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Thermal conductance measurement on vacuum glazing

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Abstract

A method is described for measuring the thermal conductance of vacuum glazing that is well-suited for integration into the manufacturing process of such devices. The sample of vacuum glazing to be measured, initially at elevated temperature, is placed in contact with a second sample of vacuum glazing with a known thermal conductance. The external surfaces of the glazings are then cooled by forced flow of air at room temperature, and a measurement is made of the rate of decrease of the temperature of the contacting glass sheets of the two samples. The method is simple to implement, and can be automated. The results obtained with the method are quite reproducible. The measurement can be made as the production samples of vacuum glazing cool at the completion of the manufacturing process, resulting in significant savings in time and labour compared with other methods.

Keywords: Thermal conductance; Vacuum glazing; Guarded hot plate; Temperature; Cooling method

1. Introduction

Vacuum glazing, illustrated in Fig. 1, consists of two flat sheets of glass, typically ~3 mm thick, joined together around the edges with a hermetic (leak-free) seal, and separated by a narrow (~0.2 mm) evacuated space [1]. An internal array of small, high strength support pillars maintains the spacing of the glass sheets under the influence of the large forces due to atmospheric pressure. The pillars are typically ~0.5 mm in diameter, and are spaced apart by ~20–30 mm. Heat flow between the glass sheets of vacuum glazing remote from the edge seal can occur due to radiation between the internal surfaces of the sheets, thermal conduction through residual gas in the evacuated gap and thermal conduction through the support pillars. The application of such devices is in thermally insulating windows.

Vacuum glazing was first described in a 1913 German patent [2]. Since that time, many attempts have been made to develop this technology, almost all of which were reported only in the patent literature. The first successful production of a highly insulating vacuum glazing occurred only recently, however, at the University of Sydney [3]. Since then, considerable progress has been made on the development of these devices, and on the understanding of the design and performance limitations of the technology. A good understanding has been obtained of the trade-offs between the heat flow through vacuum glazing and the levels of mechanical stress in the structure, particularly due to the presence of the support pillars [4]. Vacuum glazing incorporating an internal transparent low emittance coating and annealed glass sheets can be made having levels of air-to-air, center-of-glazing thermal conductance as low as $1.2\ \mathrm{W\,m^{-2}\,K^{-1}}$ without excessive levels of tensile stress. Vacuum glazing with air-to-air, center-of-glazing thermal conductance as low as $0.6\ \mathrm{W\,m^{-2}\,K^{-1}}$ can be made using tempered glass [5].

In the manufacture of vacuum glazing, two sheets of glass are cut to size, and a hole is machined in the upper sheet to accommodate a small pumpout tube. The sheets are then washed and dried. Small pillars are then positioned on the lower glass sheet and the upper sheet is placed onto these pillars. Solder glass is deposited as a

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Nomenclature

A	area (m^2)
a	pillar radius (m)
C	thermal conductance ($W\,m^{-2}\,K^{-1}$)
c	specific heat ($J\,K^{-1}\,kg^{-1}$)
k	thermal conductivity ($W\,m^{-1}\,K^{-1}$)
$\dot{Q}$	rate of heat flow (W)
T	temperature (°C)
ΔT	temperature difference (°C)
$\overline{T}$	average temperature (°C)

Greek symbols

β	roughness factor
ε	emittance
λ	pillar separation (m)
θ	temperature (°C)
ρ	density ($kg\,m^{-3}$)
σ	Stefan Boltzmann constant (5.67×10^{-8} $W\,m^{-2}\,K^{-4}$)
τ	time constant (s)

Subscripts

a	ambient
g	glass
h	hot
o	outer
i	inner
s	standard sample
t	test sample
x, y	internal surfaces of glass sheets
1, 2	first and second stages of cooling
vac	vacuum

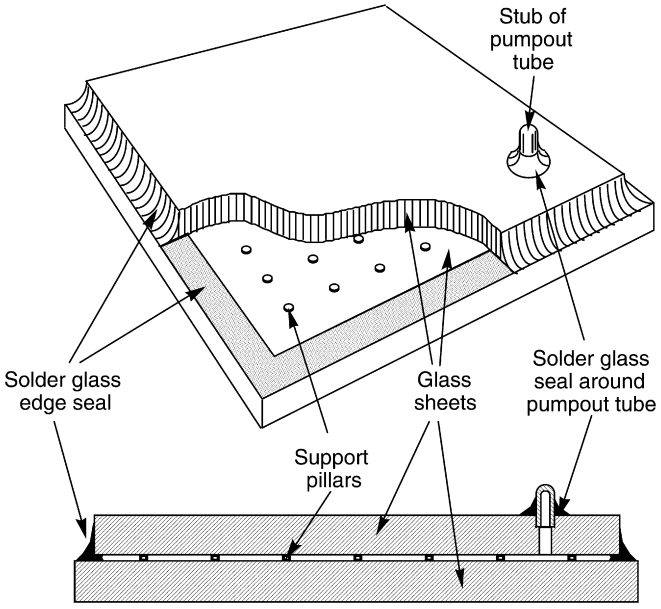

Fig. 1. Schematic diagram of vacuum glazing.

liquid slurry along the edges of the glass sheets. The pumpout tube is placed in the hole in the upper sheet, and solder glass is also deposited around this tube. A differentially pumped, all metal evacuation cup is positioned on the glass before the high temperature edge sealing process [6].

The assembly is then heated to approximately 480 °C. At this temperature, the solder glass melts and flows by capillary action into the small gap between the glass sheets, forming the hermetic edge seal. The sample is then evacuated, and the internal surfaces are outgassed. This process commences as the sample cools following the formation of the edge seal, when the solder glass has solidified sufficiently that it is not forced by atmospheric pressure into the gap between the glass sheets. At the completion of the outgassing process, the pumpout tube is sealed as the sample cools towards room temperature.

In the manufacturing process of vacuum glazing, it is important to measure the thermal conductance of each device in order to verify that it meets the product specification. Two different methods have been described for making such measurements. In one method, a guarded hot plate apparatus is used to measure the heat flow through a well-defined area of the sample of vacuum glazing [7]. In this method, a thermal conductor, referred to as the metering piece, is placed in good thermal contact with one surface of the glazing. The metering piece is surrounded on its external surfaces by a thermal guard at a well-defined temperature. The thermal guard is also in good contact with the surface of the glass sheet. The other side of the sample is maintained at a lower temperature. Electrical power is dissipated in the metering piece, and the power level is adjusted until the temperature of the metering piece is precisely the same as that of the guard. When this condition is established, all of the power being dissipated in the metering piece flows through the sample. Because the area of the metering piece is known, this method provides an absolute measurement of the thermal conductance of the sample. In one application of this method to vacuum glazing, the area of the metering piece was made very small ($\sim$1 cm^2) in order to provide separate measurements of the heat flow through the evacuated gap in the sample, and that due to thermal conduction through the support pillars [7].

In another previously described method of measuring the thermal conductance of vacuum glazing, a rapid temperature increase is applied to the glass sheet on one side of the sample [8]. A measurement is then made of the subsequent relatively small, slow rate of increase of the temperature of the glass sheet on the other side. In

the application of this method to vacuum glazing, the temperature sensor is located at the center of a unit cell of the pillar array. The measurement therefore characterises the thermal conductance associated with heat transfer through the evacuated space. This thermal conductance is proportional to the initial rate of temperature increase of the glass sheet at this point, and inversely proportional to the thermal mass of this sheet.

Both of these methods can be used with larger detection areas to provide measurements of the total thermal conductance of vacuum glazing due to the combined heat flow through the evacuated gap and the pillars. Such large area measurements have also been made with conventional heat flow meters, in which the thermal conductance is determined from the temperature drop across a known thermal resistance that is in series with the heat flow through the sample.

Each of these measurement processes typically takes many tens of minutes to perform. In addition, because they involve the measurement of very small temperature changes, the temperatures within the measuring apparatus and the test sample must be very stable before the measurement commences. During the manufacture of vacuum glazing, the samples to be tested are sealed and available for measurement when their temperature is significantly above ambient, and is decreasing rapidly. If these methods are used in the production process, it can therefore typically take many tens of minutes, and up to an hour, after sealing of the pumpout tube before the temperatures in the sample and measuring apparatus are sufficiently stable for a measurement to commence. These methods are thus not particularly suitable for use in a high-volume vacuum glazing production process.

This paper describes a method of measuring the thermal conductance of vacuum glazing that is well suited for integration into the vacuum glazing production process. The measurement is performed as the samples cool after completion of the high temperature evacuation and bakeout process. The integration of the measurement into a necessary cooling phase of the production process can significantly reduce the overall production time for the glazing.

2. Heat flow through vacuum glazing

As noted above, heat flow between the glass sheets of vacuum glazing remote from the edge seal can occur due to radiative heat transfer between the internal surfaces of the sheets, thermal conduction through the support pillars, and thermal conduction through residual gas in the internal evacuated space [9]. Additional heat flow can occur in the vicinity of the hermetic edge seal due to lateral thermal conduction along the glass sheets [10], but this is not considered in the following analysis.

As for conventional insulating glazing, in the practical application of vacuum glazing, the overall rate of air-to-air heat flow through the glazing is significantly influenced by heat transfer processes between the external surfaces of the glass sheets and the surrounding environment. To a very good approximation for both internal and external heat transfer processes, the rate of heat flow $\dot{Q}$ through area A is proportional to A and to the temperature difference ΔT associated with the specific process. The heat flow can therefore be written in terms of a thermal conductance C for the specific process

$$\dot{Q} = CA\Delta T. \tag{1}$$

The thermal conductance associated with radiative heat flow between the internal surfaces of the glass sheets can be written

$$C_{\text{radiation}} = 4\varepsilon_{\text{effective}}\sigma\overline{T}^3, \tag{2}$$

where σ is the Stefan Boltzmann constant (5.67×10^{-8} W m^{-2} K^{-4}), $\overline{T}$ is the average temperature of the two glass sheets, and $\varepsilon_{\text{effective}}$ is the effective emittance of the glass sheets. To a good approximation, the effective emittance can be written

$$\frac{1}{\varepsilon_{\text{effective}}} = \frac{1}{\varepsilon_x} + \frac{1}{\varepsilon_y} - 1, \tag{3}$$

where ε_x and ε_y are the hemispherical emittances of the internal surfaces of the two glass sheets.

The thermal conductance associated with heat flow between the glass sheets due to thermal conduction through the array of support pillars is given by [11]

$$C_{\text{pillars}} = 2\beta ka/\lambda^2, \tag{4}$$

where k is the thermal conductivity of the glass sheets (1.0 W m^{-1} K^{-1} for soda lime glass), and a and λ are respectively the radius and separation of the pillars.

For a smooth pillar, the contribution of the pillar to the overall glass-to-glass thermal conductance is determined by the spreading resistance associated with the heat flow in the glass sheets close to the pillar. In some designs of vacuum glazing, however, the surfaces of the support pillars that contact the glass sheets are rough. The heat flow through a rough pillar is less than for a smooth pillar of the same diameter due to the additional contact resistance associated with non-uniformities in the heat flow in the immediate vicinity of the rough pillar. A factor β (termed the roughness factor here) is included in Eq. (4) to allow for this effect. Most of the samples of vacuum glazing used in this work contain smooth pillars ($\beta = 1$) in order to avoid the uncertainties associated with the measurement of β. However, data are also presented below for samples that contain rough pillars. The roughness factor for these pillars was determined by constructing an experimental sample containing both rough and smooth pillars. The small area guarded hot plate apparatus was positioned directly above individual rough and smooth pillars, and the heat flow through the metering piece was measured. There are two contributions to this heat flow: thermal conduction through the pillar, and radiation between the glass sheets. The heat flow due to radiation only was measured by positioning the metering piece of the apparatus over a

pillar-free region of the sample. The radiative heat flow was subtracted from the heat flow in the vicinity of the pillars to obtain the amount of heat flow that flows through the metering piece of the guarded hot plate apparatus due to the pillar only. The value of β is equal to the ratio of the measured heat flows through rough and smooth pillars, adjusted for the different diameters of the pillar surfaces that contact the glass sheets. There are significant variations ($\pm 10\%$) in the measured values of β for nominally identical pillars, so several pillars were measured to obtain an average value of the roughness factor. The results of these measurements are reported below.

At low pressures, the heat flow through residual gas in the evacuated space is proportional to the pressure of the gas, and this heat flow can be characterised by a glass-to-glass thermal conductance C_{gas}. In well made glazing, C_{gas} is negligible.

The glass-to-glass, center-of-glazing thermal conductance that characterises the total heat flow through the glazing C_{total} is obtained simply by adding the thermal conductances associated with heat flow due to radiation, gas conduction, and through the support pillars. This thermal conductance can be written

$$C_{\text{total}} = C_{\text{radiation}} + C_{\text{pillars}} + C_{\text{gas}}. \tag{5}$$

3. Principle of the measurement method

When this method is integrated into the vacuum glazing manufacturing process, the measurement of the sealed production samples of vacuum glazing takes place immediately after they leave the hot bake out oven. In order to prevent breakage of the glass sheets due to temperature-induced stresses, the temperature of the samples is normally no greater than about 70 °C at this time. The hot sample of vacuum glazing having total (unknown) glass-to-glass thermal conductance C_t (referred to here as the Test sample), is initially at a temperature T_h. This sample is placed in contact with a second sample of vacuum glazing of (known) thermal conductance C_s (referred to as the Standard sample). The outer glass sheets of the two samples are then cooled rapidly by forced air convection, and a measurement is made of the much slower rate at which the temperature of the contacting glass sheets of the two samples T_g decreases towards ambient temperature T_a. The rate at which this temperature decreases can be related to the thermal conductance of the two samples, and to the thermal conductance associated with heat transfer between the surfaces of the external glass sheets of the two samples and the surrounding air.

The configuration of the samples during the measurement is illustrated schematically in Fig. 2. A fine thermocouple is located between the two contacting glass sheets of the Test sample and the Standard sample. In practice, the thermocouple would normally be attached to the Standard sample. Following the positioning of the room temperature Standard sample on the hot Test sample, the temperatures of the two contacting glass surfaces equalize to a value close to the mean of their initial temperatures, and remain essentially equal throughout the remainder of the measurement. This thermocouple therefore measures the temperature of these glass sheets T_g.

The temperature of the external glass sheet of the Standard sample T_s is measured with a second thermocouple that is attached to this sheet. In the measurements presented here, an additional thermocouple is attached to the external glass sheet of the Test sample to measure the temperature of this sheet T_t. This thermocouple is not necessary in order to obtain the thermal conductance of the Test sample and need not be present when the method is used in a vacuum glazing production line.

The satisfactory operation of this method is critically dependent on being able to establish a thermal conductance associated with heat transfer between the external surfaces of the glass sheets and the surrounding air C_{g-a} that is much greater than C_s or C_t. As will be seen, this is readily achieved if air at ambient temperature is blown across the external surfaces of the Test sample and the Standard sample with a fan. The temperature T_a of this air is also measured using a thermocouple located at some convenient position.

In the following analysis, it is assumed that the Standard sample is made from glass sheets that have thickness $t_{s,i}$ and $t_{s,o}$, and the Test sample from sheets of thickness $t_{t,i}$

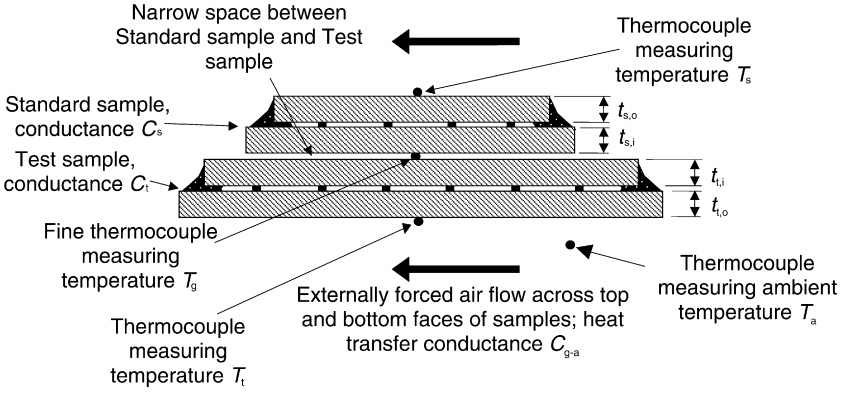

Fig. 2. Principle of the measuring method.

and $t_{t,o}$, where the subscripts i and o refer to the inner (contacting) and outer sheets, respectively. The samples are made from soda-lime glass which has a density $\rho = 2470\ \mathrm{kg\,m^{-3}}$, and specific heat $c = (813 + 1.67\theta)$ $\mathrm{J\,K^{-1}\,kg^{-1}}$ where θ is the temperature of the glass in °C.

Because of the flowing air, the thermal conductance C_{g-a} associated with heat transfer between the external surfaces of the glass sheet of the hot Test sample and the surrounding air is very large compared with that which would occur due to cooling by radiation and natural convection alone. The temperature of this glass sheet therefore decreases rapidly. If C_{g-a} is constant, the time dependence of this temperature decrease towards its steady state value is nearly exponential for the first few minutes when the temperature T_g of the contacting glass sheets is approximately constant. The time constant τ_1 for this first rapid temperature decrease is the product of the thermal resistance per unit area associated with convective heat transfer to the flowing air $1/C_{g-a}$, and the thermal capacity per unit area of the outer glass sheet of the Test sample $\rho c t_{t,o}$

$$\tau_1 = \rho c t_{t,o}/C_{g-a}. \tag{6}$$

With forced air circulation, it is straightforward to achieve a thermal conductance between the external surface of the glass sheets and the air C_{g-a} in excess of $30\ \mathrm{W\,m^{-2}\,K^{-1}}$. For 3 mm thick glass, such a thermal conductance results in a time constant for cooling of the external glass sheet of the Test sample of approximately 200 s.

Approximately $5\tau_1$ after placing of the Standard sample on the Test sample, most of the heat initially present in the external glass sheet of the Test sample has been lost to the circulating air. The temperature of this sheet is thus close to the ambient temperature. Most of the remaining heat in the assembly is in the contacting glass sheets of the Standard and Test samples. At this time, the measurement of the thermal conductance of the Test sample commences.

In order to obtain accurate results with this method, it is essential that the only significant heat losses from the contacting regions of the glass sheets are due to heat flow through the evacuated space and support pillars of the Standard and the Test samples to the external glass sheets of these samples, and from these sheets to the surroundings. There are two other possible sources of heat loss that can lead to errors in the measurement: heat transfer to air flowing in the small gap between the contacting glass sheets, and lateral heat flow along the glass sheets. The size of the gap between the glass sheets is determined by the diameter of the wires of the thermocouple used to measure T_g, and also by any residual departures from planarity of the samples. In this work, experiments in which the two glass sheets were taped together around the edges have demonstrated that heat loss due to air flow between the two samples is negligible.

It is also necessary for the lateral heat flow along the contacting regions of the glass sheets to be reduced to negligible levels. This can be achieved by positioning the thermocouple that measures T_g sufficiently far from the edges of the samples. In this work, the appropriate location of this thermocouple was determined by making measurements of the time dependence of the temperature of the contacting glass sheets at different distances from the edge seal of the sample. For glazings made from 3 mm thick glass, it was found that the thermocouple that measures T_g must be at least 80 mm from the edge seal in order that effects due to lateral heat flow along the glass sheets are negligible.

Fig. 3 shows the thermal equivalent circuit that is used to calculate the time dependence of the temperatures in the system during the slow cooling of the contacting glass sheets. The thermal capacity per unit area of the two contacting glass sheets is $\rho c(t_{t,i} + t_{s,i})$. The thermal resistance per unit area associated with heat flow from these glass sheets through the Standard sample to the flowing air is given by the series combination of the thermal resistance per unit area $1/C_s$ for heat flow through the evacuated space and pillars of this sample, and the thermal resistance per unit area $1/C_{g-a}$ associated with heat transfer from the external surface of the glass sheet to the surrounding air: $1/C_s + 1/C_{g-a}$. Similarly, the thermal resistance per unit area associated with heat transfer from the contacting glass

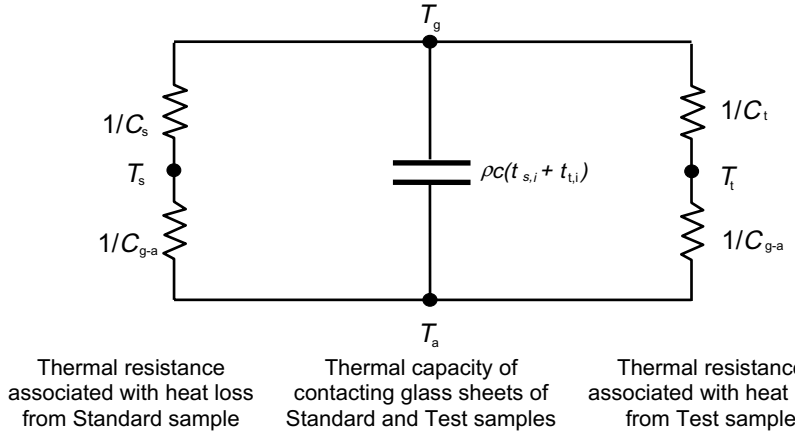

Fig. 3. Thermal equivalent circuit for heat loss from the contacting regions of the Standard and Test samples to the flowing air.

sheets through the Test sample is $1/C_t + 1/C_{g-a}$. The total thermal resistance per unit area associated with cooling of the contacting glass sheets is the parallel combination of these two thermal resistances.

For times greater than $\sim 5\tau_1$, the temperature of the two contacting glass sheets T_g decreases exponentially towards ambient temperature T_a, since all of the thermal resistances are independent of time. The time constant τ_2 for this exponential temperature decrease during this second stage of cooling is given by the product of the thermal capacity per unit area of the two glass sheets and the total thermal resistance per unit area associated with the heat loss from these glass sheets to the surroundings

$$\tau_2 = [(t_{s,i} + t_{t,i})\rho c] \times \left[(1/C_s + 1/C_{g-a})^{-1} + (1/C_t + 1/C_{g-a})^{-1} \right]^{-1}. \quad (7)$$

This equation can be rewritten to obtain the thermal conductance of the Test sample

$$C_t = \left[((t_{s,i} + t_{t,i})\rho c/\tau_2 - (1/C_s + 1/C_{g-a})^{-1})^{-1} - (C_{g-a})^{-1} \right]^{-1}. \quad (8)$$

All of the quantities in this equation are known except the thermal conductance associated with heat transfer between the external surfaces of the glass sheets and the surrounding air C_{g-a}. This quantity can be simply determined from Eq. (6) if a thermocouple is attached to the external surface of the Test sample. Alternatively, C_{g-a} can be determined from a measurement of the temperature of the external surface of the Standard sample during the second slow cooling phase

$$C_{g-a} = C_s(T_g - T_s)/(T_s - T_a). \quad (9)$$

In practice, C_{g-a} may be calculated continuously from Eq. (9) during the measurement to confirm that this quantity remains constant throughout the cooling period.

The thermal equivalent circuit in Fig. 3 does not include the effect of the thermal capacities of the outer glass sheets that are in parallel with the thermal resistances associated with heat transfer from these sheets to the flowing air. A straightforward equivalent circuit analysis of this system shows that the error introduced by ignoring these thermal capacities is less than 1%. The thermal equivalent circuit also ignores transient effects associated with the distributed thermal capacity and thermal resistance through the thickness of the glass sheets. The characteristic time for the temperatures through the thickness of these sheets to equalise is ~10 s. This is at least 100 times less than the time constant for the exponential temperature decrease of the contacting glass sheets so, again, ignoring these effects introduces negligible errors into the results obtained using the method.

In the above analysis, it is assumed that the temperatures of the glass sheets are uniform in the regions where the Standard sample is in contact with the Test sample. Strictly speaking, this is not the case because of the localised heat flow through the support pillars. The magnitude of the temperature non-uniformities that occur due to such heat flow depends on the amount of heat that flows through each pillar, and the external thermal conductance [11]. These temperature non-uniformities are usually less than about 0.5 °C, for typical experimental conditions likely to occur in this measurement. While this is quite small, the quantity $T_s - T_a$ in Eq. (9) is only a few °C. Significant errors could therefore occur in the value for C_{g-a} obtained from Eq. (9). However, most of these temperature non-uniformities occur very close to each support pillar. The magnitude of the error in C_{g-a} can therefore be reduced by locating the tip of the thermocouple that measures the temperature T_s at the center of a unit cell of the pillar array. In any case, the external heat transfer coefficient C_{g-a} has only a small effect on the value obtained for the thermal conductance of the Test sample C_t. It is therefore possible to ignore effects associated with the temperature non-uniformities on the external surfaces of the glass sheet of the Standard sample without introducing significant errors in the measured value of thermal conductance of the Test sample.

4. Experimental measurements

Experiments have been performed in order to validate the above analysis. In these experiments, custom-built samples of vacuum glazing are used as Standard and Test samples. The relevant dimensions of these samples are given in Table 1. Chromel–alumel thermocouples made from wire, 0.2 mm in diameter (including the thickness of the insulation) are

Table 1
Properties of Standard and Test samples

	Pillar separation λ (mm)	Mean pillar diameter $2a$ (mm)	Pillar type	Pillar conductance from Eq. (4) (W m^{-2} K^{-1})	Measured vacuum conductance at 13 °C (W m^{-2} K^{-1})	Gas conductance (W m^{-2} K^{-1})	Vacuum conductance at 35 °C from Eq. (2) (W m^{-2} K^{-1})	Total conductance at 35 °C from Eq. (5) (W m^{-2} K^{-1})
Standard sample A	25	0.57	Smooth ($\beta = 1.0$)	0.91	0.82	0	1.06	1.97
Standard sample B	20	0.57	Rough ($\beta = 0.76$)	1.08	0.82	0	1.06	2.14
Test sample A	25	0.57	Smooth ($\beta = 1.0$)	0.91	0.82	0	1.06	1.97
Test sample B	20	0.57	Rough ($\beta = 0.76$)	1.08	0.89	0.07	1.12	2.20

attached close to the centre of both surfaces of the Standard sample to measure T_g and T_s. The tips of the thermocouples are located at the mid-point of a unit cell of the pillar array. In some experiments, several thermocouples are used to measure the temperature of the glass sheets at different distances from the edge seal. In the measurements presented here, the temperature T_t of the outer glass sheet of the Test sample is measured with an additional thermocouple that is attached to this sheet.

In this experiment, air is flowing past the surfaces of the glass sheets on which the thermocouples are fixed. In the presence of such air flow, heat transfer between the thermocouple and the air may result in large errors in the measured temperatures T_s and T_t of these glass sheets, because of temperature gradients in the vicinity of the tip of the thermocouple. In order to obtain accurate temperature measurements, it is therefore essential that 10–20 mm of the thermocouple wires adjacent to the tip of each thermocouple is in very good thermal contact with the surface of the sheets. In the experiments reported here, the thermocouples are fixed to the surfaces of the glass sheets with adhesive tape. This problem does not exist for the thermocouple between the contacting glass sheets that measures T_g because it is not exposed to the flowing air.

The thermal conductances associated with radiative heat flow and gaseous conduction through the evacuated space C_{vac} of the Standard samples and the Test samples were independently measured using the small area guarded hot plate apparatus referred to above [7]. The effective area of this apparatus was determined by measuring the rate of radiative heat flow between uncoated soda lime glass sheets in a dynamically pumped sample. This heat flow is known to very high accuracy by integration of the infrared reflectance of the glass over all relevant wavelengths and angles for radiative heat transfer between the sheets [12]. The measurements of vacuum conductance made with this apparatus have been demonstrated to be accurate to about $\pm 1\%$.

In the measurements of vacuum conductance, the metering piece of the guarded hot plate apparatus was positioned at the centre of a pillar-free region for the custom-built samples, or at the centre of a unit cell of the pillar array for the some samples without a pillar-free region. In calculating the vacuum conductances for samples without a pillar-free region, corrections were made for the small amount of heat flow through the nearby pillars that passed through the 1.72 cm^2 area of the metering piece of the guarded hot plate. The correction factor was determined by modelling the spatial distribution of the heat flow due to a single pillar at the external surface of the glass sheets. These modelling results were validated by measuring the heat flow in the centre of a unit cell of the pillar array in otherwise identical experimental samples of vacuum glazing that also had a pillar-free region for accurate measurement of the vacuum conductance.

The guarded hot plate measurements of the vacuum conductance were made at a mean temperature of 13 °C. For gas-free samples, these conductances were scaled to the value at the average sample temperature during the cool-down measurement by multiplying them by the ratio of the cube of the respective absolute temperatures $\overline{T}^3$, according to Eq. (2). For gassy samples, only the radiative component of C_{vac} was scaled. The glass-to-glass conductance of the pillar array $C_{pillars}$ was calculated from Eq. (4) using measurements of the diameter of the contact areas of several of the pillars in each sample. For the samples with rough pillars, the roughness factor β was determined as described above. The total glass-to-glass thermal conductance of these samples C_{total} was calculated from Eq. (5) by adding the scaled vacuum conductance and the pillar conductance. The estimates of thermal conductance of the samples used in these experiments are presented in Table 1.

The glass sheets in all samples are 2.9 mm thick. All samples contain one internal pyrolytic low emittance coating. The value of the hemispherical emittance of this coating, determined by measuring the radiative heat flow in the pillar free region of a dynamically pumped sample, is 0.17. The vacuum conductance of most of the samples discussed here is close to that expected for radiative heat transfer only, indicating that the internal vacuum in these samples is quite high.

The Test sample is heated in an oven to approximately 70 °C. This sample is then removed from the oven and mounted horizontally, with approximately 90 mm space above and below to permit the free flow of air. A Standard sample is then placed onto the upper surface of the Test sample, and forced air flow commences. In these experiments, the air flow is driven by a 150 W commercial fan, approximately 0.5 m in diameter, located about 2.5 m from the edge of the sample onto which the air flows. The velocity of the air flowing past the samples was measured with a commercial meterological wind gauge, and is approximately 5 m s^{-1} in the experiments described here. A data logger is used to record the temperatures of the samples, and the temperature of the flowing air, as a function of time after commencement of the forced flow of air.

Fig. 4 shows typical experimental measurements of the temperatures of the samples as they cool down with air flowing throughout the entire measurement. In order to demonstrate the functional dependence on time of these data, they are presented as both linear, and logarithmic plots.

In all of these data, the temperature of the external glass sheet in the Test sample T_t is observed to decrease rapidly with time towards a value slightly above T_a, and then to decrease much more slowly towards T_a. From the analysis presented above, the first part of the rapid temperature decrease is expected to be exponential if the temperature of the contacting glass sheets T_g is constant. The time constant for this exponential decrease can be determined to sufficient accuracy by a logarithmic plot of T_t–T_a for the first part of the cool down period. These data are presented in this way in Fig. 4, and show that the initial rapid cool-down of the external glass sheets is indeed exponential,

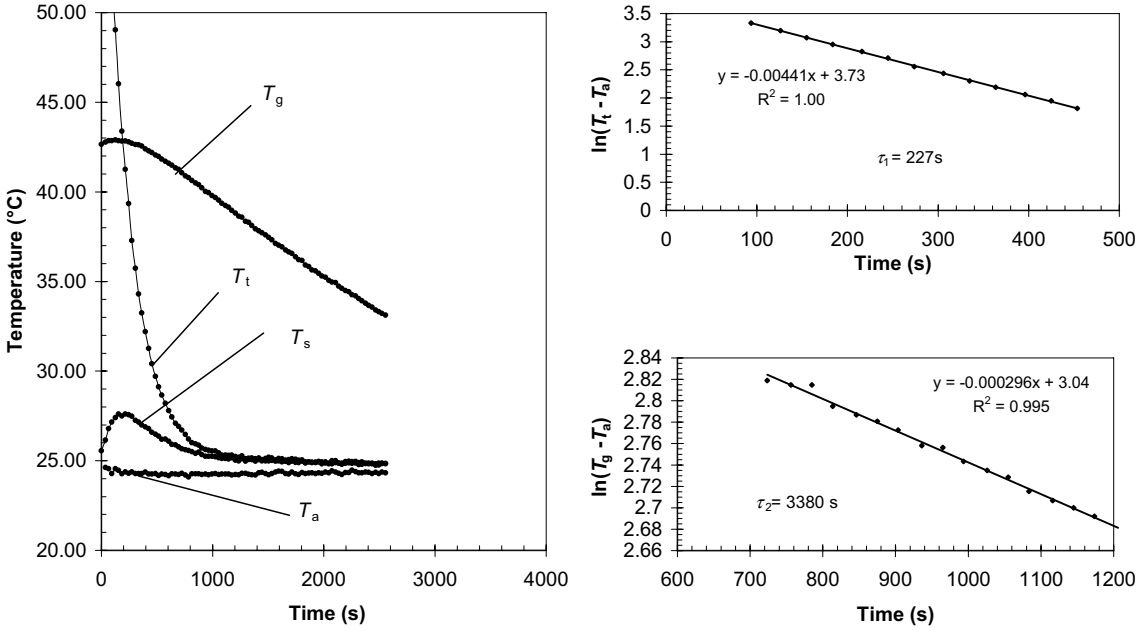

Fig. 4. Experimental measurement of temperatures of the glass sheets for Standard sample A and Test sample B.

with a time constant τ_1 of 226 s. Eq. (6) can be used to estimate the thermal conductance C_{g-a} associated with heat flow between the external surfaces of the glass sheets and the flowing air. From these data, C_{g-a} is calculated to be 30 W m^{-2} K^{-1}.

The temperature of the contacting glass sheets T_g displays a very different behaviour from that of the exposed surface of the Test sample T_t. For the first few seconds, T_g stabilises as the temperatures of the two contacting sheets become equal. T_g decreases quite slowly for the next few minutes. After about 800 s, the temperature of the contacting glass sheets above ambient $T_g - T_a$ decreases exponentially, with time constant τ_2. The behaviour predicted in the above analysis is therefore confirmed.

C_t is determined from Eq. (8) using the values of time constant τ_2 for the slower exponential cooling and values of the thermal conductances C_s of the Standard samples shown in Table 1. The estimates of the thermal conductances of the Test samples obtained with the cool down method are given in Table 2. In most cases, the results agree reasonably well with those determined from guarded hot plate measurements and calculations of pillar conductance.

5. Accuracy and reproducibility of the method

As noted above, the effective application of this method requires that the value of thermal conductance associated with heat transfer from the external surfaces of the glass sheets to the flowing air C_{g-a} is much greater than the thermal conductance of the Standard sample C_s or of the Test sample C_t. In the experimental data presented above, C_{g-a} is about 12 times greater than the typical value of C_t. When this condition is satisfied, Eq. (8) shows that the measured values of C_t are not strongly dependent on C_{g-a}. The accuracy of the method is limited by the accuracy of the calibration of the thermal conductance of the Standard sample, and on the elimination of unwanted heat losses from the contacting regions of the glass sheets.

An important factor that influences both the accuracy and the reproducibility of the method is the constancy of the temperature of the flowing air T_a. The experiments described here were performed in a non-air conditioned laboratory, and slow, but significant changes occurred in T_a over the course of the measurement. Similar variations would be expected in a manufacturing plant. In the data obtained with this method, measured values of C_t from

Table 2
Comparison of values of thermal conductance measured with the cool-down method, and obtained from guarded hot plate measurements and Eq. (4)

Samples tested		τ_1(s)	C_{g-a} from Eq. (6) (W m^{-2} K^{-1})	τ_2 (s)	C_t from cool-down data and Eq. (8) (W m^{-2} K^{-1})	C_t from Table 1 (W m^{-2} K^{-1})
Standard sample	Test sample					
A	A	200	34	3550	1.87	1.97
B	B	208	33	3090	2.33	2.20
A	B	227	33	3380	2.12	2.20

successive runs were found to be reproducible to much better than ±5%.

The heat flow through the Test sample is the difference between the total heat flow from the contacting glass sheets and that through the Standard sample. It may therefore appear that the Standard sample should be made so that its thermal conductance C_s is as small as possible. However, unless a thermocouple is used to measure T_t, or the Standard sample is preheated, the temperature difference between the external surface of the Standard sample and the flowing air must be used in Eq. (9) to determine C_{g-a}. If the Standard sample were perfectly insulating, this temperature difference would be zero, and it would not be possible to estimate C_{g-a} in this way. On the balance, the method works well if the thermal conductance of the Standard sample is approximately the same as the thermal conductance of the Test sample.

When a vacuum glazing production line is operating satisfactorily, almost all of the production samples have a high internal vacuum, and exhibit virtually identical thermal conductances. The main aim of measuring the thermal conductance of the production samples of vacuum glazing under such conditions is therefore to identify those samples that *do not* have a high internal vacuum, rather than to obtain accurate measurements of the thermal conductance of every sample. Under these conditions, the *reproducibility* of the actual thermal conductance measurements is probably more important than the *accuracy*, at least as far as the application of the method in a production line is concerned. The data from this method therefore rapidly (within about 10 min) identify defective samples, because the rate of change of the temperature of the contacting glass sheet of those samples is greater than for most of the production samples. In this sense, this method is most useful as a quality control procedure for identifying faulty samples and rejecting them, rather than as a technique for obtaining accurate measurements of the thermal conductance of every sample.

6. Conclusion

The method discussed here gives accurate and reproducible measurements of the thermal conductance of vacuum glazing samples while they are cooling down after removal from the final high temperature process in a vacuum glazing production line. The method requires the cool down of the external surfaces of the samples at the completion of the high temperature manufacturing process to be quite rapid. This is readily achieved by blowing air across the surfaces of the samples with an external fan. The method eliminates the need to measure the thermal conductance of the samples using conventional methods that require that the temperatures of the glass sheets be very stable before the measurements commence. The long time delays necessary for the temperatures of the glass sheets to stabilise may therefore be eliminated from the production process. The method discussed here thus offers the possibility of significantly increasing the efficiency of the vacuum glazing manufacturing process.

References

[1] R.E. Collins, G.M. Turner, A.C. Fischer-Cripps, J.-Z. Tang, T.M. Simko, C.J. Dey, D.A. Clugston, Q.-C. Zhang, J.D. Garrison, Vacuum glazing – a new component for insulating windows, Build. Environ. 30 (1995) 459–492.
[2] F. Zoller, Hollow pane of glass, German Patent No. 387655, 1913.
[3] R.E. Collins, S.J. Robinson, Evacuated glazing, Sol. Energy 47 (1991) 27–38.
[4] R.E. Collins, A.C. Fischer-Cripps, J-Z. Tang, Transparent evacuated insulation, Sol. Energy 49 (1992) 333–350.
[5] R.E. Collins, O. Asano. M. Misonou, H. Katoh, S. Nagasaka, Vacuum glazing: design options and performance capability, in: Glass in Buildings Conference, Bath, UK, 1999.
[6] N. Ng, R.E. Collins, M. Lenzen, Bakeable, all-metal demountable vacuum seal to a flat glass surface, J. Vac. Sci. Technol. A 20 (2002) 1384.
[7] R.E. Collins, C.A. Davis, C.J. Dey, S.J. Robinson, J.-Z. Tang, G.M. Turner, Measurement of local heat flow in flat evacuated glazing, Int. J. Heat Mass Transfer 36 (1993) 2553–2563.
[8] G.M. Turner, R.E. Collins, Measurement of heat flow through vacuum glazing, Int. J. Heat Mass Transfer 40 (1997) 1437–1446.
[9] R.E. Collins, T.M. Simko, State of the art of vacuum glazing, Sol. Energy 62 (1998) 189–213.
[10] T.M. Simko, R.E. Collins, F.A. Beck, D. Arasteh, Edge conduction in vacuum glazing, in: M. Geshwiler, J. Alger, M. Moran (Eds.), Proceedings of Thermal Performance of the Exterior Envelope of Buildings IV, Heat Transfer in Fenestration II, Florida, USA, 1995, pp. 601–611.
[11] C.F. Wilson, T.M. Simko, R.E. Collins, Heat conduction through the support pillars in vacuum glazing, Sol. Energy 63 (1998) 393–406.
[12] Q.-C. Zhang, T.M. Simko, C.J. Dey, R.E. Collins, G.M. Turner, M. Brunotte, A. Gombert, The measurement and calculation of radiative heat transfer between uncoated and doped tin oxide coated glass surfaces, Int. J. Heat Mass Transfer 40 (1997) 61–71.