KEY DESIGN FEATURES OF MULTI-VACUUM GLAZING FOR WINDOWS
A Review

by

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The use of vacuum glazed windows is increasing due to their application in modern building design. Among various types of vacuum glazed windows reported in literature, thermal transmittance of single glass sheet (conventional window) i. e 6 W/m²k is reduced by 66 and 77% using air filled double glazed and air filled triple glazed windows, respectively. Using low emittance coatings thermal transmittance of double glazed windows is reduced by 53%, however it offsets the visibility by reducing light transmittance by 5%. Stresses due to temperature/pressure gradients if not eliminated may lead to reduction in service life of vacuum glazed windows. Vacuum created between the glass sheets is used to reduce conductive heat transfer. Degradation in the vacuum is caused by number of factors such as, permeation of gaseous molecules through glass sheets, leakage through sealing, thermal/optical desorption, and photo-fragmentation of organic species have been critically reviewed and future trends are outlined.

Keywords: *vacuum glazed windows, heat transfer, energy conservation, building design, thermal transmittance*

Introduction

Windows are essential part of building design providing natural light, fresh air and visibility to the occupants and also shield them from dust, noise, rain, infiltration and excessive temperatures. Additionally, windows provide the aesthetic and psychological dimension to the building design [1, 2]. in any building the significant heat loss takes place through the windows. Energy losses through windows are over 3, 6, and 7% of the total energy consumed in United States, United Kingdom, and Sweden, respectively [3-7].

Energy efficient buildings are need of the hour, keeping in view the ever increasing energy costs and heightened sense of global warming. Significant reduction in global energy demand can be made by using vacuum glazed windows instead of conventional windows, as vacuum glazed windows reduce the heating energy demand in buildings by of a factor of 2 to

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5 [8]. Also, artificial lighting in buildings consumes up to 60% of the total energy consumed in building [9]. Significant energy can be conserved by exploiting natural lighting through vacuum glazed windows without compromising the thermal insulation of the building envelope. In the field of vacuum glazing, significant breakthroughs achieved during the 20th century have been summarized in the tab. 1.

Table 1. Development of vacuum glazing in 20th century

Authors	Contribution
Dawar [13]	Invented Dawar Flask with two concentric containers joined at one end only and vacuum was created between them
Zoller[14] and Ghoshal and Neogi [15]	Invention of flat transparent evacuated insulation
Kirling [16]	Support pillars were introduced between the glass sheets and edges were curved to accommodate thermal expansion
Whattan and Myres [17]	Improved manufacturing techniques such as, supporting the cavity gap with rods, hermetically sealing the glass panes in the shape of cells, inner glass surfaces were coated with low emittance coatings and glass sheets were fused in vacuum conditions
Calons [18]	Proposed pump out tube which allows sealing off after evacuation and contact area between glass panes was reduced by using marbles instead of rods as supports in the cavity
Falbel [19]	Proposed silver internal surfaces, outlined criteria of square support pillars
Bachli [20]	Proposed the idea of producing flexible edge seal to avoid deformation due to thermal expansion
Collins, *et al*. [21]	Developed permanently sealed, flat glass structure with good optical and thermal properties

To minimize the heat loss, good insulation between controlled indoor space and variable outdoor environment is important for efficient thermal design of the buildings. However, windows as compared to walls and doors, are considerably less thermally efficient due to limitations of allowing daylight into the building and high visibility for occupants out of the building [8].

Construction

The vacuum glazed windows generally come in two categories *i. e* double and triple glazing, as shown schematically along with its working principle in fig.1. The components and respective details are presented in tab. 2. It consists of two glass sheets having thickness of around 3 to 4 mm, separated by a vacuumed narrow space having width of around 0.1 mm. The inner surface of one or both sheets is coated with a transparent low emittance surface to avoid radiative heat transfer. The leak free, hermetic, edge seal is made around the periphery of glass, with solder glass having similar coefficient of expansion to that glass sheets, in order to avoid deformation due to thermal expansion. The support pillars (0.1-0.2 mm high, 0.25-0.5 mm diameter, and 20-25 mm spaced apart) are provided to avoid the crushing of sheets under atmospheric pressure. Such forces are estimated to be of the order of 10 ton per square meter.

Low emittance coatings, on the inside surface of one glass or both, act as a *radiation filter* that is transparent to daylight and reflect thermal radiation. for coating to be used on a

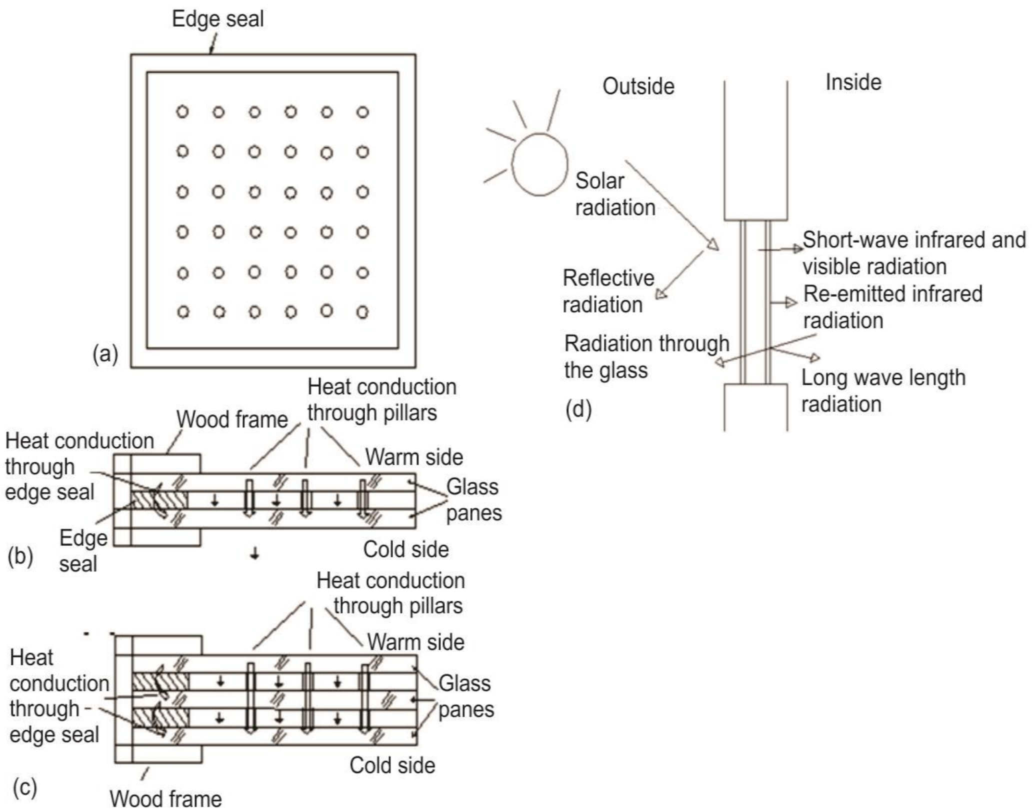

Figure 1. Types of vacuum glazed windows and working principle; (a) plan view of double/triple vacuum glazing, (b) schematic of heat-flow through the double vacuum glazing, (c) schematic of heat-flow through the triple vacuum glazing [10-12], and (d) working principle of reduction in heat loss due to radiation

window installed in a cold climate should allow the visible light as well as shortwave radiation. However, it should trap the long wave radiation emitted from indoors. Whereas, for a coating to be used on window installed in hot climate should allow visible light, transmit longwave radiations emitted from objects indoors and reflect back any shortwave radiation from outdoors [22].

The thermal performance of windows can be quantitatively evaluated by thermal transmittance, U, W/m^{2}K, defined as rate of heat loss per square meter, at steady-state conditions at a temperature difference of one Kelvin between indoors and outdoors, separated by a glass sample [30]. Table 2 shows the values of thermal transmittance of double/triple glazing, gas filled and with low emittance coatings [31].

As shown in tab. 3 thermal transmittance using double and triple glazed windows is reduced by 54 and 71%, respectively, as compared to that of single glass sheet. Low emittance coatings reduce thermal transmittance for double and triple glazed windows by 28 and 23%, respectively, as compared to that of windows without the coatings. Also, by filling low conducting Argon gas in double glazed windows reduce thermal transmittance by 15% [35].

Table 2. Details and challenges related to components of vacuum glazed window

Feature	Purpose	Details	Challenges
Glass pane	Provide visibility, safety, natural light to occupants and protect them from excessive temperatures, noise, dust, rain and infiltration air	Material: soda lime glass (73% SiO_2, 17% NO_2O, 5% CaO, 4% MgO) [23] tempered glass t = 3 – 4 mm	Testing and validation against safety standards; withstand stresses due to atmospheric pressure, wind, accidental mechanical impact and non-uniform thermal expansion; avoid permeation of gas molecules
Pillars	Fixed in the glass cavity to avoid crushing of glass panes under atmospheric pressure [38]	Materials: high strength nikel based alloy, alumina and stainless steel [24] p = 25 mm, h = 0.15 mm a = less than 0.25 mm [25, 26]	High compressive strength, low thermal conductivity, high visual transmittance and mechanical stability
Transparent low *e* coatings	Used on the internal surfaces of one or more glass panes to act as radiation filter, that allows sunlight to pass through and blocks thermal radiations	Pyrolytic transparent coatings, such as Tin oxide [27] e = 0.04 to 0.16 [17, 24]	High visual transmittance, low thermal transmittance, maintain adhesion with glass surface, withstand high temperatures of around 500 °C
Vacuum	Maintained between glass panes to reduce conduction and convection heat transfer	Pressure differential of around 100 kPa (10 ton per m^2)	Maintain vacuum over service life; avoid permeation of gas molecules through glass panes, leakage through edge sealing, thermal desorption, optical desorption and fragmentation and selection of appropriate getter material
Edge sealing	Hold the glass panes together by sealing at the edges	Material: solder glass, metal, indium alloy [25, 28]	Low thermal conductivity, reduce leakage of gases from atmosphere to cavity; withstand stresses due to non-uniform thermal expansion; more recently, the concern has been to find low thermally conducting sealing materials with thermal coefficient of expansion similar to that of glass pane.
Gases	Reduce the vacuum stresses, and reduce heat transfer through conduction by using gases with lower thermal conductivity as compared to that of air	Maintain vacuum at a pressure below 0.1 kPa [29]	Low thermal conductivity, high density. Should not: – decompose on exposure to sunlight – react with glass surface, edge sealing and support pillars, and – diffuse through glass and edge sealing
Window frames	Provide mechanical support and insulation to edge sealing using low conducting materials such as wood or polymers	Material: wood, polymer	Withstand stresses and deformation due to thermal expansion.

Table 3. Typical thermal transmittance values for conventional and high performance windows [4, 32-34].

Glazing system	Thermal transmittance [$Wm^{-2}K^{-1}$]
Single glass sheet (conventional window) (3-4 mm)	6.00
Double glazing, air filled (6-8 mm)	2.78
Double glazing, low-emittance coating, air filled (6-8 mm)	1.99
Double glazing, low-emittance coating, argon filled (6-8 mm)	1.70
Triple glazing, air filled (9-12 mm)	1.76
Triple glazing, low-emittance coating, air filled (9-12 mm)	1.36

The design of vacuum glazed window involves trade-offs between the stresses and the heat transfer through it. In this paper key design parameters have been discussed such as low emissivity coatings, stresses induced, pillars, edge sealing, and gas conduction. These parameters influence the durability, visibility, mechanical strength, and heat transfer insulation. The review of the existing literature suggests that it is important to the limit stresses and maintain vacuum over product's service life in the presence of large temperature and pressure differentials across the vacuum glazed windows.

Heat transfer

Heat transfer through conventional single glass pane is partially affected by glass properties and significantly by the convection on both sides [21]. However, several modes of heat transfer effect the energy transport through multi-glazed windows such as conduction, convection and radiation, schematic is shown in fig. 1. Conduction heat transfer takes place through support pillars, edge sealing and at times gas present in the cavity. Convection takes place from the glass surfaces on the outside and indoor. This is primarily dependent on the indoor and outdoor conditions of temperature and air velocity [36].

As could be seen in tab. 4 that superior heat transfer insulation can be obtained using vacuum glazed windows as compared to conventional single glass window. In case of double glazed windows, heat transfer by conduction is primarily reduced by vacuum cavity between the two glass panes and heat transfer by radiation is reduced by low emissivity coatings on the glass panes. However, as shown in fig. 1, heat conduction takes place through pillars and edge sealing, but the drawbacks of using pillars and edge sealing are outnumbered by enhanced insulation due to vacuum cavity and low emittance coatings.

Low emissivity coatings

Low emittance coatings are used to reflect the radiations, hence reducing the amount of energy absorbed while allowing the daylight to pass through. for ordinary windows, around 60% of the heat loss takes place through long wave infrared radiation (3-30 micrometres) [38].

Low emissivity coating on the glazed glass has very little effect of the daylight transmitivity *i. e* it is reduced by 5%. However, thermal transmittance, the much critical factor related to thermal insulation, is reduced by 53% [39]. Also, it was demonstrated that, coating having emissivity of less than 0.2, compared with that of 0.8 of standard uncoated glass redu-

Table 4. Components and equations related to various modes of heat transfer through vacuum glazed windows

Heat transfer mode	Related components		Equations of thermal resistance	Remarks
Conduction	Conventional window	Vacuum glazed window	$R_\mathrm{p} = \dfrac{p^2}{2k_\mathrm{p}a}$ (1)	High strength, low thermally conducting materials are preferred such as: high strength nikel based alloy, ceramics, alumina, and stainless steel [24]
	n/a	Pillars		
	n/a	Gases in the cavity/ vacuum	–	Pressure of around 0.1 Pa is maintained using low conducting gases like Argon or Krypton
	Edge sealing		$R_\mathrm{s} = \dfrac{l_\mathrm{s}}{k_\mathrm{s}}$ (2)	High strength, low thermally conducting and low diffusive material
Convection	Glass panes		$R_\mathrm{g} = \dfrac{1}{h_c}$ (3)	Natural convection at indoors and forced convection at outdoors: (h_in = 8.5 W/m^{2}K, T_in = –17.5 K h_out = 30 W/m^{2}K, T_in = 21.1 K) [37]
Radiation	n/a	Low emissivity coatings	$R_\mathrm{rad} = \left(\dfrac{1}{\varepsilon_1} + \dfrac{1}{\varepsilon_2} - 1\right)\left(4\sigma T_{1,2}^3\right)^{-1}$ (4)	Pyrolytic low emissivity coatings, sustainable up to a temperature of 500 °C; typical values of emissivity range from 0.04 to 0.16 [17, 27]

ces radiation exchange by 75% [40]. Net radiative heat flow Q_rad between two parallel surfaces (double glazed) can be determined by following equations:

$$Q_\mathrm{rad} = \varepsilon_T \sigma A\left(T_1^4 - T_2^4\right) \tag{5}$$

$$Q_\mathrm{rad} = 4\varepsilon_T \sigma A T_\mathrm{avg}^3 \left(T_1 - T_2\right) \tag{6}$$

$$\frac{1}{\varepsilon_T} = \frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1 \tag{7}$$

where A is the area of parallel surfaces, T_1 and T_2 are the mean surface temperatures of surface, ε_T is the total emittance of the surface, and ε_1 and ε_2 are the emittance of individual surfaces [10]. Overall heat transfer coefficient of two low emittance coatings on both glass surfaces is less than the one with coating on one surface [41, 42].

Table 5 shows the effect of emittances on thermal conductance. It is evident that better performance could be achieved using coatings with low emittance as lower emissivity coating provides better thermal insulation [17].

Ideally coatings should be able to withstand higher temperatures of the order of 500 °C and maintain adhesion with glass surface over the period of product life that is spanned over decades [8, 43].

Stresses

Stresses are generated on the glass sheet and support pillars due to atmospheric pressure on the edge sealing due to temperature differential between indoor/outdoor temperatures and frame constraints [10, 21]. Also, short term stresses can arise from wind loading and accidental mechanical impact [21]. Significant stresses can lead to catastrophic break down in vacuum glazing assembly, failure or dislocation of support pillars or crack propagation in the glass pane especially close to edge sealing [40, 44, 45].

Table 5. Experimental values of thermal conductance for different low emittance coatings on inside of glass surfaces [17]

Low emissivity coatings		Thermal conductance, $[Wm^{-2}K^{-1}]$
$\varepsilon_1 = 0.16$	$\varepsilon_2 = 0.16$	1.3
$\varepsilon_1 = 0.12$	$\varepsilon_2 = 0.16$	1.2
$\varepsilon_1 = 0.04$	$\varepsilon_2 = 0.16$	1.15

Glass panes under the effect of high atmospheric stresses (100 kPa), had to be accounted for by using high density array of support pillars and/or stronger glass. The maximum allowable tensile stress for glass surface is 8 MPa, but recommended stress should be around 4 MPa to make sure the safe and durable operation of vacuum glazed window over the service life of 30 years [1, 44]. Use of high density, low conductivity gases like argon or krypton have been proposed to reduce the vacuum stresses without significantly compromising the thermal insulating ability [24].

Temperature difference between inside glass and the one on outside cause the differential expansion between the two glass sheets and results in tensile, compressive and bending stresses [25]. Bending stresses are caused by the differential expansion of two glass panes due to corresponding temperature differences, whereas, compressive and tensile stresses arise from differential expansion due to temperature difference between bonded edge seal and rest of the glass pane. The compressive stress acts on warm glass sheet, whereas tensile stress acts on the cold one [46]. Experimental and modelling data of Simko and Collins [47] shows that deflection is minimum at the edges and maximum at the glass centerline for a glass sample of size 500 × 500 mm, tab. 6. Also, it was demonstrated that deflection at the centerline was linearly dependent on the temperature difference across the vacuum glazed window, as shown in tab. 7.

Table 6. Deflection at various points on the sample of vacuum glazing of size 500 × 500, due to temperature difference between the glass panes [25]

Distance across glazing, [mm]	Deflection, [μm]			
	$\Delta T_{g-g} = 7.1$ K	$\Delta T_{g-g} = 11.3$ K	$\Delta T_{g-g} = 16.9$ K	$\Delta T_{g-g} = 22.0$ K
100	150	240	380	480
150	200	340	500	660
200	230	370	580	750
250	240	400	600	790

Constraints in the window frame results in reduction of stresses in glass surfaces, especially on the edge seals. Also, flexible edge seals may be used to avoid stresses, however, no such seal has been investigated so far [47]. For glass samples of 1 by 1 m, at temperature difference of 40 K, maximum deflection of 10 mm (normal to glass surface) was determined [25].

Table 7. Deflection at centre line of 500 × 500 mm glass sample, for various temperature differences between the glass panes [25]

Temperature difference across glazing, [K]	Centre line deflection, [μm]
5	190
10	350
15	540
20	700

Pillars

Vacuum glazed windows should be able to withstand pressure difference of 101 kPa (10 tone m^{-2}) across each glass sheet. Array of support pillars is used to maintain separation between the panes. Support pillars are used to avoid crushing of glass panes under atmospheric stresses. Pillars also provide thermal contact for conduction heat transfer and in certain cases pillars can also reduce the visibility for occupants. The optimal properties of pillars are small size, high light transmittance, high compressive strength, and low thermal conductivity. Simple analytical models have been used to calculate surface temperature distribution due to conduction through the pillar [26]. They presented the small temperature variation in the pillar array due to difference in temperature between glass pane and edge sealing. Moreover, vapor condensation was obtained on certain instances when temperature of glass surface is lower than the dew point temperature of the inside air.

Analysis of pillar design was investigated and proposed optimum dimensions for diameter (0.25 to 0.5 mm), height (0.1 to 0.2 mm), glass thickness (3 to 6 mm), and square array to be separated by 20 to 35 mm. The recommended materials are alumina, stainless steel, and inconel (a nickel bases alloy) with minimum compressive strength of 1 GPa. In general, the size of the pillar is too small and array density is too coarse to have any hindrance of view through the glass [24].

The finite element method was used and validated by numerical and experimental results. Based on the findings, following design criteria was outlined [21, 26, 40, 41].

- Since, support pillars are essential to avoid the crushing of glass panes under atmospheric pressure. The recommended compressive strength for pillar material is at least 1.5 GPa.
- Glass should have tensile strength of 4 MPa.
- Glass surface should not indent at areas supported by pillars under compression. However, indentation was found less critically important than that of compression in pillars.
- Support pillar radii should be small as compared to pillar height to avoid mechanical instabilities and ease of assembly while attaching pillars on the inside glass surface.
- The pillars should be as small as possible to avoid the conductive heat transfer and visual obstruction while keeping the stresses within the design limits. in general the recommended radii should be smaller than 0.25 mm.
- Thermal conductance, U_{pillar} of the pillars should be less than a given value and is determined by eq. (8).

$$U_P = \frac{2k_g a}{p^2} \tag{8}$$

where k_g` is the thermal conductivity of glass, a – the pillar radius, and p – the pillar separation.

Following the design criteria previously listed, Collins and Simko [10] and Yueping *et al*. [41] conducted simulations using finite volume method.

Allowable pillar diameter and spacing increases and conductance of pillar array decreases with increase in glass thickness. Variation in pillar radius, pillar separation and conductance of pillar array with changing glass pane thickness could be seen in tab. 8 [48].

Table 8. Variation in thermal conductance by changing pillar radius, pillar separation, and glass pane thickness

Glass pane thickness t, [mm]	Pillar radius a, [mm]	Pillar separation p, [mm]	Conductance of pillar array U, [$Wm^{-2}K^{-1}$]
2	0.08	15	0.70
3	0.10	20	0.50
4	0.13	25	0.40
5	0.15	30	0.34
6	0.16	35	0.30

Pillars also reduce the visibility for occupants. Hence, to overcome this drawback, more recently, the idea of transparent and insulating pillars has been proposed and research is in progress to develop suitable materials for transparent insulating systems [49].

Edge sealing

Glass panes are separated by a narrow gap, to maintain vacuum [50]. Edge seal is used to hold the two glass panes together by joining them together around the periphery.

The stresses induced due to cyclic thermal loading and consequent deformation cause the weakening of the seal and infiltration of gases into the vacuum space. Due to permeability to gases ordinary polymer based adhesives can not be used [25] also the coefficient of expansion of sealing should be similar to that of glass in order to minimise the stresses generated due non-uniform thermal expansion. The temperature required to seal the two glass panes should not be too high to destroy the low emittance coatings and also should be lower than that of melting point of glass used [41, 44]. This highlights the importance of careful selection of sealing technology and materials.

Both metals and solder glass seals are used as sealing maternal, however, glass seals are recommended due to their less corrosion, lower thermal conductivity, durability and compatible coefficient of thermal expansion with glass. The drawback of using such a glass edge sealing technique is that the melting temperature of 450 °C is too high to prevent low emissivity coating to be protected from degradation. To address this problem, more recently metal based sealing materials have been proposed, providing melting temperatures of around 200 °C [48, 51-53].

Since, conductivity of edge sealing is significantly higher than that of glass. Most of the conductive heat transfer takes place through it [48]. This effect can be reduced using edge frame insulation made of lower conductivity materials such as polymers or wood. Another benefit of using this insulation is that the uniform temperature distribution is obtained, corresponding thermal stresses and probability of failure is reduced [54].

As shown in fig. 2 it was demonstrated by Liu [48] that thinner glass lead to lower heat transfer coefficient in case of glass pane sizes of (0.3 m by 0.3 m and 0.5 m by 0.5 m). For these sizes heat transfer coefficient increases with increasing glass pane thickness. However, in case of glass pane size of 1m by 1m heat transfer coefficient decrease by increasing glass thickness. In all the cases no change in heat transfer coefficient was observed by increasing glass thickness more than around 5 mm.

The ratio of heat transfer through edge seal decreases with increasing glass pane size and decreases with increasing glass thickness. Hence, by increasing the glass thickness for sizes greater than the 1 m^2, thermal performance is improved. Also, other related factors such as pillar size and spacing, maximum allowable stress in glass pane and over all thermal conductance through pillar array should also be taken into consideration.

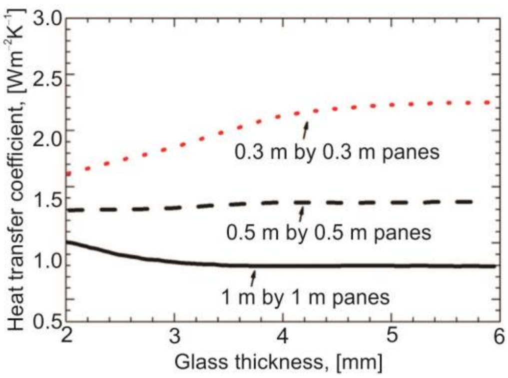

Figure 2. Effect of glass pane thickness and size on thermal conductance of vacuum glazing [48]

In case of triple vacuum glazing, mechanical stresses and deflections are lower as compared to double vacuum glazed systems, thus improving the aesthetics of building façade [48].

Gas conduction

Compared to ordinary double glazed windows, the vacuum in the middle of two glass panes serve as added resistance to conductive and convective heat transfer. In general, the size of the gap is ten times smaller than that of the double glazed window. Also, surface to volume ratio of a typical vacuum glazed window is around two orders of magnitude larger than typical vacuum chambers [8]. That is why it is highly impractical to evacuate the cavity using pump during service life. Hence, cavity should be sealed with great care during manufacture to make sure cavity pressure is well below the design limitations *i. e* 0.1 kPa.

Total elimination of gases and creation of ideal vacuum conditions are most suitable to obtain high thermal resistance. Heat loss by conduction can be significantly reduced by maintaining low pressure in the gap, as low as 0.1 kPa. At this pressure the mean free path for interaction between molecules is comparable to the thickness cavity between glass panes (around 0.2 mm), over which heat is to be conducted through gas [21, 55-58].

Appropriate selection of gas is important for prolonged efficient working of vacuum glazed window, safety and well being of occupants. Following essential requirements were outlined [35]:
– Should not decompose when exposed to sunlight and UV radiation.
– Should not react with glass, seal, and support pillars.
– Should not be toxic.
– Should not diffuse through glass and seal.
– Should not condense on the inner side of glass on exposure to low temperature.

Granular translucent materials are also proposed to be suitable to be filled in the interpanel space. The thermal transmittance is reduced to around 0.98 W/m^{2}K. However, the translucent or at times opaque nature of these materials makes them less suitable to be used in cases where high visibility for occupants is desired [59-63] .

Degradation in the vacuum between the glass panes was identified as the major source of decrease in insulation ability of the vacuum glazed windows. An increase in internal pressure is related to the following factors [8]:
– Permeation of small gaseous molecules (air-constituents), particularly helium.
– Leakage through the edge seal.
– Thermal and optical desorption of organic adsorbate species.
– Photo-fragmentation.

Permeation of gaseous molecules through glass surface

The glass structure, composed of irregular lattice structure, contain cavities of the order of nanometres which are large enough to allow small gas molecules to pass through.

The gaps are quite large for structures made of SiO_2, P_2O_5, and B_2O_3. The size of gaps can be reduced using network modifiers such as, alkaline or alkaline earth oxides [13, 14, 16]. Among the other gases and water vapour present in the air, helium is by far most rapidly permeating gas as compared to that of other gases, primarily due to its smaller molecular size and chemically inert behaviour. In case of air permeation through silica based glass at a cavity pressure of 0.1 Pa or lower with helium, neon, and nitrogen/oxygen posses the concentrations of 92, 6, and 2 %, respectively, [64, 65]. Apart from gases in the air, permeation of water vapour is quite insignificant, as pressure rise due to water transport would result in pressure rise of 0.003 Pa over a span of 100 years [8, 66].

Leakage through edge seal

Effective sealing of the glass panes is the most important factor for durable performance. Gases could enter either due to the cracks in the sealing or through the inter-atomic spaces in the seal. Magnitude of leakage is strongly dependent on the material and method of sealing. Permeation through metallic seals in general and indium based in particular are strongly recommended because of their infinitesimally small permeation and coefficient of expansion similar to that of glass [67]. Also, optimum sealing temperature of lithium is 250 °C to 350 °C, this temperature is suitable as it is low enough to prevent damage the low emissivity coating [51]. Sealing in vacuum is also necessary precaution to eliminate problems related to subsequent evacuation [68]. Sealing effectiveness reduces over the service life due to periodic thermal and/or mechanical loads incurred on the glass surfaces. The mechanical stresses due to temperature gradients in the glass surface and edge sealing have been discussed earlier in the edge sealing section.

Thermal and optical desorption of organic adsorbate species

During the service life, vacuum glazed window undergoes thermal and optical loads. It was shown that the underlying physical mechanism of gas evolution under thermal and optical loading is entirely different from each other. Thermal ageing results in the desorption of water molecules from the internal surface, yet this is not a big concern because water molecules are adsorbed back into the glass surface. However, presence of water vapours can result in crack propagation in the glass sheet [52]. Optical ageing (exposure to sunlight) results in evolution of CO_2 and CO. Once these gases are evolved, they remain in the evacuated space, hence results in permanent increase in pressure and insulating ability of the vacuum glazed window.

Ng *et al.* [69] conducted X-ray electron spectroscopy of samples baked at 150 °C and 350 °C and concluded that samples baked at 350 °C had lower concentration of carbon-oxygen functional groups on the internal surface of glass. The reduced content of this functional group will result in lower concentration of CO and CO_2 that would otherwise be released in the presence of carbon-oxygen functional group on the glass surface.

Photo-fragmentation of large organic molecules

Long chain aliphatic molecules such as hydrocarbons, tensides, and silicones present on the glass surface, decompose on exposure to light. The optical decomposition reaction of large molecule can be repeated several times before it is converted to numerous small molecules. The small molecules desorb into the vacuum and contribute to the increase in pressure. Apart from the long molecules present on the glass surface, sometimes the glass surface is contaminated with photo-degradable molecules during manufacturing, processing, and cleaning on vacuum glazed window. Such as, detergent solutions, used to remove dust and contamination contain long chain molecules of sulfonic, trialkyl ammonium, and polyethylene glycol. These can degrade into numerous small molecules, such as, polyethylene glycol degrade into acetaldehyde, causing massive increase in cavity pressure up to 10 Pa [8].

Glass surface should be purified from long chain photo-fragmenting molecules. Various cleaning methods such as RCA silicon wafer, UV/ozone cleaning and plasma cleaning has been used in semiconductor and ultrahigh vacuum industry and could be used for vacuum glazed applications [70-72].

Despite all the precautions, the increase in pressure seems inevitable over the service life period [68]. To overcome this discrepancy, getter materials are used that have the ability to trap the volatile gases permanently, maintain prolonged evacuation, thus decreasing the gas conduction in the vacuum space over the working life of the system [47, 51, 64].

Conclusions and future trends

Use of vacuum glazed windows can be very effective in achieving energy efficient buildings. In this research work various types of vacuum glazed windows along with the factors affecting their performance have been qualitatively and quantitatively reviewed. Conclusion are summarized below.

- Conventional windows transmit heat six times more than that of walls and roofs [12]. Vacuum glazed windows have significant potential of reducing heat energy and lighting demands.
- Vacuum glazed, coated with low emissivity material, inter-pane space filled with inert gas at low pressure, which are claimed to have an overall thermal transmittance value of 0.4 W/m^2K.
- Vacuum glazed windows are around 6-8 mm thick, these can easily be replaced into conventional window frames [11].
- Vacuum stability between glass panes has been identified as most important concern to maintain the insulating ability of the windows.

In order to enhance the durable insulation capability, further research is required in various areas such as flexible edge seals, appropriate getter materials, glass purification techniques and low temperature sealing methods. To ensure safety of occupants from broken pieces of glasses, samples should be tested and validated against safety standards such as British and Australian standards for glass safety [21, 73-75].

Nomenclature

a – pillar radius, [mm]
h – heat transfer coefficient, [$Wm^{-2}K^{-1}$]
h_c – convection heat transfer, [$Wm^{-2}K^{-1}$]
k – thermal conductivity, [$Wm^{-1}K^{-1}$]
l – length, [mm]
p – pillar separation, [mm]
Q – heat transfer rate, [W]
R – thermal resistance, [KW^{-1}]
T – temperature, [K]
t – thickness of glass sheets, [mm]
ΔT – temperature difference, [K]
U – thermal transmittance, [$Wm^{-2}K^{-1}$]

Greek symbols

ε – emissivity
σ – Stefan-Boltzmann constant

Subscripts

1, 2 – first and second glass sheet
avg – average
g, g-g – glass, glass to glass
in – indoor
out – outdoor
p – pillars
rad – radiation
s – sealing

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