure 14 represents thermal gradients for the overall system and sectional details for the VIP spandrels.

Table 9. Thermal performance of various curtain wall spandrel configurations.

Description	Case 1	Case 2	Case 3
Linear thermal transmittance, ψ (W/mK)	0.23	0.22	0.19
1-D thermal transmittance, U_{1-D} (W/m ² K)	0.21	0.20	0.18
Effective thermal transmittance, U_{eff} (W/m ² K)	0.87	0.85	0.84
Lowest indoor surface temperature	13.8 °C	14.3 °C	14.3 °C
Lowest temperature factor	0.57	0.66	0.67

Figure 14. Temperature distributions of overall system and across VIP spandrel sections: (a) Case 1, (b) Case 2, and (c) Case 3.

As expected, the one-dimensional thermal transmittance (U_{1-D}) of VIP spandrel elements was lowest for Case 3 because of the additional layers of XPS. Nonetheless, the linear thermal transmittance (ψ) of the cases can be ranked in the order: Case 3 > Case 2 > Case 1. This is rightly attributed to the configuration of the sandwich VIP spandrel components. The effective thermal transmittance (U_{eff}), which factors thermal contributions of the framing component, followed a similar trend. It is worth noting that the center-of-spandrel U_{1-D} for VIP spandrels is more than four times lower than the reported U_{1-D} for the spandrel with 100 mm thick mineral wool insulation [20]. For all the spandrel cases, the lowest indoor surface temperature was found around the junctions of the spandrel element and framing component. The lowest indoor surface temperatures can be ranked as: Case 3 (14.3 °C) = Case 2 (14.3 °C) > Case 1 (13.8 °C). This is mainly due to the thermal insulation effect of the extra XPS layers for Case 2 and Case 3. Consequently, the lowest temperature factor (T_f) for the cases can be ranked in the order: Case 3 (0.67) > Case 2 (0.66) > Case 1 (0.57). T_f is a dimensionless quantity that expresses the difference between internal surface temperature and external temperature divided by the difference between internal

temperature and external temperature [70]. Practically, it can be used to assess the risk of surface condensation at the internal surface. The higher the T_f coefficient, the lesser the risk of surface condensation. Some countries have set limits for T_f , for instance, in France ($T_f > 0.52$ at reference conditions of $T_{out} = 0$ °C, RH = 80%, and $T_{in} = 18$ °C), Germany (T_f of 0.87), and Estonia (T_f of 0.55) [71], and in the UK and Netherlands a T_f of 0.50 is reported [60]. Thus, some researchers deduced that the definitive T_f value is not solely based on indoor moisture access, building purpose, and ventilation status but also on the prevailing local climate [34]. For Case 1, Case 2, and Case 3, the T_f values were all greater than 0.57, with the highest being 0.67 for Case 3. Therefore, surface condensation risk is not expected to occur. Concerning temperature distributions across VIP spandrels (Figure 14 bottom), the temperatures at the exterior and interior VIP surfaces were about -10.9 °C and 19.2 °C for Case 1, respectively. Similarly for Case 2, the exterior and interior VIP surface temperatures were around -9.8 °C and 19.3 °C, respectively. For Case 3, the temperature at the exterior surface of the outer lying 10 mm VIP was -9.9 °C, while that for the interior surface was 1.4 °C. For the inner lying 15 mm VIP, the temperatures at its exterior and interior surfaces were 2.5 °C and 19.3 °C, respectively. Based on boundary conditions and design factors used, the numerical results clearly show the thermal effects of the distinctive VIP spandrel configurations.

3.3. Thermal Performance of In Situ VIP Spandrels

The in situ VIP spandrel system's performance in a real-scale building has been monitored for over 1.5 years, and monitoring is still ongoing. Thus, for the sake of clarity, data for selected days will be presented in this manuscript. The results presented in this section are for representative cold winter days (4–6 February 2020).

3.3.1. Thermal Bridge Evaluation

Temperatures at the internal surface areas where the VIP spandrel intersected the Al frame (referred to as the VIP spandrel–Al frame thermal bridge junction, T_{tbj}) were measured and are summarized in Table 10.

Table 10. Summary of interior surface temperatures at the VIP spandrel–Al frame thermal bridge junction.

Description		Outdoor Air Temperature (°C)	Solar Radiation (W/m ²)	VIP Spandrel–Al Frame Thermal Bridge Junction Interior Surface Temperature (°C)		
				Case 1	Case 2	Case 3
Day	Max	−2.5	911.55	11.2	9.6	9.2
	Min	−8.8	1.43	1.7	2.6	3.2
	Avg	−4.4	581.48	6.8	6.3	6.1
	SD	1.92	285.25	3.71	2.79	2.32
Night	Max	−5.8		7.5	7.2	7.5
	Min	−10.9		−0.5	0.2	0.8
	Avg	−8.2		2.4	3.1	3.6
	SD	1.55		2.14	1.89	1.86

Max = maximum, Min = minimum, and SD = standard deviation.

Generally, by comparing temperatures at the VIP spandrel–Al frame thermal bridge junction (Table 10) with temperatures measured at the center of the VIP spandrels (Table 11), it can be deduced that average temperatures at thermal bridge junctions were higher than at the center of the spandrel. For instance, during the day, the T_{max} at the spandrel–frame thermal bridge junction was 2.3 °C, 1.2 °C, and 0.6 °C higher than the T_{max} at the center of the spandrel for Case 1, Case 2, and Case 3, respectively. The Case 1 spandrel was the one most affected by the thermal bridge junctions, as proved by the highest temperature differences coupled with the biggest deviations. Higher thermal bridge temperatures for Case 1 compared to Case 2 and Case 3 could also imply a higher magnitude of associated

heat fluxes due to the junction thermal bridges. On the contrary, the Case 3 spandrel had the lowest temperature deviations at the spandrel–frame thermal bridge junctions. The thermal bridge characteristics of the Case 2 spandrel were, on average, between Case 1 and Case 2. During the night, $T_{\min}$ at the spandrel–frame thermal bridge junction was 2 °C, 1.2 °C, and 1 °C lower than $T_{\min}$ at the center of the spandrel for Case 1, Case 2, and Case 3, respectively. Therefore, during daytime, maximum temperatures at the spandrel–frame thermal bridge junction areas were higher than at the center of the spandrels, while at night-time, minimum temperatures at the spandrel–frame thermal bridge junction areas were lower than at the center of the spandrels. This indicates that the existence of thermal bridges, particularly caused by the framing element, cannot be marginalized because the internal surface temperature profile could be influenced by outdoor conditions due to the existence of the spandrel–frame junction thermal bridges. Nonetheless, concerning resistance to spandrel–frame thermal bridges, the VIP spandrel cases can be ranked in the order: Case 3 > Case 2 > Case 1. The VIP spandrel configuration for Case 3, applying extra layers of XPS insulation, is the main contributing factor to its being the least affected by spandrel–frame thermal bridges.

Table 11. Summary of temperature at interior surfaces of the VIP and spandrel (measured at center position).

Description		Outdoor Air Temperature (°C)	Solar Radiation (W/m ²)	VIP Interior Surface Temp. (°C)			Spandrel Interior Surface Temp. (°C)		
				Case 1	Case 2	Case 3	Case 1	Case 2	Case 3
Day	Max	−2.5	911.55	8.7	8.5	8.5	8.9	8.4	8.6
	Min	−8.8	1.43	3.7	3.7	4	3.9	3.9	4.2
	Avg	−4.4	581.48	6.2	5.89	6.09	6.3	5.9	6.1
	SD	1.92	285.25	1.90	1.75	1.68	1.82	1.64	1.58
Night	Max	−5.8		7.4	7.2	7.6	7.5	7.3	7.7
	Min	−10.9		1.4	1.3	1.6	1.5	1.4	1.8
	Avg	−8.2		4.0	3.9	4.3	4.2	4.1	4.5
	SD	1.55		1.72	1.69	1.69	1.68	1.67	1.66

Max = maximum, Min = minimum, and SD = standard deviation.

3.3.2. Temperature Characteristics at Internal and External VIP/Spandrel Surfaces

The temperature evolution at internal VIP surfaces (inside the spandrel cavity) are plotted in Figure 15, while a summary including spandrel surface temperatures is presented in Table 11. The VIP internal surface is the surface of the panel facing indoors. Similarly, spandrel internal surface is the surface of the spandrel facing indoors.

The thermal performance of the spandrel alternatives was reasonable, however, with subtle but clear differences. From Table 11, it can be seen that, during the day, the Case 1 spandrel had the maximum interior surface temperature, while showing higher fluctuations, resulting in the highest deviation. This is likely because of high heat fluxes for the Case 1 spandrel compared to the other spandrel cases. Consequently, among the spandrel cases, the Case 1 spandrel was the most susceptible to fluctuating outdoor weather conditions. Conversely, the Case 3 spandrel had the least standard deviation facilitated by the highest minimum surface temperature. This is attributed to the superior thermal resistance of the Case 3 spandrel aided by the incorporation of XPS insulation within the spandrel to primarily restrict thermal bridge effects, which also improved the spandrel's insulation performance. The thermal behavior of the Case 2 spandrel was roughly between the Case 1 and Case 3 spandrels. Moreover, these specific characteristics reflected the thermal performance of the spandrel cases at night-time. Referring to Table 11, during the night (with outdoor temperatures ranging from −5.8 to −10.9 °C), internal surface temperatures for the Case 3 spandrel recorded the highest (maximum, minimum, and average) surface temperatures, which corresponded to an average of about 0.3 °C higher than those recorded for the Case 1 and Case 2 spandrels. The results are in agreement with

previous findings in the literature, allowing the conclusion that the double-layer VIP design had better insulation performance compared to the single-layer VIP design [72].

Figure 15. Temperature fluctuations at interior VIP surfaces inside the spandrel cavity.

Similarly, temperature fluctuations at external VIP surfaces (inside the spandrel cavity) are plotted in Figure 16, while a summary including spandrel surface temperatures is reported in Table 12.

Figure 16. Temperature characteristics at exterior VIP surfaces inside the spandrel cavity.

Table 12. Summary of temperature at the exterior surfaces of the VIP and spandrel (measured at center position).

Description		Outdoor Air Temperature (°C)	Solar Radiation (W/m ²)	VIP Exterior Surface Temp. (°C)			Spandrel Exterior Surface Temp. (°C)		
				Case 1	Case 2	Case 3	Case 1	Case 2	Case 3
Day	Max	−2.5	911.55	37	37.6	35.9	31.3	32.7	31.8
	Min	−8.8	1.43	−11	−10.7	−10.5	−11.3	−11.2	−11.2
	Avg	−4.4	581.48	20.8	20.9	19.9	16.8	17.5	17
	SD	1.92	285.25	14.75	15.54	14.61	12.83	13.22	12.85
Night	Max	−5.8		−7.5	−4.8	−6.3	−8	−8	−7.9
	Min	−10.9		−13.4	−13	−12.9	−13.8	−13.8	−13.6
	Avg	−8.2		−10.6	−10	−10	−10.9	−10.9	−10.7
	SD	1.55		1.73	1.95	1.81	1.72	1.72	1.74

Max = maximum, Min = minimum, and SD = standard deviation.

The VIP external surface is the surface of the panel facing outdoors. Likewise, the spandrel external surface is the surface of the spandrel facing outdoors. Generally, the temperature profiles at the external surfaces of the VIPs and spandrels fluctuated with outdoor conditions. Nonetheless, during the day, external surface temperatures (measured at the center of panel and spandrel surfaces) were higher than outdoor air temperatures due to solar radiation incident on a highly insulated surface. However, at night, external temperatures for VIP and spandrel surfaces were dictated by outdoor temperature conditions due to night sky radiation effects. The spandrels showed similar exterior surface temperature profiles.

3.3.3. Heat Losses/Gains

Table 13 reports and compares results for heat losses/gains for both experimental and numerical procedures. Both experimental and numerical computations showed a similar trend with a mean agreement margin of about 10%. One plausible reason for this difference is that, as a limitation, the simulation tool used could not factor the effect of the UV protective control film. Reasonably, the numerically computed heat losses were slightly higher. Nonetheless, the overall heat loss/gain of the cases can be ranked in the order: Case 3 < Case 2 < Case 1.

Table 13. Comparison of experimental and numerical results for heat loss/gain.

Description	Case 1	Case 2	Case 3
Experimental (calculated average), W	3.51	3.42	3.23
Numerical (steady state simulation), W	3.90	3.74	3.60

3.4. Durability of VIPs in Spandrel Cavities

Thermocouples were installed on the external and internal surfaces of the VIPs (inside the spandrel cavity) and on the spandrel surface to measure temperature variations. Throughout the months of monitoring, temperature measurements have been within the same range of values, indicating the integrity of the panels and proving that the performance of the VIPs is stable to date. In addition, the VIP integrated spandrels were configured in such a manner that the internal facing VIP surfaces can be visually seen through transparent glazing. It is well known that VIP failure is accompanied by bulges of the envelope material (caused by moisture uptake), which is quite visible even in an opaque building façade. To date, no such phenomenon has been observed. Finally, IR thermographic investigations were conducted from time to time. Figure 17 displays IR thermal images taken from the interior on 28th June 2019 at mean indoor relative humidity and temperature conditions of about 55% (± 5) and 24 °C (± 1) respectively. The emissivity for the measurements was 0.92. Generally, the mean spandrel surface temperature was

lower than for the frame temperature. Noticeable areas of heat loss or gain were observed along the edges of the aluminum frames, which agrees well with the results presented in Section 3.3. The IR images also show that the VIPs performed satisfactorily with no failure.

3.5. Further Reflections

Regarding the discussed results for any performance index, Case 2 often showed average characteristics, with Case 1 and Case 3 presenting extremes. Case 1 was particularly easy to fabricate due to its relatively simple design. Mainly due to its single-layer VIP configuration, Case 1 had the highest linear thermal transmittance and consequently the highest effective U -value, accompanied by a higher thermal bridge at the spandrel–Al frame junctions. In addition, its tolerance for surface condensation was not comparable to Case 2 and Case 3, as evidenced by the lowest indoor surface temperature and temperature factor. Although satisfactory, under steady state conditions and very high relative humidity conditions, surface condensation could occur, theoretically. Conversely, Case 3 showed the strongest case for resistance against surface condensation. It is worth noting that the thermal performance of Case 2 and Case 3 VIP spandrels was almost comparable. However, boosted by a double-layer VIP configuration, together with face-covering XPS layers, Case 3 had the lowest one-dimensional U -value. Both experimental assessments and numerical computations proved that the outer lying VIP protected the inner lying VIP from fluctuating and direct outdoor conditions, particularly soaring temperatures due to solar radiation. This resulted in an average temperature difference of about 15 °C according to experimental results and 12 °C according to numerical computations. The double-layer design coupled with the XPS face coverings raised the temperature of the VIP surface, which is a phenomenon that restricts moisture transport. This observation was unique to Case 3. In addition, the Case 3 spandrel showed the best resistance against spandrel–Al frame junction thermal bridges and related heat losses or gains. Based on the study conditions and results, it can be deduced that Case 3 is the most improved configuration for the integration of VIPs in curtain walls as spandrel insulation. The only downside of Case 3 is that, due to its multilayered design, it is not the easiest configuration to fabricate.

Figure 17. Cont.

Figure 17. IR thermal images. (a) Case 1; (b) Case 2; (c) Case 3.

3.6. Limitations and Challenges

For VIP enclosures, it is important to know the conditions that the panels can be subjected to in real applications. Temperature and moisture transport have been identified in the literature as some of the key mechanisms driving the aging of VIP. So, an idea of the prevailing hygrothermal conditions, especially inside the spandrel cavity, are also necessary to design a suitable scheme for VIP integration into curtain wall spandrels. However, most humidity measuring apparatuses are bulky and cannot easily fit on the surface of the VIP within the slim space of the spandrel cavity. So, for this study, hygrothermal conditions outside the VIP spandrel were easily measured, but only the temperature inside the VIP spandrel was assessed. This challenge calls for more robust VIP spandrel designs that can accommodate the size of humidity measuring tools without compromising the durability of the VIP or the overall system. Alternatively, small sized humidity testers could also be suitable solutions. Secondly, various approaches can be used to evaluate the durability of

VIPs inside a spandrel cavity. The quickest method involved using an IR camera which instantaneously produced thermal imaging for analysis. Nonetheless, the surfaces of the VIP spandrel, especially the exterior surface, was reflective because of solar radiation incident on the outer glass material. So, techniques were needed to overcome this challenge. The approach used in this study was to carry out the IR camera investigations after midday, when the sun azimuth was not highest. This approach was examined using a conventional brick façade and the results were found to be accurately repeatable. Finally, this study contributes substantially to VIP applications, particularly in curtain wall constructions. Nonetheless, due to convenience and cost factors, VIP spandrels were tested using standard window frames. Since this study concerned the thermal characterization of VIP spandrels and not their structural properties, this approach was conveniently adequate. Additionally, because of size limitations of the mockup test building facility, large size VIP spandrels could not be tested. Going forward, opportunities to evaluate the thermal and insulation performance of bigger sized VIP spandrels in large-scale curtain walls is needed.

4. Conclusions and Outlook

In this study, the thermal performance of curtain wall spandrels integrated with vacuum insulation panels (VIPs) as spandrel insulation has been investigated. To this purpose, three VIP spandrel alternatives were fabricated and tested in a mockup test building. Case 1 and Case 2 both utilized single-layer 25 mm VIP, whereas Case 3 used double-layered VIP of thicknesses 10 mm (towards outdoors) and 15 mm (towards indoors). All VIPs used in the study were composed of fumed silica core material encapsulated in a tri-metalized laminate envelope. IR thermography assessments proved that VIPs had been properly integrated in the system, with no defects or failure. During daytime, on a representative winter day (5th February 2020), the maximum temperatures ($T_{\max}$) at the spandrel–frame thermal bridge junction were 2.3 °C, 1.2 °C, and 0.6 °C higher than the $T_{\max}$ at the center of the spandrel for Case 1, Case 2, and Case 3, respectively. During the night, the minimum temperatures ($T_{\min}$) at the spandrel–frame thermal bridge junction were 2 °C, 1.2 °C, and 1 °C lower than the $T_{\min}$ at the center of the spandrel for Case 1, Case 2, and Case 3, respectively. Thus, the thermal bridge effect of the aluminum frame had the least effect on Case 3. This also indicates that the existence of thermal bridges, caused by the framing element, cannot be marginalized. Although the thermal characteristics of Case 2 was slightly comparable to Case 3, the latter showed the strongest resistance against surface condensation and the lowest thermal bridge effect at the spandrel–Al frame junctions, as well as the lowest heat losses or gains. This is particularly due to the Case 3 VIP spandrel's unique configuration, boosted by a double-layer VIP configuration together with an additional covering of a thin XPS layer.

Considering the technical space constraints related to the insulation of slim curtain wall spandrel systems, a VIP is a viable mode of insulation for a curtain wall spandrel due to its high thermal resistance per unit thickness compared to any other kind of insulation currently available. Therefore, the integration of VIPs as insulation for curtain wall spandrels can be seen as a tenable solution. Future research efforts on the subject could focus on investigating the energy performance and economic payback of bigger sized VIP spandrels in large-scale occupied curtain walled constructions. Finally, noteworthy limitations of experimental methods employed and future perspectives were discussed. This study will be interesting and provide new knowledge to building researchers, scientists and engineers, and general stakeholders in the building industry.

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