World Renewable Energy Congress 2020
26 - 30 July, 2021
Instituto Superior Técnico – Lisboa, Portugal.

THE SCOPE OF ADVANCED SMART VACUUM INSULATION TECHNOLOGIES FOR NET-ZERO ENERGY BUILDINGS

Saim Memon*[1]

[1] Solar Thermal Vacuum Engineering Research Group, London Centre for Energy Engineering, School of Engineering, London South Bank University, London, UNITED KINGDOM.
Email: S.Memon@lsbu.ac.uk; memonsaim@gmail.com Website: https://saimmemon.com

ABSTRACT

The conception at which, modernly, buildings are being aspired to achieve to be net zero-energy buildings (NZEBs) are broadly recognized. The heat loss through the windows of buildings is one of the factors contributing to high energy consumption for space heating ensuing in preventable carbon emissions. This talk/paper aims to present the novel constructions and performance attributes of the advanced smart vacuum insulation technologies that are: (i) Vacuum Glazing (VG), (ii) Triple Vacuum Glazing (TVG), (iii) Electrochromic Vacuum Glazing (EVG), (iv) Semi-transparent Photovoltaic Electrochromic Vacuum Quadruple Glazing (STPV-EVQG), (v) Translucent Vacuum Insulation Panel (TVIP), and (vi) Fusion-sealed Vacuum Glazing (FVG). The experimental results show VG achieved U-value of 0.97 $Wm^{-2}K^{-1}$, it was further reduced with TVG that achieved U-value of 0.33 $Wm^{-2}K^{-1}$. To control the solar heat gains from 0.41 (transparent mode) to 0.13 (opaque mode), ECG is constructed that achieved a U-value of 0.82 $Wm^{-2}K^{-1}$, it required electrical power of < 0.4 Wm^{-2}. To make it self-reliant, the semi-transparent PV glazing was integrated to EVG to supply the power and store the generated energy using NiMH battery, the STPV-EVQG achieved U-value of 0.7 $Wm^{-2}K^{-1}$. Due to the cost/edge-effects of hermetic glass edge-sealing materials, a new structured core transparent vacuum insulation panel (TVIP) is constructed, to accomplish insulation for the windows without edge sealing effects, that achieved U-value of 1.72 $Wm^{-2}K^{-1}$ but suffered the vacuum pressure degradation. The development of a novel cost-effective fusion seal for the construction of fusion-sealed vacuum glazing (FVG) is detailed that achieved the U-value of 1.24 $Wm^{-2}K^{-1}$.

Keywords: *Electrochromic, Fusion Seal, Semi-transparent Photovoltaics, Vacuum Glazing, Translucent Vacuum Insulation Panel,*

1. INTRODUCTION

The perception at which, currently, net zero energy building (NZEB) cannot be imagined without glass is because glazed windows play an imperious role of allowing natural daylighting but with repercussion of space-heating energy loss in cold-arid and space-cooling energy loss in hot-arid areas [1]. As such, evitable energy losses through glazed windows of buildings indirectly contribute to carbon emissions and, thus, impelling climate change. This is, particularly, due to an inadequate thermal transmittance value (U-value) of a glazing. In this paper, brief discussions of the scope of advanced smart vacuum insulation technologies developed by the author of this paper's collaborative contributions are presented. This paper presents the new and existing published findings by the author on i) Vacuum Glazing (VG), (ii) Triple Vacuum Glazing (TVG), (iii) Electrochromic Vacuum Glazing (EVG), (iv) Semi-transparent Photovoltaic Electrochromic Vacuum Quadruple Glazing (STPV-EVQG), (v) Translucent Vacuum Insulation Panel (TVIP), and (vi) Fusion-sealed Vacuum Glazing (FVG).

2. VACUUM GLAZING (VG)

A VG encompasses evacuated space between two sheets of low-e coated glass supported by pillars and edges sealed with hermetic (vacuum-tight) material [2]. Fig. 1a illustrates a design proposed in Memon et al (2019) [3] distinguished in terms of its composite edge seal made of $Sn_{56}Pb_{39}Zn_3Sb_1$- $AlTiSiCu_1$ wt%) (CS-186), it was considered as an alternative to indium-sealed VG. This composite hermetically sealed the edges of glass sheets, as exhibited in Fig. 1b, and obtained the vacuum pressure of 0.0042 Pa, as presented in Fig. 1c. The pump-out hole was also sealed with this composite as shown in Fig. 1d. Thus, predicted the U-value of 0.91 $Wm^{-2}K^{-1}$, as shown in the hot-side isotherm in Fig. 1e, and experimentally achieved 0.97 $Wm^{-2}K^{-1}$, as demonstrated in Fig. 1f. This method overcomes the cost issue, without compromising the scope of using tempered glass and soft coatings, but its composite edge seal owns 39% of Pb, complete details are published elsewhere [3].

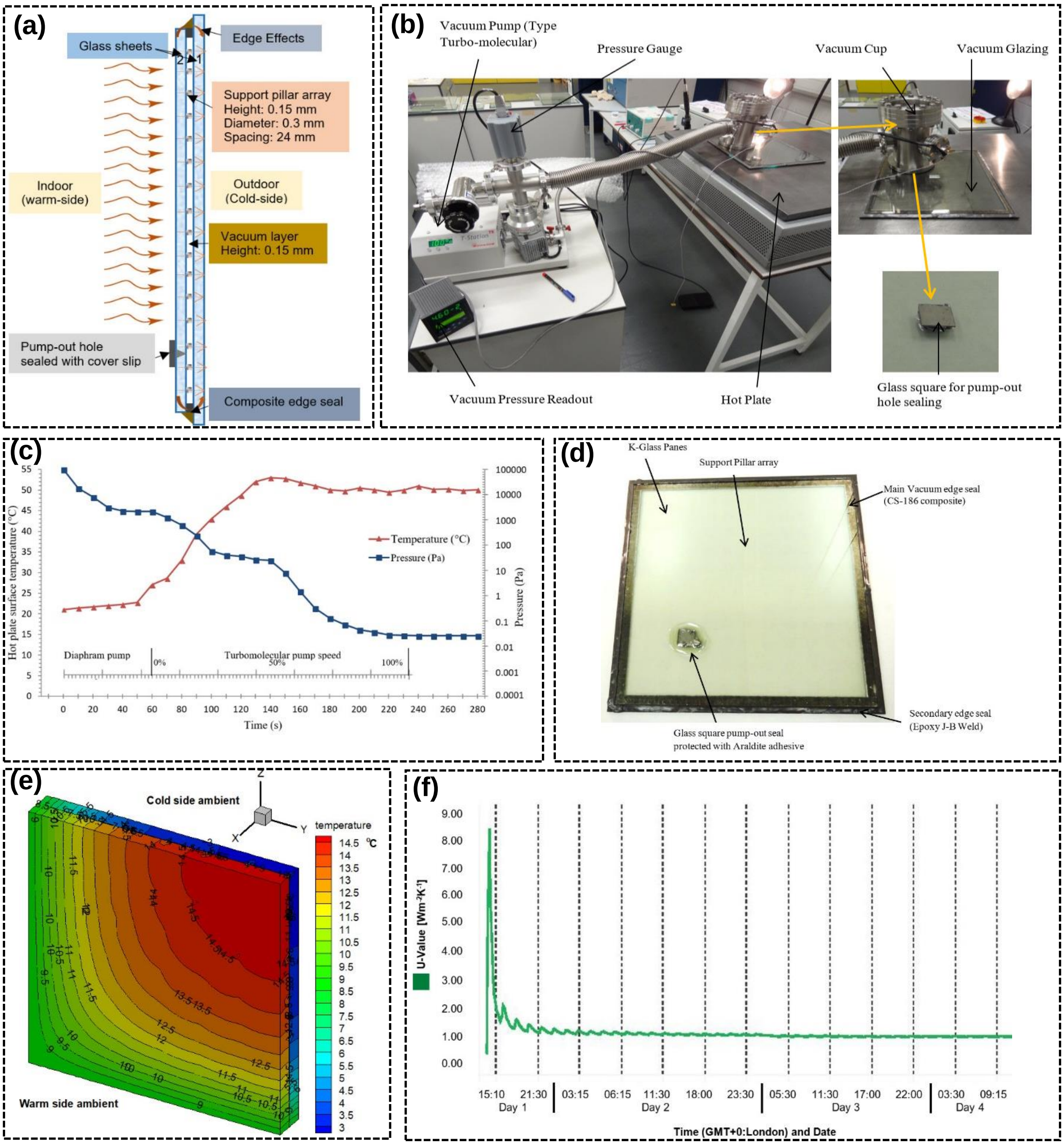

Fig.1. Illustrates VG (a) design diagram, (b) experimental setup for evacuation and pump-out hole sealing, (c) temperature/pressure profiles, (d) constructed VG, (e) FEM model for thermal performance predictions, and (e) experimental measurement of U value.

3. TRIPLE VACUUM GLAZING (TVG)

An evacuated cavity of a typical VG will not achieve ultra-high vacuum pressure under laboratory conditions. Thus, an extra layer of evacuated space allows an improvement to the thermal performance (U-value) <0.5 $Wm^{-2}K^{-1}$. The concept of TVG introduced in [4] and a new development of TVG, with the same composite edge seal utilised for VG, reported by Memon et al. (2015) [5]. Fig. 2a illustrates a design diagram of TVG and Fig. 2b displays the constructed TVG in which an evacuated pressure attained was 0.48 Pa as demonstrated in Fig. 2c. A 3D FEM model of the constructed TVG was developed and the hot-side isotherm is shown in Fig. 2d. The U value obtained was concluded to be 0.33 $Wm^{-2}K^{-1}$. It was predicted using the developed model that the thermal performance could be improved by shortening the width of the composite edge seal as the U value was compromised due to the edge effects [6]. This method was the first successful construction of TVG but it is complex-to-construct, mainly due to the need of precision involved in ultrasonically soldering the edges of glass sheets. Long-lasting endurance and gradation of vacuum pressure are mainly reliant on the edge-seal [7]. Thus, such stepped arrangement of glass sheets, as exhibited in Fig. 2a and Fig. 2b, and the level of precision required to ultrasonically solder the edges are developmental challenges. If cavity-vacuum pressure leaks then the thermal performance could deteriorate to 2.4 $Wm^{-2}K^{-1}$. Full details of TVG are reported elsewhere [5-7].

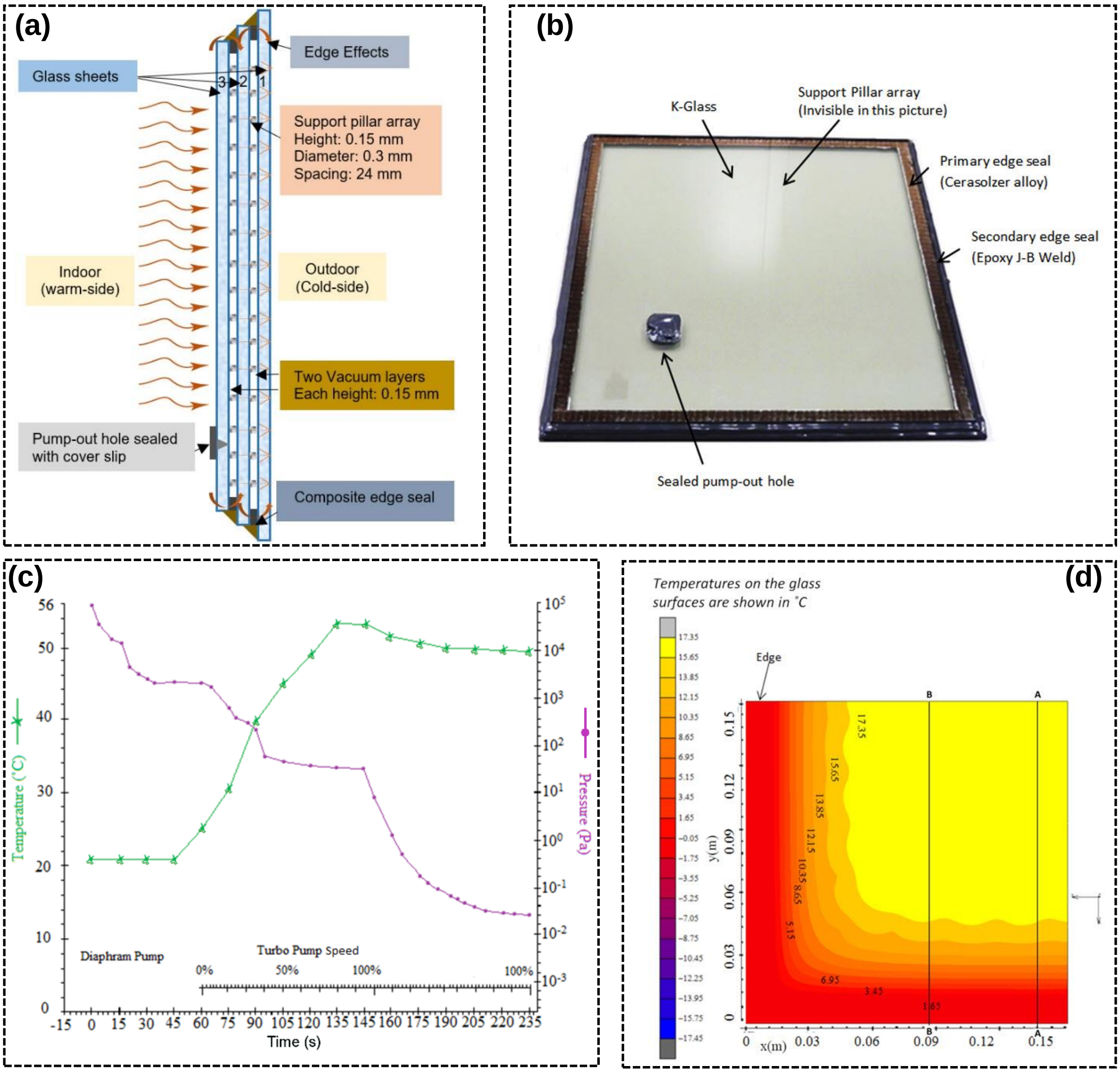

Fig. 2. Elucidates TVG (a) design diagram, (b) constructed sample, (c) experimental temperature/pressure profiles, and (d) 3D FEM model for thermal performance prediction.

4. ELECTROCHROMIC VACUUM GLAZING (EVG)

An idea of EVG was first reported in [8]. In this study, EVG is an integration of electrochromic film, made of WO_3 (Tungsten anhydride), with solder glass edge-sealed VG, made by SPACIA [9], to form a single component capable of performing the task of repelling heat escape from glazed windows and exhibit the smart characteristics of an electrochromic film, as illustrated in Fig. 3a, which is a reversible change from opaque to transparent by the application of low-electric field from power supply, as illustrated in the in Fig. 3b. This electrochromic film required electrical power of < 0.4 Wm^{-2} that allowed reaction of WO_3 with the electrons and charge balancing ions enabled its reverse transformation. Using the hot guarded box thermal testing method, following ISO 9869 standards, experimental measurements of U-value was performed for minimum 72 hours maintaining a minimum of 5°C. EVG achieved U-value of 0.82 $Wm^{-2}K^{-1}$, as shown in Fig 3c, which slightly better than VG. Although degradation occurs in electrochromic films caused by a variety of environmental factors, such as water but it hinges on on ways of chemical deposition and the advancement of electrochromic materials. A EVG is a promising solution for adaptive solar heat gain and shading control.

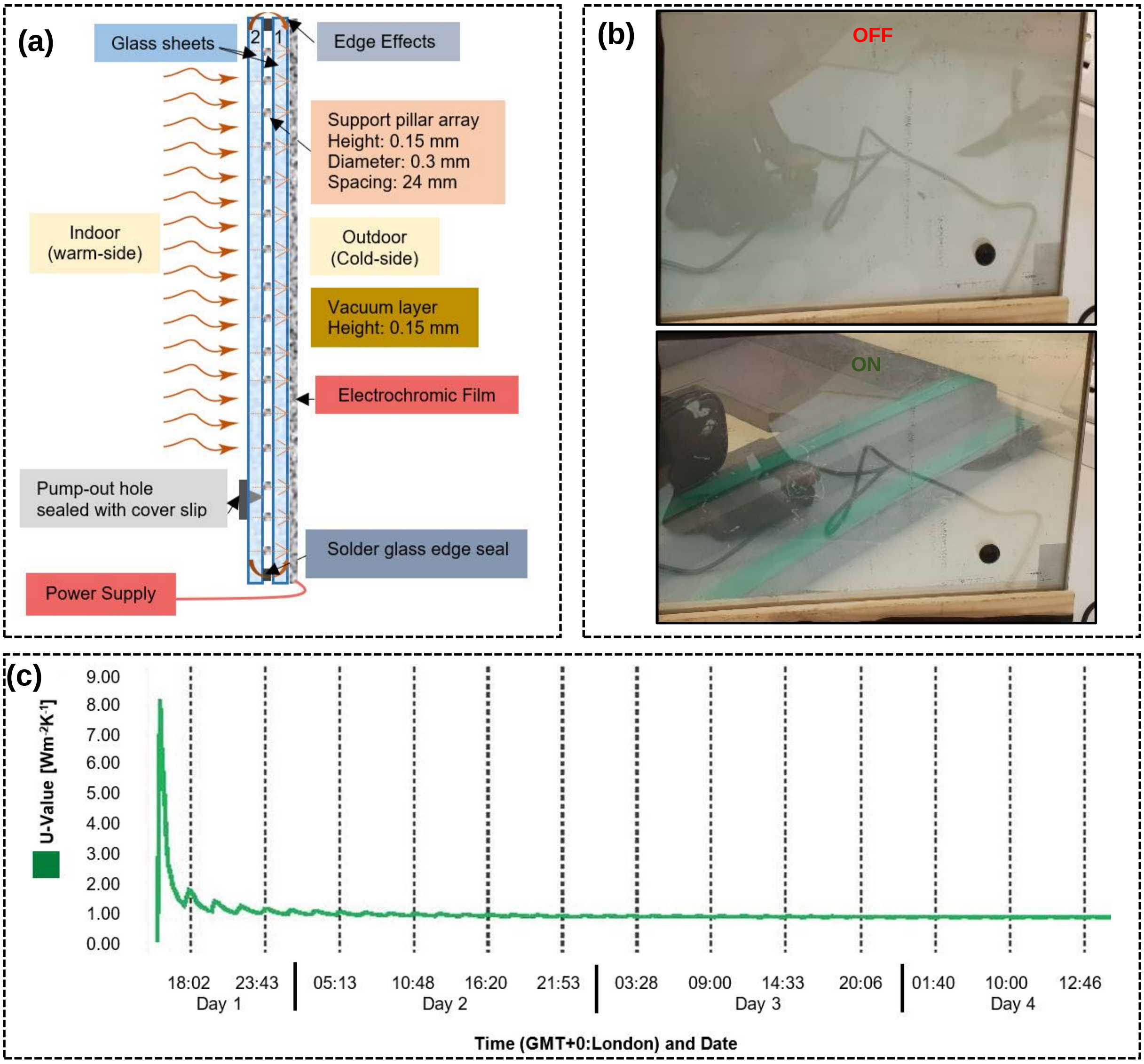

Fig. 3. Illustrates (a) design diagram of EVG, (b) reversible change from opaque to transparent by the application of low-electric field from power supply, and (c) experimental measurement of U value of EVG with heat flux meter.

5. SEMI-TRANSPARENT PHOTOVOLTAIC ELECTROCHROMIC VACUUM QUADRUPLE GLAZING (STPV-EVQG)

A STPV-EVQG conception is developed and patented(provisional) by the author of this paper and initial results published elsewhere [10]. This concept was developed with ultimate aim of bringing glazed windows to achieve (a) lower thermal transmittance U value, (b) excellent sound insulation, (c) automatic control of solar heat gains and control over transparency with electrochromic film and (d) With STPV, a reasonable generation of electrical power to operate electrochromic film and electronic device to control over WIFI for mobile user interface. The research in this area is ongoing. Fig. 4a shows design diagram of STPV-EVQG that integrated semi-transparent CdTe solar cell strings-based glazing to EVG. Initial investigations are presented here that is the assembled STPV-EVQG as shown in Fig. 4b. In which, the electrochromic film layer faces the internal environment, VG sandwiched in between and STPV on the outer part to allow the capture of the solar radiations. To make it self-reliant, the STPV CdTe solar cell strings-based glazing was integrated to EVG to supply the power and store the generated energy using NiMH battery, the STPV-EVQG achieved U-value of 0.7 $Wm^{-2}K^{-1}$ as shown in Fig. 4c.

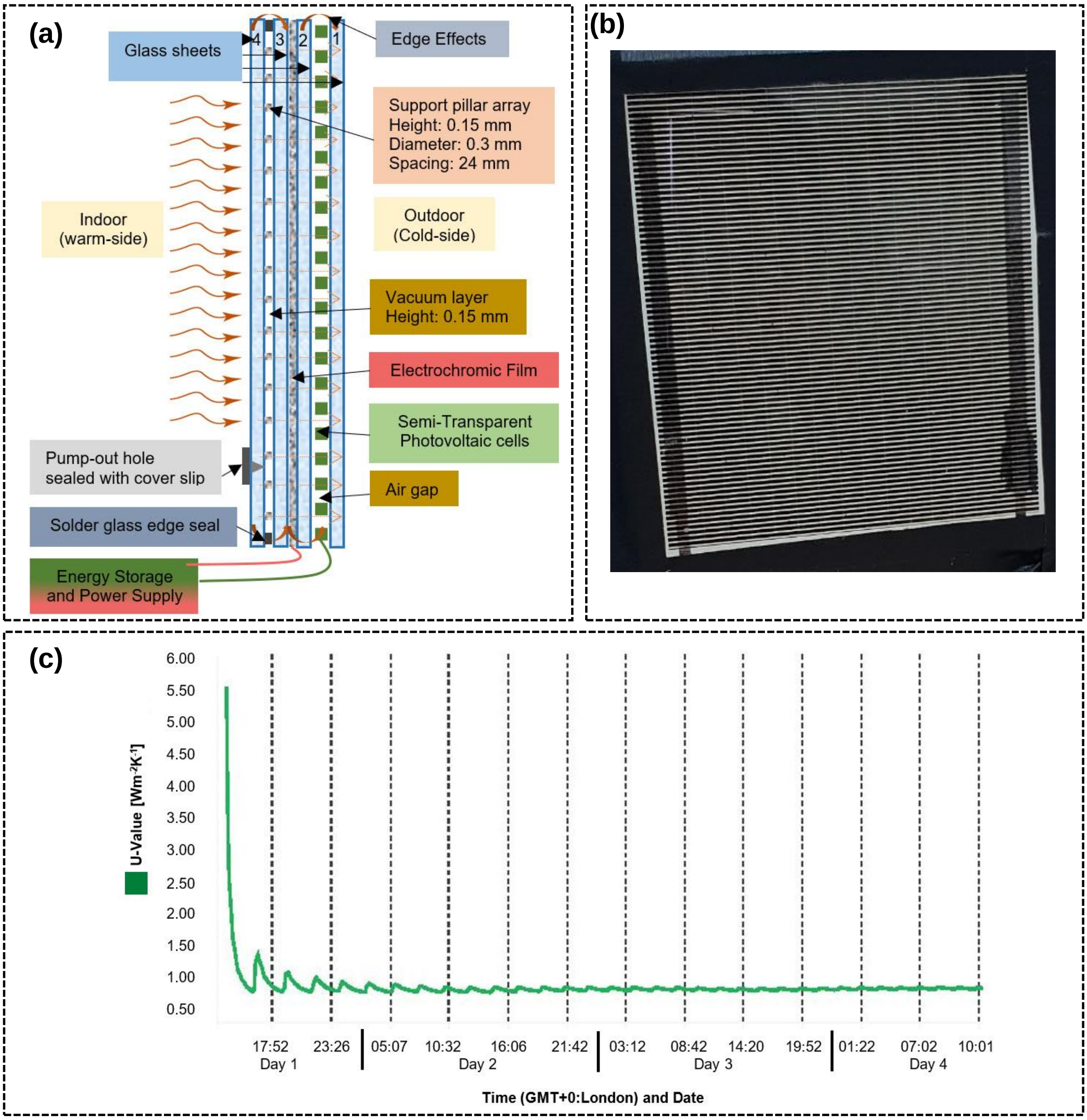

Fig. 4. Illustrates STPV-EVQG (a) design diagram, (b) assembly for initial experimentations, and (c) experimental measurement of U value with heat flux meter.

6. TRANLUCENT VACUUM INSULATION PANEL (TVIP)

Traditionally, VG suffers with the complex-to-construct and subsequent edge effects issues. A concept of TVIP [11] is eminent in terms of it has no edge effects, easier to construct, its cost is lower than VG and has lower thermal conductivity as compared to traditional opaque vacuum insulation panels (VIP) as shown in Fig. 5a. The TVIP has been a progressive development with a scope to replace existing insulated windows. This TVIP consists of a hollow-frame structured-core material encapsulated in a transparent multi-layered polymeric envelope and the spacers are 3D-printed, as shown in Fig. 5b [11]. The TVIP with frame and mesh spacers achieved thermal conductivity of $7 \cdot 10^{-3}$ $Wm^{-1}K^{-1}$ at a vacuum pressure of 1 Pa and the light transmittance of 0.88. Fig. 5c shows hot-side isotherm of TVIP as a result of the 3D validated FEM simulation. On one hand, TVIP has no edge effects and on the other hand 3D printed polymeric structure increases the thermal short-circuit around the central TVIP area. Thus, TVIP achieved 1.7 $Wm^{-1}K^{-1}$, which is slightly higher than VG as shown in Fig. 5d. Full details of TVIP are reported elsewhere [11]. However, the TVIP vacuum-sealed with the transparent gas barrier envelope which is made of PET (Polyethylene terephthalate), SE-PET (Silica Evaporated PET) , PA (Polyamide) and CPP (Cast Poly Polypropylene) layers. It means the problems of future gas leaks, outgassing and absorption of moisture challenges are remained that limit the practicality of this TVIP design.

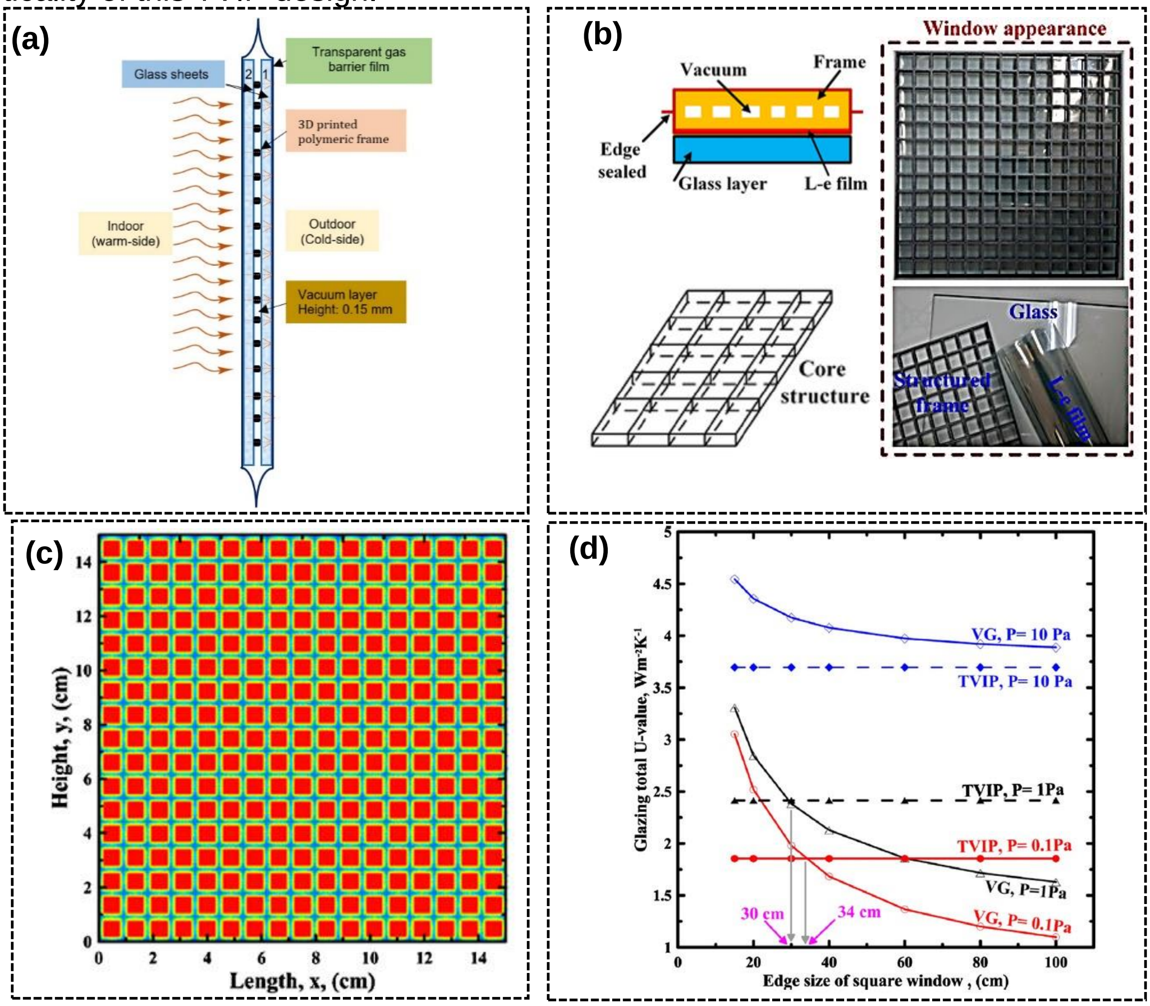

Fig. 5. Illustrates TVIP (a) design diagram, (b) hollow-frame 3D printed structured-core material encapsulated in a transparent multi-layered polymeric envelope, (c) hot-side isotherm of TVIP as a result of the 3D validated FEM simulation, and (d) comparative U value.

7. FUSION-SEALED VACUUM GLAZING (FVG)

Advancement in hermetic (vacuum-tight) edge-sealing materials has been one of the challenges since decades because of the existing cost, use of hazardous substance and complexity-to-construct issues in VG. A novel concept of glass-metallic textured layer for hermetic fusion edge-sealed VG invented, as shown in Fig. 6a, and reported in Memon & Eames (2020) [12] when Sn62-$B_2O_3$38 wt% fused with Sn90-In10 wt% alloy, as shown in Fig. 6b. The pump-out hole seal of FVG achieved at the hot-plate surface heat induction of 50±5˚C with the cavity vacuum pressure of $8.2 \cdot 10^{-4}$ Pa, as shown in Fig. 6c. The FVG is cost-effective (at least 70% reduction to edge-sealing materials such as indium, CS-186 and solder-glass cost), energy efficient (ultrasonic-soldering free), and Pd-free (hazardous-substance free) solution and has a potential for mass production. A validated 3D FEM predicted central and overall U value of FVG to be 1.03 and 1.24 $Wm^{-2}K^{-1}$, respectively. Fig. 6d shows the influence of edge effects due to the use of a 10mm wide fusion seal, the edge effects can be seen to extend to a distance of up to 72mm from the edge on the warm side surfaces. Overall, it can be seen that the FVG is implied to be the most low-cost solution for mass production. Full details are reported elsewhere [12].

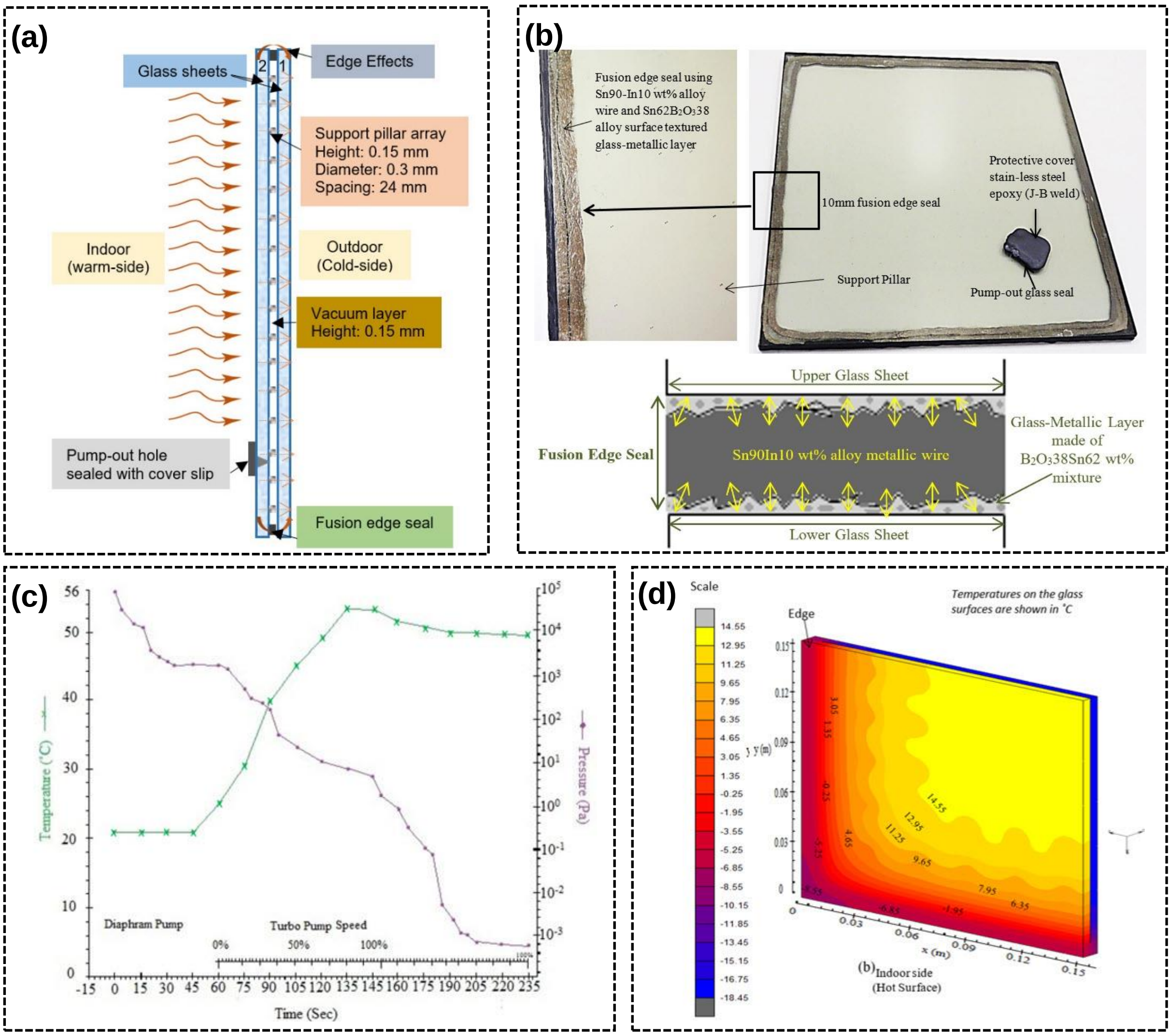

Fig. 6. Illustrates FVG (a) design diagram, (b) constructed photograph showing the fusion edge-sea composition, (c) experimental temperature/pressure profiles, and (d) 3D FEM simulated model for thermal performance prediction.

8. CONCLUSION

This paper briefly discussed the scope of advanced smart vacuum insulation technologies for NZEB. The results implicate that VG achieved U-value of 0.97 $Wm^{-2}K^{-1}$, it was further reduced with TVG that achieved U-value of 0.33 $Wm^{-2}K^{-1}$. To control the solar heat gains from 0.41 (transparent mode) to 0.13 (opaque mode), ECG is constructed that achieved U-value of 0.82 $Wm^{-2}K^{-1}$, it required electrical power of < 0.4 Wm^{-2}. To make it self-reliant, the semi-transparent PV glazing was integrated to EVG to supply the power and store the generated energy using NiMH battery, the STPV-EVQG achieved U-value of 0.7 $Wm^{-2}K^{-1}$. Due to the cost/edge-effects of hermetic glass edge-sealing materials, a new structured core transparent vacuum insulation panel (TVIP) is briefly discussed that achieved U-value of 1.72 $Wm^{-2}K^{-1}$ but suffered the vacuum pressure degradation. This paper briefly discussed novel concept of glass-metallic textured layer for hermetic fusion edge-sealed vacuum glazing (FVG) invented when Sn62-$B_2O_3$38 wt% fused with Sn90-In10 wt% alloy achieved vacuum pressure of $8.2{\cdot}10^{-4}$ Pa that achieved the U-value of 1.24 $Wm^{-2}K^{-1}$.

ACKNOWLEDGEMENTS

This work was supported by Daiwa Anglo-Japanese Foundation (12549/13360), EPSRC of the UK (EP/G000387/1), LSBU NSS Project grants.

REFERENCES

[1] Memon S. Katsura T. Radwan A. Zhang S. Serageldin AA. Abo-Zahhad EM. Sergey S. Memon, AR. Khan SW. Yang S. Jama HH. Hoseinzadeh S. Sara ID. Fang Y. Danilevski L. Isaev R. Kiani A. (2020). Modern eminence and concise critique of solar thermal energy and vacuum insulation technologies for sustainable low-carbon infrastructure, International Journal of Solar Thermal Vacuum Engineering, 1, 1, pp. 52-71. DOI: https://doi.org/10.37934/stve.1.1.5271. ISSN online (2716-6953).

[2] Memon S. (2013). Design, Fabrication and Performance Analysis of Vacuum Glazing Units Fabricated with Low and High Temperature Hermetic Glass Edge Sealing Materials. PhD Thesis. Loughborough University: UK. DOI: https://dspace.lboro.ac.uk/2134/14562

[3] Memon S. Fang Y. Eames PC. (2019). The influence of low-temperature surface induction on evacuation, pump-out hole sealing and thermal performance of composite edge-sealed vacuum insulated glazing. Renewable Energy, 135, pp. 450-464.

[4] Manz H. Brunner S. Wullschleger L. (2006). Triple vacuum glazing: Heat transfer and basic mechanical design constraints. Solar Energy, 80(12), 1632-1642.

[5] Memon S. Farukh F. Eames PC. Silberschmidt VV. (2015). A new low-temperature hermetic composite edge seal for the fabrication of triple vacuum glazing. Vacuum, 120, pp. 73-82.

[6] Memon S. (2017). Experimental measurement of hermetic edge seal's thermal conductivity for the thermal transmittance prediction of triple vacuum glazing, Case Studies in Thermal Engineering, 10, pp. 169-178. ISSN 2214-157X. DOI: https://doi.org/10.1016/j.csite.2017.06.002.

[7] Memon S. Farukh F. Kandan K. (2018). Effect of Cavity Vacuum Pressure Diminution on Thermal Performance of Triple Vacuum Glazing. Appl. Sci. 2018, 8(9), p. 1705.

[8] Fang Y. Eames PC. (2006). Thermal performance of an electrochromic vacuum glazing. Energy conversion and management, 47(20), 3602-3610.

[9] Memon S. (2014). Analysing the potential of retrofitting ultra-low heat loss triple vacuum glazed windows to an existing UK solid wall dwelling. Int. Journal of Renewable Energy Development, 3(3), 161-174.

[10] Radwan A. Katsura T. Memon S. Serageldin AA. Nakamura M. Nagano K. (2020). Thermal and Electrical Performances of Semi-Transparent Photovoltaic Glazing Integrated with Translucent Vacuum Insulation Panel and Vacuum Glazing, Energy Conversion and Management, 215, 112920.

[11] Katsura T. Memon S. Radwan A. Nakamura M. Nagano K. (2020). Thermal performance analysis of a new structured-core translucent vacuum insulation panel in comparison to vacuum glazing: experimental and theoretically validated analyses. Solar Energy, 199, pp. 326-346.

[12] Memon S. Eames PC. (2020). Design and development of lead-free glass-metallic vacuum materials for the construction and thermal performance of smart fusion edge-sealed vacuum glazing, Energy and Buildings. (in press)