

Cuce, Erdem; Cuce, Pinar Mert

Article

Optimised performance of a thermally resistive PV glazing technology: An experimental validation

Energy Reports

Provided in Cooperation with:

Elsevier

Suggested Citation: Cuce, Erdem; Cuce, Pinar Mert (2019) : Optimised performance of a thermally resistive PV glazing technology: An experimental validation, Energy Reports, ISSN 2352-4847, Elsevier, Amsterdam, Vol. 5, pp. 1185-1195, <https://doi.org/10.1016/j.egy.2019.08.046>

This Version is available at:

<https://hdl.handle.net/10419/243662>

Standard-Nutzungsbedingungen:

Die Dokumente auf EconStor dürfen zu eigenen wissenschaftlichen Zwecken und zum Privatgebrauch gespeichert und kopiert werden.

Sie dürfen die Dokumente nicht für öffentliche oder kommerzielle Zwecke vervielfältigen, öffentlich ausstellen, öffentlich zugänglich machen, vertreiben oder anderweitig nutzen.

Sofern die Verfasser die Dokumente unter Open-Content-Lizenzen (insbesondere CC-Lizenzen) zur Verfügung gestellt haben sollten, gelten abweichend von diesen Nutzungsbedingungen die in der dort genannten Lizenz gewährten Nutzungsrechte.

Terms of use:

Documents in EconStor may be saved and copied for your personal and scholarly purposes.

You are not to copy documents for public or commercial purposes, to exhibit the documents publicly, to make them publicly available on the internet, or to distribute or otherwise use the documents in public.

If the documents have been made available under an Open Content Licence (especially Creative Commons Licences), you may exercise further usage rights as specified in the indicated licence.



<https://creativecommons.org/licenses/by-nc-nd/4.0/>



Research Paper

Optimised performance of a thermally resistive PV glazing technology: An experimental validation

Erdem Cuce^{a,b,*}, Pinar Mert Cuce^{b,c}^a Department of Mechanical Engineering, Faculty of Engineering, Recep Tayyip Erdogan University, Zihni Derin Campus, 53100 Rize, Turkey^b Low/Zero Carbon Energy Technologies Laboratory, Faculty of Engineering, Recep Tayyip Erdogan University, Zihni Derin Campus, 53100 Rize, Turkey^c Department of Energy Systems Engineering, Faculty of Engineering, Recep Tayyip Erdogan University, Zihni Derin Campus, 53100 Rize, Turkey

ARTICLE INFO

Article history:

Received 25 May 2019

Received in revised form 10 July 2019

Accepted 22 August 2019

Available online xxxx

Keywords:

Windows

PV glazing

U-value

Thermal insulation

CFD

Co-heating test

ABSTRACT

Thermally resistive PV glazing (TRPVG), which is a recently developed technology for low/zero carbon buildings, is in the centre of interest worldwide as a consequence of multifunctional benefits of this novel product such as remarkably better thermal insulation performance compared to conventional PV and other fenestration technologies in market, clean energy generation, self-cleaning, sound insulation, UV and IR absorption, etc. In this study, thermal insulation performance of TRPVG is numerically optimised through a well-known CFD software ANSYS FLUENT. Optimisation is based on determining the optimum inert gas (argon) thickness (τ) behind the amorphous silicon (a-Si) PV module which yields to minimum overall heat transfer coefficient (U-value) for the entire structure. For a typical case ($\tau = 16$ mm), CFD results are compared with the experimental data derived from the standardised co-heating tests, and a good accordance is achieved. CFD results are also compared with the findings of thermal resistance approach, which assumes heat conduction takes place in the inert gas medium only. The results reveal that natural convection effects become notable for the values of τ over 10 mm. In other words, τ stands as a parameter that needs to be optimised for its values greater than 10 mm. For the typical TRPVG sample with $\tau = 16$ mm, the overall U-value from the CFD research is determined to be 1.19 W/m²K, which is in good agreement with the experimental data. The optimised value of τ for the TRPVG structure introduced is determined to be 20 mm, which guarantees the minimum total heat transfer rate (Q) across the glazing and maximum temperature difference between internal and external glazing surfaces.

© 2019 Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

1. Introduction

Remarkably rising trend of energy use in both developed and developing countries has raised concerns over limited reserves of energy resources, unavoidable dependence of fossil fuels and serious environmental effects such as ozone layer depletion, global warming and climate change (Cuce, 2014). As a consequence of this, sectoral energy consumption analyses are carried out to determine the most sensitive areas in terms of urgent mitigation of energy consumption figures and relevant greenhouse gas emissions at global scale (Santamouris et al., 2018). According to the findings of sectoral energy consumption analyses, buildings are of significant relevance to reduce global energy use through cost-effective and eco-friendly retrofit strategies. In 2008, building-oriented energy use is reported to be in the range of 20%–40%,

which already exceeds other some major sectors like transportation and industrial (Pérez-Lombard et al., 2008). In 2017, 40% of global energy use is ascribed to building sector, and today priority action plans are in the centre of interest for buildings which aim at meeting the latest low/zero carbon building standards (Cuce, 2017). Today, the greatest percentage of buildings in total energy use in the world can be explained with two main reasons, which are insufficient thermal resistance characteristics of existing building elements (Volf et al., 2018), and poor thermal and electrical performance figures of traditional energy systems commonly utilised in private, public and industrial buildings (Cuce and Cuce, 2017).

When a typical building envelope is considered, the areas where heat losses take place can be identified as external walls, windows, roof and ground (Cuce and Riffat, 2015b). It is also pointed out in literature that a significant part of energy losses in buildings occurs through glazed components of the building envelope (Gryning et al., 2013). In most of the developed and developing countries, windows are still responsible for about 40%–60% of total heat losses from building fabric (Cuce, 2019a).

* Corresponding author at: Department of Mechanical Engineering, Faculty of Engineering, Recep Tayyip Erdogan University, Zihni Derin Campus, 53100 Rize, Turkey.

E-mail address: erdem.cuce@erdogan.edu.tr (E. Cuce).

The outstanding role of windows in heat losses from building envelope can be associated with the poor thermal resistance figures of existing glazing structures in market, which are commonly utilised in buildings (Bouvard et al., 2018). For instance, double glazing as an example of multilayer glazing technology dominates the fenestration market, however overall heat transfer coefficient (U-value) of air or argon filled double glazing units is above $2.00 \text{ W/m}^2 \text{ K}$ in most cases (Cuce, 2018). When 2030 and 2050 low/zero carbon building standards released in recent building codes are taken into consideration, it is not difficult to assert that the existing fenestration products are incapable of meeting the aforesaid performance figures. As an example, glazed areas in the UK buildings are expected to have a U-value in the range of $1.20\text{--}1.40 \text{ W/m}^2 \text{ K}$ for the worst case, and among the commercialised products, only vacuum glazing can meet such a standard (Cuce and Cuce, 2016). Therefore, there is a noticeable stimulation into developing novel glazing technologies which are cost-effective, eco-friendly and suitable for retrofit applications.

When latest research on alternative fenestration technologies is gone through, PV integrated glazing structures are adopted as one of the most promising solutions owing to their remarkable role in mitigating heating and cooling demand of buildings as well as electricity generation (Gorgolis and Karamanis, 2016). However, the U-value range of PV glazing products is still very poor, which considerably affects the commercialisation process of this novel technology. The inadequate U-value is essentially a consequence of thermophysical properties of PV, window pane and edge seal materials (Cuce, 2019b). In this respect, there are various attempts in literature to improve the thermal resistance of PV glazing by integrating the unit with additional media such as inert gas, vacuum or phase change material. Vacuum is an effective phenomenon for enhancing the U-value of PV glazing especially when vacuum medium is optimised. For instance, Ghosh et al. (2018) experimentally evaluate the U-value and the solar factor of a semi-transparent PV-vacuum glazing. The U-value is determined to be $0.80 \text{ W/m}^2 \text{ K}$, and solar factor 0.42. Compared to PV double glazing, 66 and 46% reduction is reported in the U-value and solar factor, respectively. Support pillars are the main shortcomings of PV-vacuum glazing applications especially when they are made of metallic materials like stainless steel. They cause thermal bridging effects inside the glazing and deteriorate the overall U-value (Cuce and Riffat, 2015a). Chen et al. (2019) evaluate the potential enhancement in the U-value of PV-vacuum glazing when the support pillars are replaced with aerogel. A reduction of $0.33 \text{ W/m}^2 \text{ K}$ is reported in the U-value of PV-vacuum glazing, which is promising. In another research, Huang et al. (2018) justifies the practicality of PV-vacuum glazing systems in extreme climatic conditions because of their very low U-value range. Despite the unequivocal benefits of considering vacuum medium in PV systems, commercialisation is still a challenge for PV-vacuum glazing concept due to some reasons such as high cost, fragile structure and degradation of vacuum pressure with time (Memon et al., 2019).

Inert gas integrated PV glazing is also in the centre of interest as a consequence of its low cost and high thermal resistance in comparison to conventional air or argon filled double glazed windows. Similar to multilayer glazing technology, inert gas layers at certain thicknesses are reinforced behind the semi-transparent PV cells, and thermal insulation feature of the entire PV glazing structure is improved (Cuce, 2016). Heat insulation solar glass (HISG) is such a concept in which air and/or argon is utilised as an inert gas medium behind an amorphous silicon (a-Si) PV module to enhance the thermal insulation feature of conventional PV glazing products (Cuce et al., 2016). Two 6 mm thick air layers are separated by a reflective nano film, which provides extra thermal resistance and enables secondary energy generation by reflecting

the transmitted light back on the surface of a-Si PV module. For an entire glazing thickness of 28 mm, the average U-value of HISG is reported to be about $1.10 \text{ W/m}^2 \text{ K}$ (Cuce et al., 2015). In another research, HISG is found to be capable of producing over 40 W electricity from a PV module area of 0.66 m^2 for a solar intensity of 850 W/m^2 . The U-value is similar to the air case, and the unit is addressed to block 100% of incoming UV and IR light (Cuce et al., 2014).

PV glazing with inert gas medium and low-e coating provides an effective control of glazing transparency (Ghosh and Norton, 2018), which yields to notable reduction in solar heat gain coefficient (SHGC). Mitigation of solar radiation penetrating through the PV glazing is of vital importance especially in hot climatic regions for energy-efficient and eco-friendly reducing of cooling demand of buildings (Skandalos and Karamanis, 2015). In this respect, several works stress the potential use of PV glazing in building-integrated photovoltaic (BIPV) (Norton et al., 2011) and building-integrated photovoltaic/thermal (BIPVT) systems through facade and roof applications (Lee et al., 2017). Han et al. (2010) numerically evaluate the U-value of a double glazing equipped with a-Si PV cells and low-e coatings. The U-value is determined to be in the range of $2.40\text{--}2.80 \text{ W/m}^2 \text{ K}$ for the case of one and two low-e coatings. The reported U-value is surprisingly higher compared to the similar works in literature. This can be attributed to the thickness of air gap which is not optimised in the said research. Because, it is well-documented in literature that there is an optimum inert gas thickness which maximises the thermal resistance. For the greater values, natural convection effects remarkably deteriorate the U-value (Aydin, 2000). In literature, there are also some attempts on modelling the air gap inside quadruple, triple and double pane windows. In such works, natural convection in enclosures is numerically studied, which has the identical modelling characteristics with PV glazing having inert gas media. However, the inert gas gap needs to be extensively analysed to be able to make a generalisation related to research. For instance, Arici et al. (2015) model the heat transfer in different enclosures, however air gap is limited to 21 mm. The U-value remains constant after a particular gap width, but there is no further investigation for the greater values of air gap to observe the level of buoyancy effects thus the impact of air gap thickness on the U-value.

Within the scope of this research, a novel PV glazing technology called TRPVG is introduced first with illustrative sketch views and constructional details. TRPVG provides a significant number of advanced features compared to the previous works in literature in terms of thermal insulation, power generation, energy saving, cost and lifetime. As an important step of an elaborative research project (TUBITAK – 216M531), inert gas thickness within TRPVG is optimised through a well-known and reliable commercial CFD software. Different inert gas thicknesses are considered to date in PV glazing research notably in the range of 12–16 mm, however, there is no attempt so far for determining the optimum gap width. TRPVG prefers to use argon as inert gas behind the a-Si PV cells due to its remarkably better thermal resistance characteristics than air. Argon gap (τ) is varied from 1 to 27 mm, and natural convection inside inert gas medium is numerically modelled to achieve the overall U-value of the entire PV glazing. The U-value of TRPVG is reduced with the increasing argon thickness, however there is a turning point in the U-value as predicted. The numerical results are verified through calibrated hot box co-heating tests. Thermal resistance approach is utilised in some works in literature to obtain the U-value of glazing systems with inert gas medium. However, it needs to be noted that this approach can be considered only until a certain value of inert gas thickness. For the greater values, natural convection is expected to play a noticeable role in the overall U-value, which is also comprehensively analysed in this research for the first time in literature.

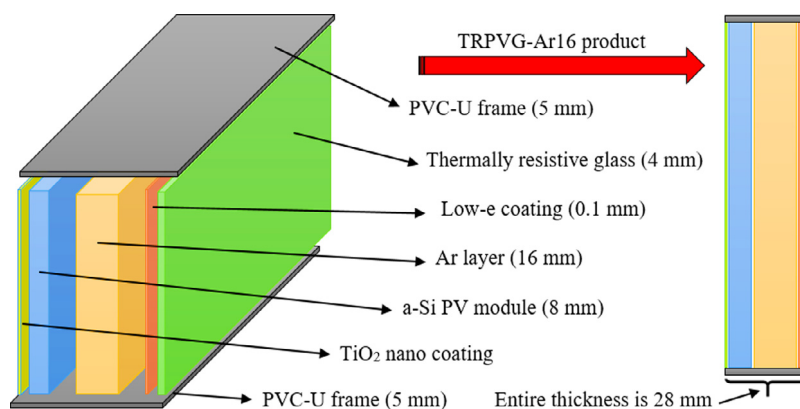


Fig. 1. TRPVG-Ar16 technology with structural and dimensional details (Cuce, 2019a).

2. Thermally resistive PV glazing (TRPVG)

PV glazing systems, in general, suffer from some essential performance parameters notably poor thermal resistance feature. The concept of TRPVG basically aims at improving thermal insulation feature of PV glazing systems through optimised inert gas medium and appropriate materials and coatings with ideal thermophysical properties. TRPVG is a recently developed PV glazing technology within the scope of a research project funded by TUBITAK. The technology can easily be distinguished from the conventional PV glazing products in terms of various aspects such as enhanced thermal insulation ability, which is competitive with even triple glazed windows; improved energy generation and energy saving potential owing to the nano reflective film and self-cleaning feature through TiO₂ nano coating on PV cells. Moreover, TRPVG has ability to block all of the UV and IR light content of incoming solar radiation. There are different TRPVG products devised, fabricated and tested within the scope of the research project. However, TRPVG-Ar16 concept is numerically and experimentally analysed in this study since it represents the reference design of TRPVG without any further improvements.

TRPVG-Ar16 is illustrated in Fig. 1 with the structural and dimensional details (Cuce, 2019a). In this reference design, argon width is considered to be 16 mm, and a novel thermally resistive window pane is preferred at the rear. The aforesaid window pane is also integrated with a low-e coating to enhance the thermal insulation feature of the design. The thermal conductivity of low-e coating is reported to be 1.20 W/m K, however, its influence on overall U-value of TRPVG-Ar16 is almost negligible due to its ignorable thickness. The thermally resistive window pane has a thermal conductivity of 0.96 W/m K, which is promising to overcome thermal bridging effects likely to occur in operation. Edge effects are of vital significance in such designs in terms of thermal bridging, hence appropriate edge seal materials need to be considered not to cause undesired conductive effects across the metallic dividers and support elements in PV glazing structures. In the design of TRPVG-Ar16, unplasticised polyvinyl chloride (PVC-U) is utilised for edge sealing and thermal insulation. PVC-U has a thermal conductivity of 0.19 W/m K, which is suitable for such applications. Semi-transparent a-Si PV cells are used in the design to provide visual and thermal comfort conditions. However, a-Si PV cells are not thermally resistive enough with a thermal conductivity of 1.50 W/m K. There is a TiO₂ nano coating on PV cells with dual functions. The TiO₂ nano coating both mitigates the reflection losses over PV cell surfaces and provides self-cleaning feature to the product, which is indispensable for tall buildings.

The total thickness of TRPVG-Ar16 is 28 mm, which can be considered slim and lightweight enough for retrofitting of current

Table 1

Thermophysical properties of main materials inside TRPVG-Ar16 (Cuce, 2019a).

	d (kg/m ³)	c _p (J/kg K)	k (W/m K)
Low-e coated window pane	2700	880	0.96
a-Si PV module	2330	703	1.50
Ar layer	1.6228	520.64	0.0158
PVC-U	1400	900	0.19

buildings. The technology is also an alternative fenestration product for new-built applications. For the standard test conditions (25 °C PV cell temperature, 1000 W/m² solar intensity), it can generate more than 100 W electricity. The unit cost of the product is about 200 €/m², which is comparable with traditional argon filled double glazed windows in market. The thermophysical properties of the main materials utilised in the fabrication of TRPVG-Ar16 are given in Table 1.

3. CFD research

Inert gas thickness inside TRPVG is numerically optimised in this research via a reliable CFD software ANSYS FLUENT (ANSYS FLUENT, 0000). For the geometry construction, GAMBIT software is preferred, which is in good agreement with ANSYS FLUENT. For the actual material and operational parameters, natural convection in the enclosure filled with argon behind a-Si PV cells is numerically analysed. The modelling research is carried out for the argon width from 1 to 27 mm. Geometry construction and analyses are repeated for each case, and the results are comprehensively evaluated. 2D approach is considered since it is effective enough for such a research. In the CFD analyses, TRPVG is subjected to forced convection from its external surface, and natural convection through the indoor. Adiabatic boundary conditions are assumed to take place at the edges, however, heat conduction inside the edge seal is taken into consideration. Following the selection of pressure-based solver, PRESTO approach is adopted in the research for an accurate modelling of heat transfer in the enclosure. Quadratic mesh is preferred in the analyses with convergence criteria of 10⁻⁴ for continuity, momentum and energy equations. To be able to achieve the identical convergence tendency, under-relaxation factors are carefully controlled during the iteration stages. Density, thermal conductivity and specific heat capacity of environmental chamber air are taken to be 1.225 kg/m³, 0.0242 W/m K and 1006.43 J/kg K, respectively. Indoor air temperature is selected to be 25 °C whereas it is 5 °C for outdoor air to be able to represent the winter case. On the other hand, heat convection coefficient for indoor and outdoor environment is assumed to be 5 and 25 W/m² K, respectively. The U-value analysis is conducted through the numerical data achieved from ANSYS

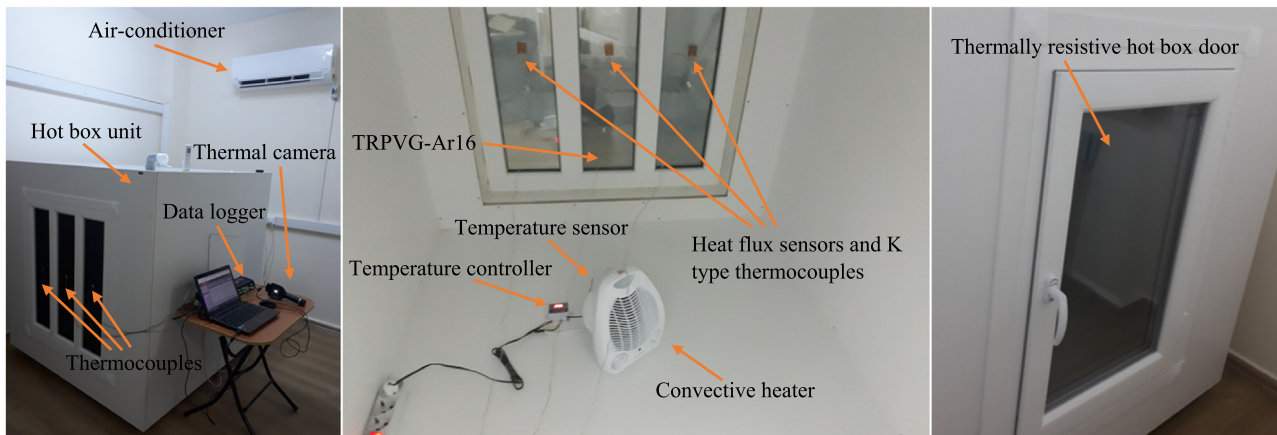


Fig. 2. Hot box, environmental chamber, measurement systems and co-heating test details of TRPVG-Ar16.

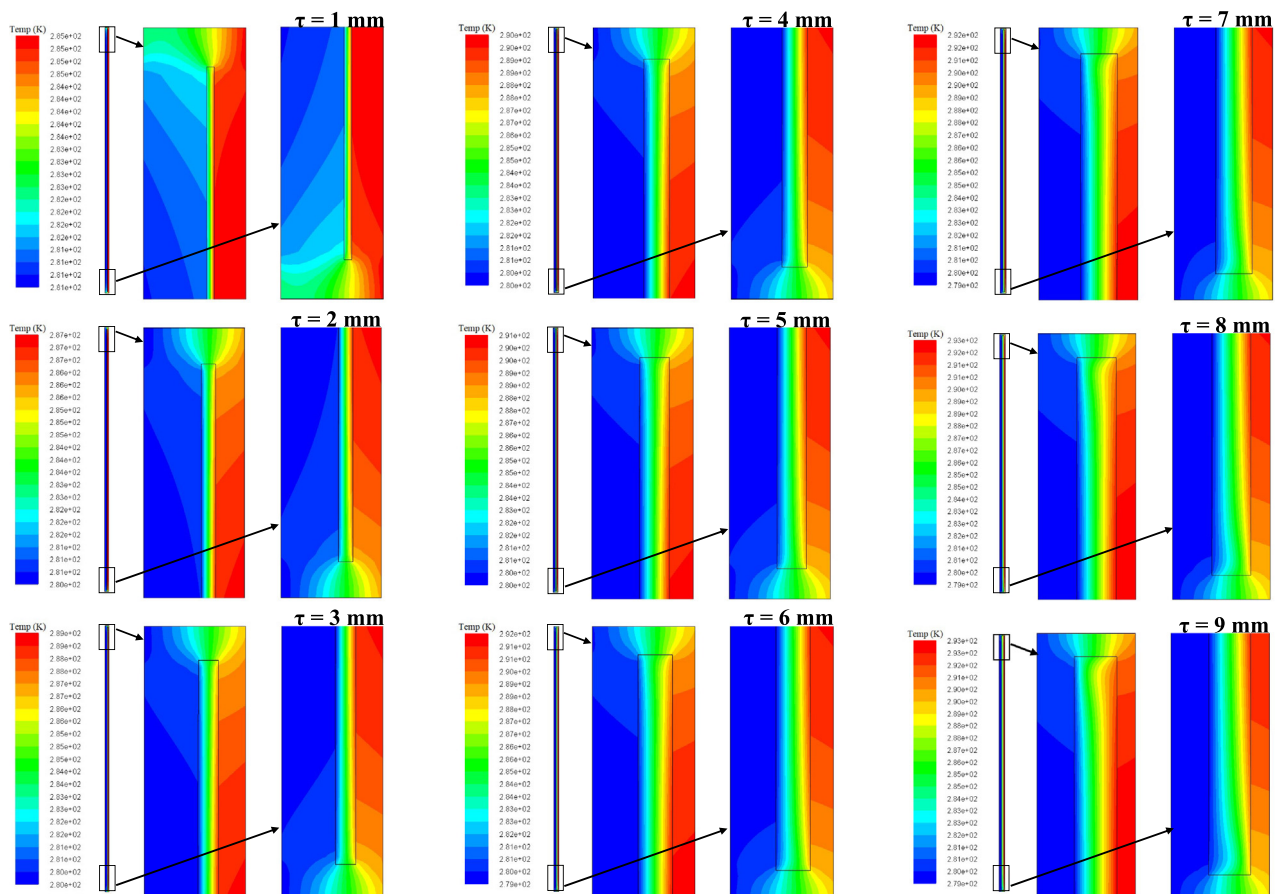


Fig. 3. Static contours of temperature inside TRPVG for the values of inert gas thickness (τ) from 1 to 9 mm.

FLUENT. In this respect, total heat transfer rate from TRPVG is determined via the reports section of the software. Through the surface integrals interface, average internal and external surface temperatures are achieved. Dividing the total heat transfer rate by the temperature difference across TRPVG and PV module area, the numerical U-value is specified.

4. Co-heating tests in environmental chamber

Within the scope of the research, CFD analyses of different inert gas thicknesses are verified through a standardised co-heating test methodology. The tests are carried out in Low/Zero

Carbon Energy Technologies Laboratory at Recep Tayyip Erdogan University. A calibrated hot box unit, which is illustrated in Fig. 2, is utilised for the co-heating tests. One side of the hot box is equipped with different TRPVG technologies including TRPVG-Ar16, and a transparent highly thermally resistive door from PVC and argon is positioned on the opposite side as shown. 100 mm thick XPS foams are located between two 20 mm thick particleboards to guarantee the adiabatic boundary conditions on the rest surfaces. A 1000 W convective heater connected to a temperature controller system is placed on the ground of hot box to achieve a constant indoor air temperature of 25 °C. Environmental chamber temperatures are varied from 5 to 15 °C

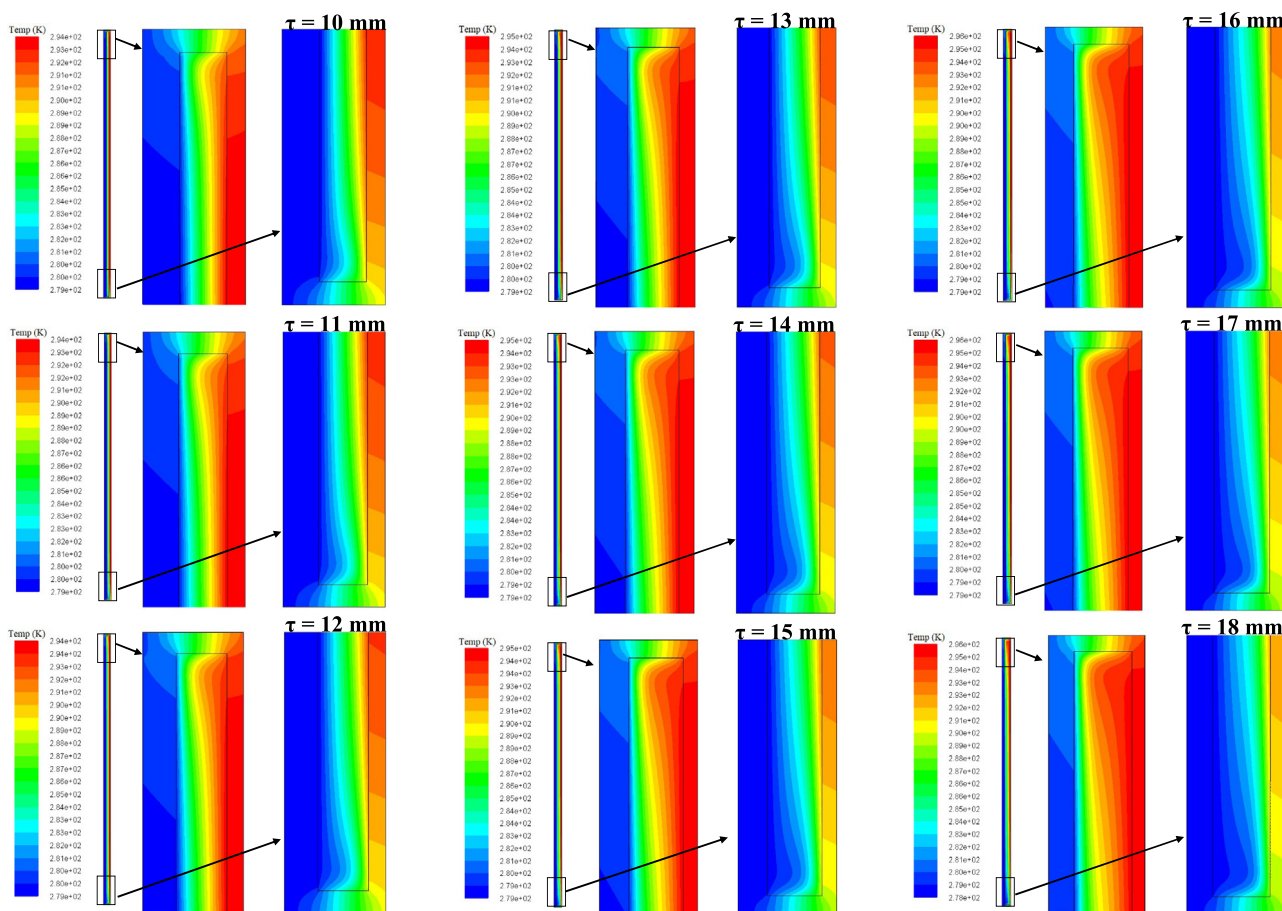


Fig. 4. Static contours of temperature inside TRPVG for the values of inert gas thickness (τ) from 10 to 18 mm.

to evaluate the impacts of dynamic conditions on the U-value of TRPVG-Ar16. Highly sensitive Omega HFS-4 thin film heat flux sensors are used in the tests for heat flux measurements across the PV glazing. The said heat flux sensors have a nominal thickness of 0.18 mm and already include K type thermocouples, thus no additional sensors are placed internally for internal PV surface temperature measurements. For the external surfaces, standard K type thermocouples with Teflon cover from Tekon Company are utilised. Hot box and chamber temperatures are also measured via the same type of sensors. Data collection is performed time-dependently via DT85 data logger from DataTaker Company. DT85 data logger has a dual channel isolation technology with two serial smart sensor ports and up to 48 analog (± 30 V) sensor inputs. Thermal imaging is also done in the research to check the potential thermal bridges inside TRPVG-Ar16, and for this purpose, FLIR E6 thermal imaging camera is utilised. The FLIR E6 utilises an uncooled microbolometer detector. IR resolution is given to be 160×120 pixels.

5. Results and discussions

Argon as an inert gas is of vital importance for the average U-value of TRPVG, hence the thickness of argon gap within TRPVG needs to be optimised in terms of maximum thermal resistance and minimum product cost since argon is remarkably more expensive compared to ordinary air. In this respect, argon gap (τ) is varied from 1 to 27 mm, and the static contours of temperature are obtained numerically. In order to illustrate the change in heat transfer mode precisely inside the argon medium, the analysis of temperature contours for steady-state conditions is split into

three parts as τ values from 1 to 9, 10 to 18 and 19 to 27 mm as depicted in Figs. 3, 4 and 5, respectively. It is understood from the behaviour of argon for the τ values from 1 to 9 mm that the heat transfer in the enclosure is dominated by conductive effects. Buoyancy forces are found to be almost negligible for the first set of τ values. Conductive effects, in other words, can be ascribed to the validity of thermal resistance approach in calculating the overall U-value of the product. By assuming the thermal conductivity of argon equals to 0.0158 W/m K, and the change of this value with the said temperature range across TRPVG is negligible, the U-value from the CFD analyses is determined to be 14.028 W/m² K whereas it is 13.897 W/m² K from the thermal resistance approach for $\tau = 1$ mm. This U-value is enhanced with the increasing argon width, and for $\tau = 9$ mm, the aforesaid U-values are calculated to be 1.837 and 1.729 W/m² K for CFD and thermal resistance approach, respectively.

For the second set of τ values from 10 to 18 mm, natural convection effects inside the inert gas medium are much more noticeable, and thermal resistance approach is observed to be no longer acceptable. Temperature difference across TRPVG still has a rising tendency, and total heat transfer rate from the PV glazing continues to reduce. In other words, argon still behaves as a thermal insulator for the said range. According to the CFD results, the U-value of TRPVG is enhanced from 1.669 to 1.153 W/m² K when τ is increased from 10 to 18 mm. The U-value is expected to be about 0.871 W/m² K for $\tau = 18$ mm if argon is assumed to be stagnant within the enclosure. The deviation between the values prove the natural motion of argon behind the PV glazing. For the third set of τ values from 19 to 27 mm, natural convection dominates in the enclosure, and the velocity

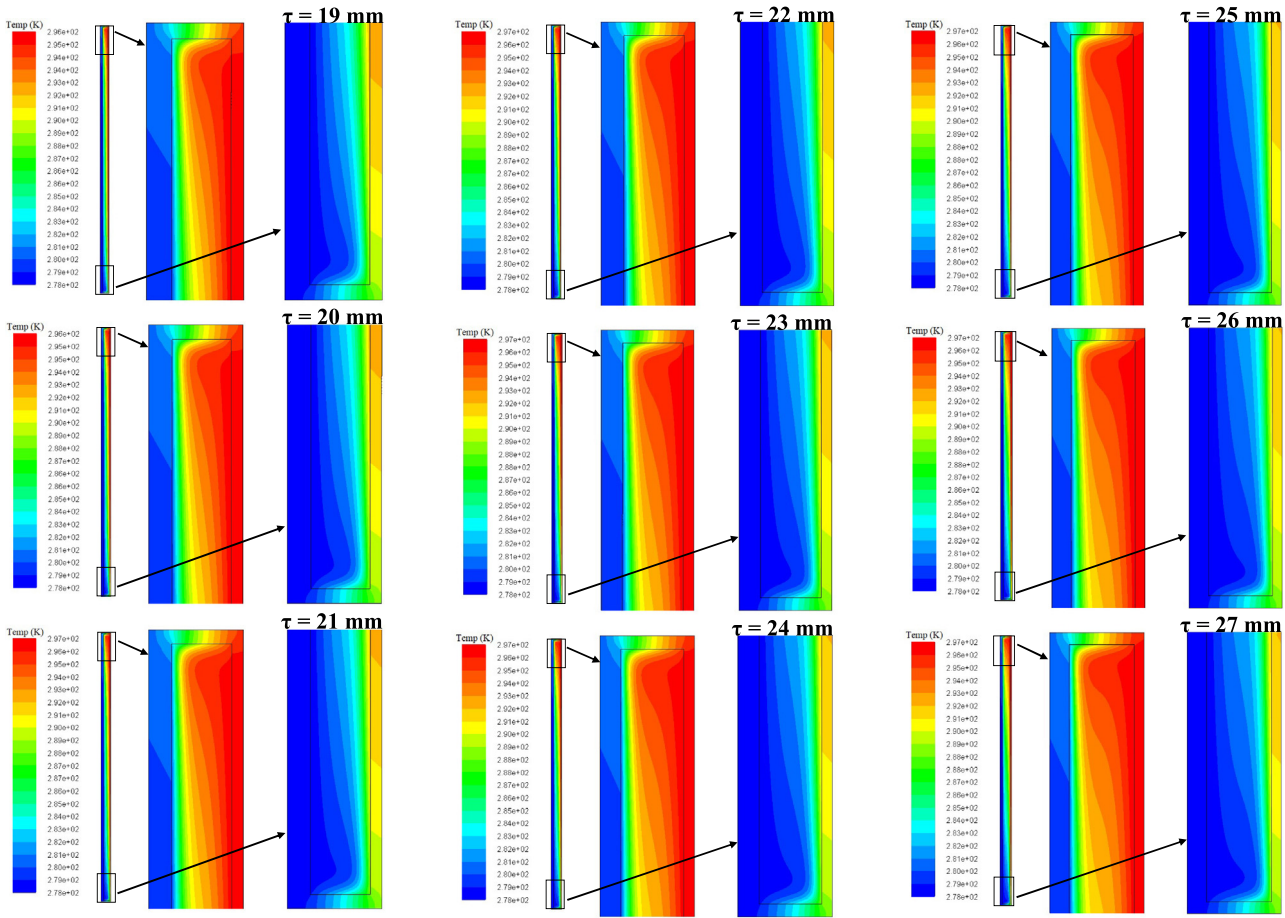


Fig. 5. Static contours of temperature inside TRPVG for the values of inert gas thickness (τ) from 19 to 27 mm.

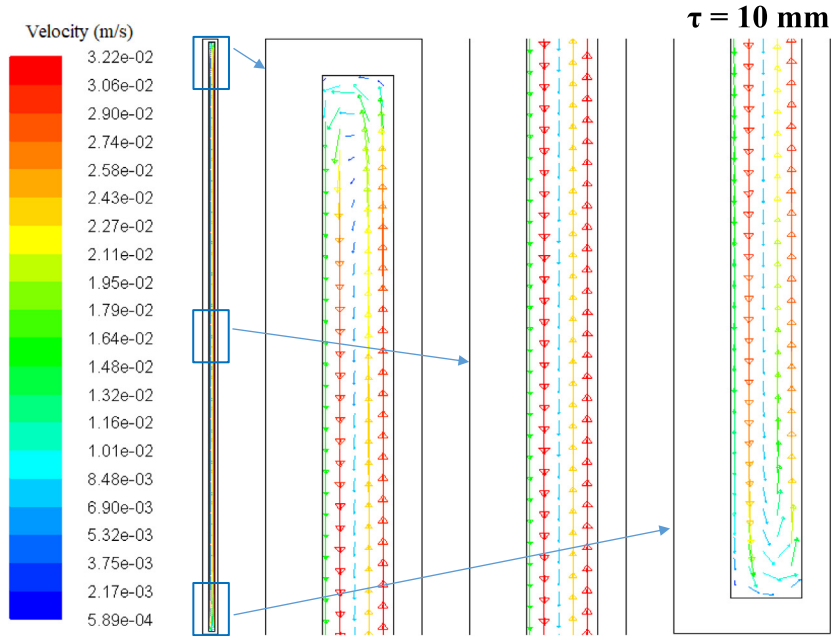


Fig. 6. Negligible velocity vectors and natural convection effects inside TRPVG for $\tau = 10$ mm.

magnitudes are much more considerable. This can be justified through the velocity vectors for the cases of $\tau = 10$ and 20 mm given in Figs. 6 and 7, respectively. Maximum velocity magnitude is determined to be 0.0322 m/s for $\tau = 10$, whereas it is

0.125 m/s for $\tau = 20$. Another significant point for the said τ range is the turning point of temperature difference (ΔT) across the PV glazing and total heat transfer rate (Q). This is clearly demonstrated in Figs. 8 and 9 for ΔT and Q , respectively. When

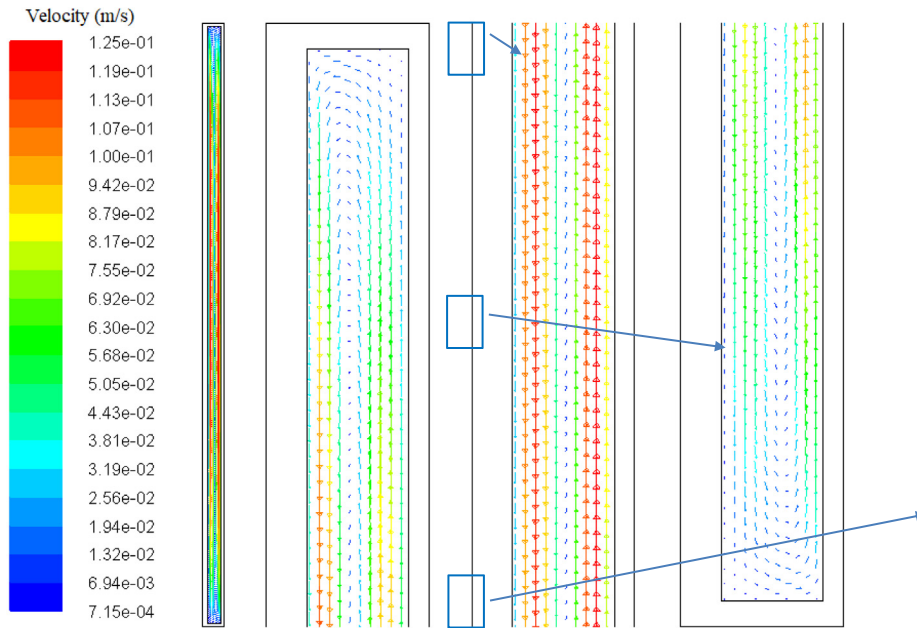


Fig. 7. Remarkable velocity vectors and natural convection effects inside TRPVG for $\tau = 20$ mm.

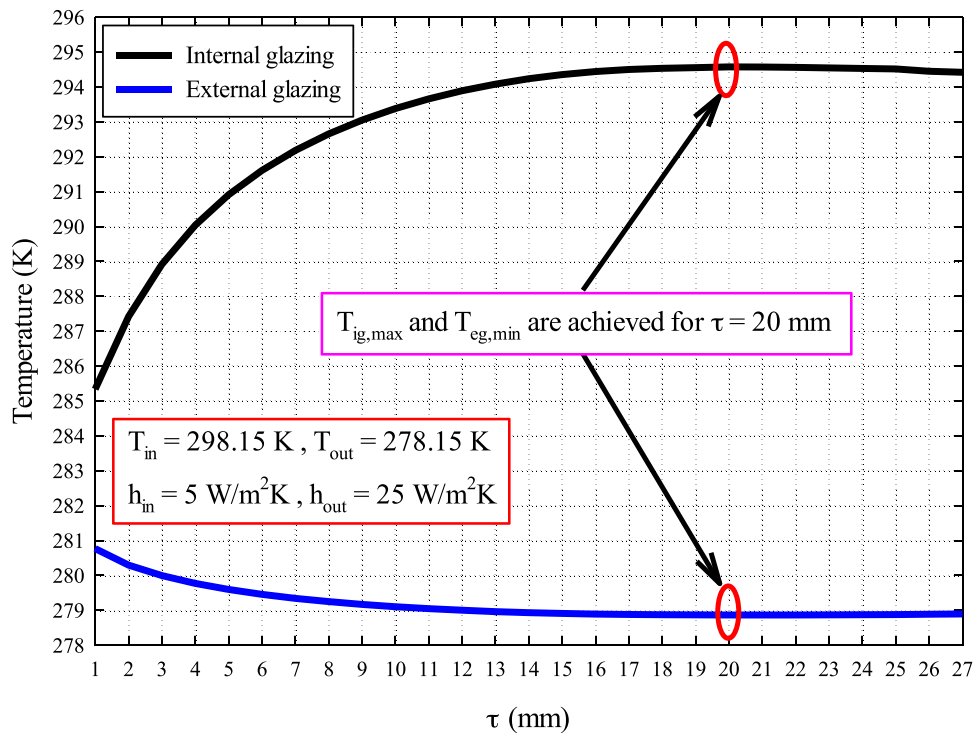


Fig. 8. Internal and external glazing temperatures of TRPVG for the different values of inert gas thickness (τ).

internal and external glazing temperatures (T_{ig} , T_{eg}) are plotted as a function of τ , it is observed that the maximum internal ($T_{ig,max}$) and minimum external glazing temperature ($T_{eg,min}$) values are achieved for $\tau = 20$ mm. In this respect, maximum ΔT is reported to be 15.712 °C for the said τ value. A similar scenario takes place for the heat dissipation. For the minimum U-value from TRPVG, minimum heat transfer is expected to occur across the glazing, and that is observed again for $\tau = 20$ mm with 16.259 W. This is a natural phenomenon arising from Newton's cooling law. Finally, the numerical U-value is calculated as shown in Fig. 10 for different values of τ , and the minimum U-value

is achieved for $\tau = 20$ mm with 1.137 W/m² K. As previously mentioned, thermal resistance approach is no longer valid after a certain value of τ . The turning point in the U-value is proved with the zoom image as depicted.

Following the demonstration of CFD results, hot box measurements are conducted for accuracy justification for a period of 3000 min, and data triggering is performed per minute. In other words, 3000 data are collected for each parameter analysed in the research. In this respect, first of all, internal and external glazing temperatures are plotted during the test period as well as temperature difference across TRPVG-Ar16 as shown in Fig. 11. The

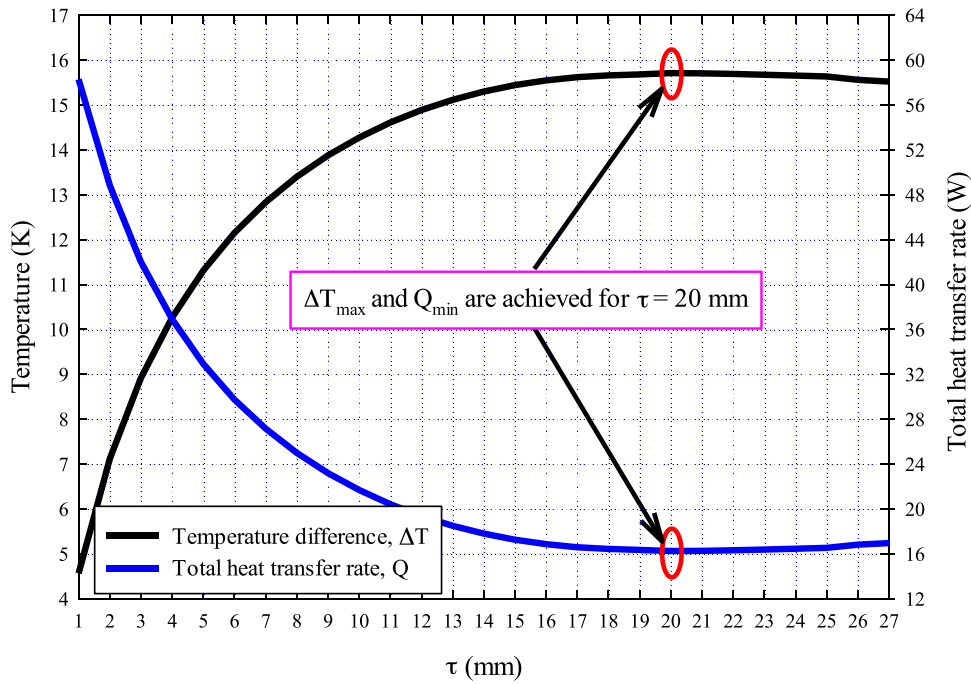


Fig. 9. Internal and external glazing temperature difference (ΔT) and total heat transfer rate across TRPVG for the different values of inert gas thickness (τ).

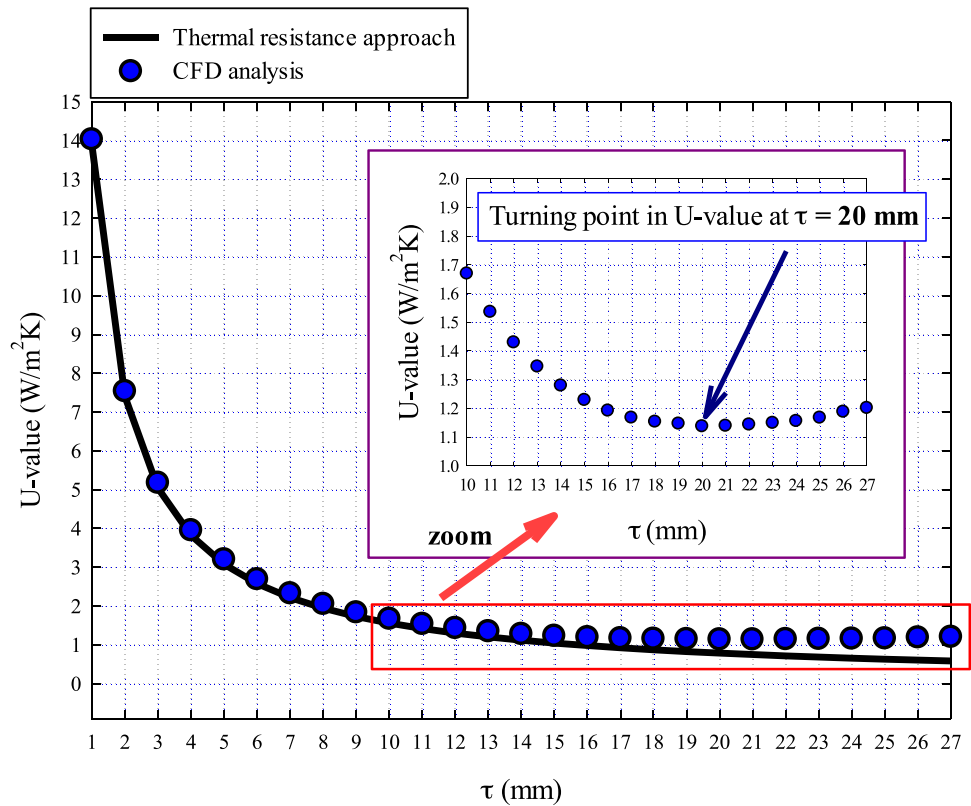


Fig. 10. U-value of TRPVG for the different values of inert gas thickness (τ) through CFD and thermal resistance approach.

average temperature difference for the whole tests is calculated to be 5.099 °C. The results are obtained for hot box and chamber temperatures of 25 and 15 °C, respectively. Afterwards, heat flux measurements are carried out, and the experimental U-value is determined for TRPVG-Ar16 as illustrated in Fig. 12. Despite the noticeable fluctuations in the heat flux measurements, the average values are found to be in accordance with the numerical

data. The average U-value from the hot box tests is 1.135 W/m² K whereas it is 1.192 W/m² K from the CFD research. The deviation between numerical and experimental U-value is found to be 5.02%, which is acceptable.

Thermal imaging is also conducted in the research in order to check whether thermal bridging effects occur in operation.

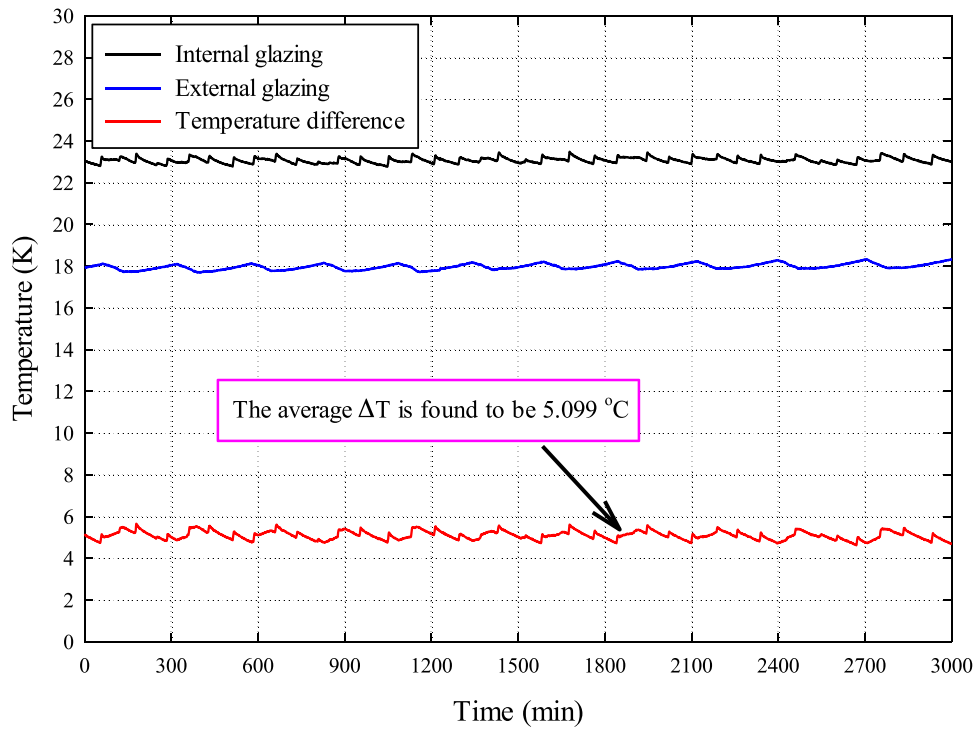


Fig. 11. Internal and external glazing temperature from the hot box measurements.

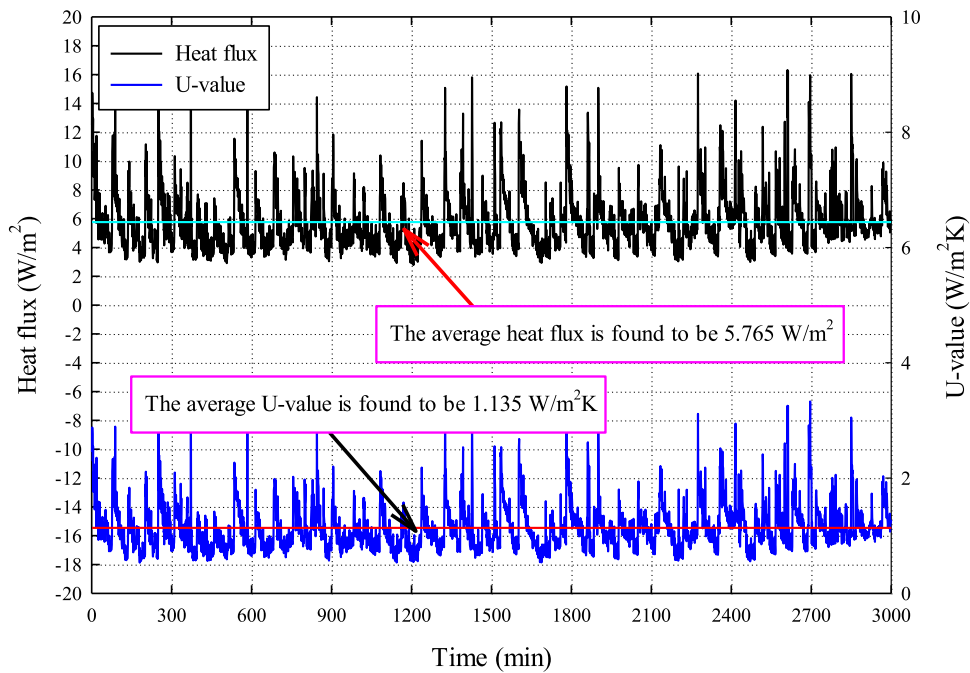


Fig. 12. Heat flux and U-value calculations from the hot box measurements.

Fig. 13 illustrates the temperature distribution around the chamber and hot box. It is observed from the results that hot box is totally adiabatic, and heat flux across the TRPVG-Ar16 is sensible because of temperature differences between surfaces and convection environment. Thermal bridging effects are somewhat available especially on the upper edges due to metallic dividers and buoyancy forces. However, the said effects are almost eliminated owing to PVC-U edge seals. Further investigations are also required to enhance the thermal resistance figures of dividers and support pillars especially for PV-vacuum glazing applications.

6. Conclusions

A novel argon filled PV glazing technology called TRPVG-Ar16 is introduced, and optimum inert gas thickness for the said design is numerically determined. Numerical results are justified through calibrated co-heating tests conducted in a hot box unit. Thermal imaging analyses are also carried out to analyse the potential thermal bridging effects within the PV glazing in real operating conditions. The results reveal that the inert gas thickness plays a key role in the average U-value of TRPVG.

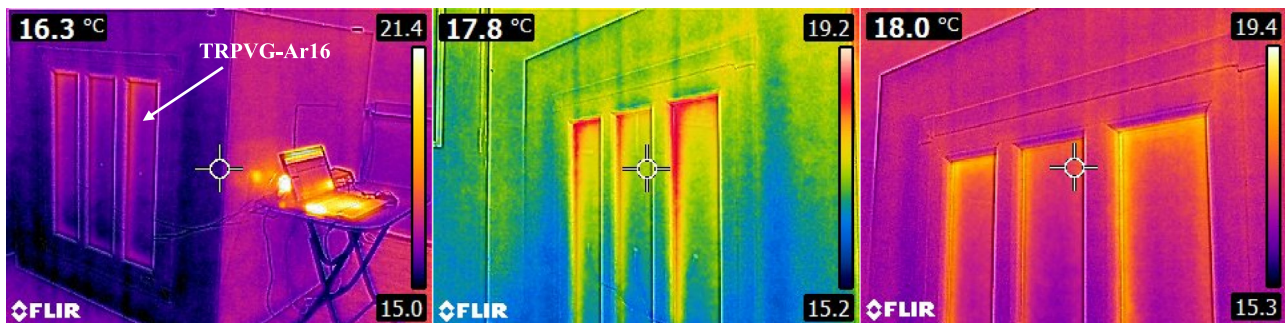


Fig. 13. Thermal imaging tests for TRPVG-Ar16 conducted at different times of operation.

The U-value of the product exponentially decreases with the increasing argon width, and after a critical thickness it again starts to increase since argon behaves as a heat dissipater rather than a thermal insulator. Following characteristic findings can be concluded from the research:

- TRPVG-Ar16 has multifunctional benefits to be considered as a novel building element for low/zero carbon buildings especially because of its highly thermally resistive structure. The numerical and experimental U-value of TRPVG-Ar16 is determined to be 1.192 and 1.135 W/m² K, respectively, which is capable meeting the latest building standards regarding glazed areas.
- The inert gas thickness plays a key role in the overall U-value of TRPVG-Ar16. Argon behaves as a thermal insulator up to τ value of 20 mm. For the greater values, notable natural convection effects take place in the enclosure, and the U-value undesirably rises.
- Thermal resistance approach is valid in the U-value analysis only a certain value of inert gas thickness. For this typical case, the critical argon width is determined to be 12 mm, when a 10% deviation is considered as the limit value.
- The optimum τ value of 20 mm is achieved at minimum total heat transfer rate and maximum temperature difference across the PV glazing. The said Q value is calculated to be 16.259 W whereas ΔT is found to be 15.712 °C.
- For the concept of TRPVG-Ar16, CFD results are observed to be in good agreement with the experimental data. About 5% difference between the said values is reported, which is promising.
- Thermal imaging tests are also found to be in accordance with the experimental and CFD findings. Due to metallic dividers, some thermal bridging effects occur around the upper edges especially, however, these are eliminated owing to the PVC-U edge seals.
- TRPVG-Ar16 can be considered for the energy-efficient retrofitting of existing homes and for new buildings because of its multifunctional benefits as well as thermally resistive structure.

Acknowledgement

The corresponding author gratefully acknowledges the financial support of TÜBİTAK (The Scientific and Technological Research Council of Turkey) through the project grant of 216M531.

References

- ANSYS FLUENT. Fluent 6.3 Version.
- Arici, M., Karabay, H., Kan, M., 2015. Flow and heat transfer in double, triple and quadruple pane windows. *Energy Build.* 86, 394–402.
- Aydin, O., 2000. Determination of optimum air-layer thickness in double-pane windows. *Energy Build.* 32 (3), 303–308.

- Bouvard, O., Burnier, L., Oelhafen, P., Tonin, A., Wüst, P., Sidler, F., Zweifel, G., Schüller, A., 2018. Solar heat gains through train windows: a non-negligible contribution to the energy balance. *Energy Effic.* 11 (6), 1397–1410.
- Chen, B., Lv, H., Liao, J., Dong, S., Cheng, C., Lv, Q., Li, J., Su, Y., Riffat, S., 2019. Thermal insulation performance of an advanced photovoltaic vacuum glazing: A numerical investigation and simulation. *J. Renew. Sustain. Energy* 11 (1), 015101.
- Cuce, E., 2014. Development of innovative window and fabric technologies for low-carbon buildings (Ph.D. Thesis). The University of Nottingham, Nottingham, United Kingdom.
- Cuce, E., 2016. Toward multi-functional PV glazing technologies in low/zero carbon buildings: Heat insulation solar glass - Latest developments and future prospects. *Renew. Sustain. Energy Rev.* 60, 1286–1301.
- Cuce, E., 2017. Role of airtightness in energy loss from windows: Experimental results from in-situ tests. *Energy Build.* 139, 449–455.
- Cuce, E., 2018. Accurate and reliable U-value assessment of argon-filled double glazed windows: A numerical and experimental investigation. *Energy Build.* 171, 100–106.
- Cuce, E., 2019a. Impacts of edge seal material on thermal insulation performance of a thermally resistive photovoltaic glazing (TRPVG): CFD research with experimental validation. *J. Energy Syst.* 3 (1), 26–35.
- Cuce, E., 2019b. Impacts of edge seal material on thermal insulation performance of a thermally resistive photovoltaic glazing (TRPVG): CFD research with experimental validation. *J. Energy Syst.* 3 (1), 26–35.
- Cuce, E., Cuce, P.M., 2016. Vacuum glazing for highly insulating windows: Recent developments and future prospects. *Renew. Sustain. Energy Rev.* 54, 1345–1357.
- Cuce, P.M., Cuce, E., 2017. Toward cost-effective and energy-efficient heat recovery systems in buildings: Thermal performance monitoring. *Energy* 137, 487–494.
- Cuce, E., Cuce, P.M., Young, C.H., 2016. Energy saving potential of heat insulation solar glass: Key results from laboratory and in-situ testing. *Energy* 97, 369–380.
- Cuce, E., Riffat, S.B., 2015a. Aerogel-assisted support pillars for thermal performance enhancement of vacuum glazing: A CFD research for a commercial product. *Arab. J. Sci. Eng.* 40 (8), 2233–2238.
- Cuce, E., Riffat, S.B., 2015b. Vacuum tube window technology for highly insulating building fabric: An experimental and numerical investigation. *Vacuum* 111, 83–91.
- Cuce, E., Young, C.H., Riffat, S.B., 2014. Performance investigation of heat insulation solar glass for low-carbon buildings. *Energy Convers. Manage.* 88, 834–841.
- Cuce, E., Young, C.H., Riffat, S.B., 2015. Thermal performance investigation of heat insulation solar glass: A comparative experimental study. *Energy Build.* 86, 595–600.
- Ghosh, A., Norton, B., 2018. Advances in switchable and highly insulating autonomous (self-powered) glazing systems for adaptive low energy buildings. *Renew. Energy* 126, 1003–1031.
- Ghosh, A., Sundaram, S., Mallick, T.K., 2018. Investigation of thermal and electrical performances of a combined semi-transparent PV-vacuum glazing. *Appl. Energy* 228, 1591–1600.
- Gorgolis, G., Karamanis, D., 2016. Solar energy materials for glazing technologies. *Sol. Energy Mater. Sol. Cells* 144, 559–578.
- Grynning, S., Gustavsen, A., Time, B., Jelle, B.P., 2013. Windows in the buildings of tomorrow: energy losers or energy gainers?. *Energy Build.* 61, 185–192.
- Han, J., Lu, L., Yang, H., 2010. Numerical evaluation of the mixed convective heat transfer in a double-pane window integrated with see-through a-Si PV cells with low-e coatings. *Appl. Energy* 87 (11), 3431–3437.
- Huang, J., Chen, X., Yang, H., Zhang, W., 2018. Numerical investigation of a novel vacuum photovoltaic curtain wall and integrated optimization of photovoltaic envelope systems. *Appl. Energy* 229, 1048–1060.

- Lee, H.M., Yoon, J.H., Kim, S.C., Shin, U.C., 2017. Operational power performance of south-facing vertical BIPV window system applied in office building. *Sol. Energy* 145, 66–77.
- Memon, S., Fang, Y., Eames, P.C., 2019. The influence of low-temperature surface induction on evacuation, pump-out hole sealing and thermal performance of composite edge-sealed vacuum insulated glazing. *Renew. Energy* 135, 450–464.
- Norton, B., Eames, P.C., Mallick, T.K., Huang, M.J., McCormack, S.J., Mondol, J.D., Yohanis, Y.G., 2011. Enhancing the performance of building integrated photovoltaics. *Sol. Energy* 85 (8), 1629–1664.
- Pérez-Lombard, L., Ortiz, J., Pout, C., 2008. A review on buildings energy consumption information. *Energy Build.* 40 (3), 394–398.
- Santamouris, M., Haddad, S., Saliari, M., Vasilakopoulou, K., Synnefa, A., Paolini, R., Ulpiani, G., Garshasbi, S., Fiorito, F., 2018. On the energy impact of urban heat island in Sydney: Climate and energy potential of mitigation technologies. *Energy Build.* 166, 154–164.
- Skandalos, N., Karamanis, D., 2015. PV Glazing technologies. *Renew. Sustain. Energy Rev.* 49, 306–322.
- Volf, M., Lupíšek, A., Bureš, M., Nováček, J., Hejtmánek, P., Tywoniak, J., 2018. Application of building design strategies to create an environmentally friendly building envelope for nearly zero-energy buildings in the central European climate. *Energy Build.* 165, 35–46.