# Thermal conductivity of float glass at room temperature

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When the heat transfer coefficient of multiple glazings is to be determined, it is important to know the exact thermal conductivity value of the glasses used for building purposes. The values given for flat glass lie between 0.8 and 1.15 W/(m K). The thermal conductivity of 11 float glass samples of 4 different colours, manufactured in 5 European countries, has been determined in the temperature range between 10 and 90 °C with an uncertainty of less than 1.5 %. At 10 °C, the mean value of all glasses investigated amounts to 1.022 W/(m K); the individual values vary between 1.033 and 1.017 W/(m K). On the basis of the composition, the basicity and the density, the measurement results could be well interpreted by known theoretical considerations. The slight variation of the thermal conductivity values obtained by measurement is in agreement with the values calculated from the composition and the density and can be explained by the fact that all float glasses are of nearly the same composition. By interpolation of the measurement data, coefficients could be determined to calculate the thermal conductivity from the oxide composition.

The investigation has shown that – at 10 °C – a value of 1.02 W/(m K) can be applied for the thermal conductivity of flat glasses used for building purposes, independent of their colour or manufacturer.

### Wärmeleitfähigkeit von Floatglas bei Raumtemperatur

Die Kenntnis des genauen Wertes der Wärmeleitfähigkeit von Baugläsern ist von Bedeutung für die Bestimmung der Wärmedurchgangszahl von Mehrfachverglasungen. Die für Flachglas angegebenen Werte liegen zwischen 0,8 und 1,15 W/(m K). An 11 Floatglasproben in 4 verschiedenen Farben, hergestellt in 5 europäischen Ländern, ist die Wärmeleitfähigkeit im Temperaturbereich von 10 bis 90 °C mit einer Unsicherheit unter 1,5 % bestimmt worden. Der Mittelwert für alle untersuchten Gläser beträgt 1,022 W/(m K) bei 10 °C, die Einzelwerte schwanken zwischen 1,033 und 1,017 W/(m K). Die Meßergebnisse konnten an Hand der Zusammensetzung, der Basizität und der Dichte gut mit bekannten theoretischen Überlegungen interpretiert werden. Der geringe Unterschied der Meßwerte der Wärmeleitfähigkeit steht im Einklang mit den aus der Zusammensetzung und aus der Dichte berechneten Werten und kann mit der Tatsache erklärt werden, daß alle untersuchten Floatgläser nahezu gleiche Zusammensetzung haben. Durch Interpolation der Meßdaten konnten Koeffizienten für die Berechnung der Wärmeleitfähigkeit aus der Oxidzusammensetzung ermittelt werden.

Die Untersuchung hat gezeigt, daß für die im Bauwesen eingesetzten Flachgläser bei 10 °C für die Wärmeleitfähigkeit der Wert 1,02 W/(m K) verwendet werden kann, unabhängig von Farbe und Hersteller.

## 1. Introduction

National standards and regulations on thermal insulation attribute widely different values (ranging from 0.8 to 1.15 W/(m K)) to the room temperature thermal conductivity, $\lambda$, of soda–lime–silica glass for the building industry. An accurate value of $\lambda$ is necessary to calculate the heat transfer coefficient of multiple glazing and in metrology for a number of corrections (such as edge corrections in the hot box measurement of thermal conductivity or substrate corrections in the measurement of the emissivity of coated glass).

In preparation for the standardization activities of CEN, it was therefore considered useful to perform a campaign of measurements on float glass in order to assess the range of values due to different glass compositions or production conditions that can be measured on a representative set of industrial samples.

Float glass is the standard basic product for the manufacture of insulating glass units and solar protection glazing. Non-float glass (such as cast and rolled glass) was therefore excluded from the present study. In the present context the expression "room temperature conductivity" designates the conductivity measured in a temperature range (up to several 100 °C), where thermal (or phonon) conduction is the predominant mode of transport. As explained in [1], for higher temperatures the radiation (photon) conductivity increases rapidly and soon becomes predominant. Such behaviour is due to the fact that soda–lime–silica glass is opaque beyond 5 µm. As the temperature increases, the spectral range relevant for the corresponding black-body radiation shifts to blue and progressively includes the near-infrared region where absorption bands due to transition metal ions (iron, chromium, cobalt, nickel) and hydroxyl groups are located. For higher temperatures, conductivity therefore varies quite significantly as a function of glass colour and melting conditions [1].

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Table 1. Conductivity values of float glass measured at 10, 50 and 90 °C

| temperature in °C | heat conductivity in W/(m K) | | |
|---|---|---|---|
| | average, rms deviation | minimum values | maximum values |
| 10 | 1.022 ± 0.005 | 1.017 to | 1.033 |
| 50 | 1.069 ± 0.005 | 1.063 to | 1.081 |
| 90 | 1.108 ± 0.006 | 1.102 to | 1.121 |

Table 2. Range of compositions and densities observed for the float glass samples analyzed

| composition | | density in g/cm³ measured at 20 °C |
|---|---|---|
| oxide | mass fraction in kg/kg | |
| $SiO_2$ | 0.707 to 0.728 | 2.480 to 2.518 |
| $Al_2O_3$ | 0.004 to 0.018 | |
| $Na_2O$ | 0.128 to 0.141 | |
| $K_2O$ | 0.001 to 0.011 | |
| CaO | 0.083 to 0.095 | |
| MgO | 0.038 to 0.043 | |
| $SO_3$ | 0.002 to 0.004 | |
| $Fe_2O_3$ | 0.001 to 0.006 | |
| other oxides | < 0.001 | |

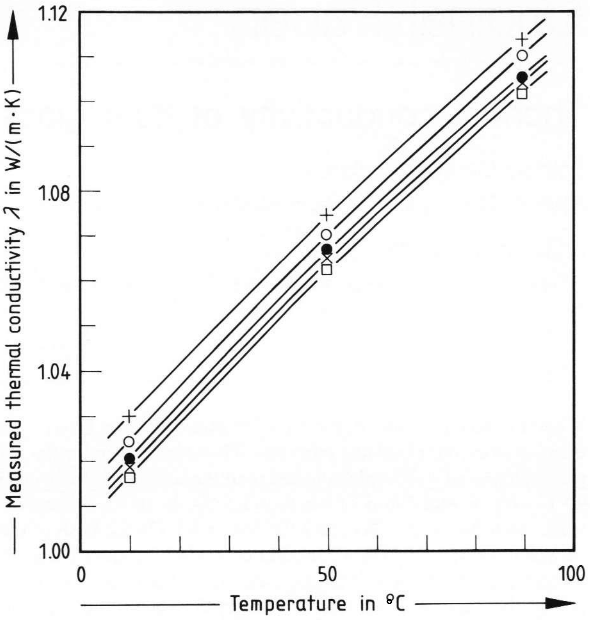

Figure 1. Plots of measured thermal conductivity versus temperature for some selected glass samples. ○ = clear no. 1, ● = clear no. 2, × = grey, + = bronze, □ = green.

As will be confirmed by the present paper, the phonon conductivity is essentially independent of the colour of the glass.

## 2. Measurements and results

11 samples of float glass of 4 colours (6 clear, 2 bronze, 2 green and 1 grey), produced in as many different furnaces located in 5 European countries were sent by GEPVP members (Groupement Européen des Producteurs de Verre Plat, Brussels (Belgium)) to PTB (Physikalisch-Technische Bundesanstalt, Braunschweig (Germany)) and analyzed using a particularly accurate hot plate apparatus. This equipment was used some years ago to calibrate a BCR reference material (BCR = Community Bureau of Reference, Brussels (Belgium)) for thermal conductivity (borosilicate glass plates). The BCR project included contributions from PTB, NPL (National Physical Laboratory, Teddington (Great Britain)), FIW (Forschungsinstitut für Wärmeschutz e. V., München (Germany)), IFT (Istituto di Fisica Tecnica, Padova (Italy)) and LNE (Laboratoire National d'Essais, Paris (France)) [2]. For such purposes PTB developed a high-precision guarded hot plate apparatus designed specifically for measurements on glass plates, and this was taken as the reference instrument for the calibration. The reproducibility attained for a given sample was 0.4 %. The agreement with the conventional apparatus used by NPL, FIW and IFT was within 1 %. It is difficult to evaluate the absolute uncertainty of the PTB data for lack of comparison with equipment of comparable level. A conservative estimate of the sum of statistical and systematic errors is better than 1.5 % [2 and 3].

For an accurate measurement the equipment requires cylindrical samples at least 8 mm thick, with a diameter of 100 mm and a surface flatness better than 10 µm. The samples were obtained by drilling shell cylindrical samples from float glass plates with a thickness of 8 to 10 mm, with an auger diamond. In some cases the surfaces were ground and polished.

The average conductivity of the 11 float glass samples measured at 10 °C was 1.022 ± ± 0.005 W/(m K) (rms (root mean square) deviation). The values actually measured ranged between 1.017 and 1.033 W/(m K). In order to assess the variation of conductivity with temperature, the samples were also measured at 50 and at 90 °C. The results are reported in table 1. As can be seen, the conductivity increases significantly (by 0.03 W/(m K), corresponding to a 3 % increase) if the measurement temperature is increased from 0 to 25 °C. This means that $\lambda$ values can be compared only if measured at the same temperature. Some discrepancies observed in the past may thus be explained by the fact that $\lambda$ values obtained at different temperatures had been compared. In figure 1 a plot of measured conductivity versus measurement temperature is shown for representative samples with various colours. As can be seen, all the samples follow a similar trend (parabolic with concavity facing downwards).

A similar behaviour was reported for Pyrex glass by Williams et al. and Hemminger et al. [2 and 3], whose results in the range from −75 to +200 °C it was possible to fit with a third-order polynomial.

In order to justify the narrow spread of values observed, the compositions and densities of the float glass samples were measured by X-ray fluorescence and by pycnometry at 20 °C, respectively. The ranges of composition and density observed are given in table 2. In view of the sampling procedure adopted, the reported compositions can be considered representative of the European market.

## 3. Discussion and conclusions

The narrow range of thermal conductivity values measured at room temperature can be explained in view of the narrow composition range typical of float glass. According to literature [4] the thermal conductivity of glass varies with composition; more specifically, it increases with the bond strength.

For example, a comparison of data at 0 °C shows that for fused silica (with 100 % Si–O–Si bonds) $\lambda$ = 1.33 W/(m K); for Pyrex glass and window glass (where an increasing percentage of siloxane bonds are "broken", i. e. substituted by weaker Si–O––modifier bonds), $\lambda$ = 1.13 and 1.05 W/(m K), respectively. (With the equipment used for the measurement here: 1.10 and 1.01 W/(m K), respectively.) Such data, measured by various authors and taken from a literature review [1], are reported to illustrate the correlation between the percentage of modifiers and conductivity rather than to provide reference values.

In the case of multicomponent soda–lime–silica glass, the percentage of modifiers can be estimated by calculating the basicity (or $O^{2-}$ ion concentration) from the composition, as suggested in [5]. The range of basicity number values for the 11 float glass samples considered is 34 to 36; in comparison, the values for Pyrex glass and for fused silica (with no modifiers) are 15.6 and 13.0, respectively.

In figure 2 the basicity numbers calculated from the composition are plotted as suggested by [5] as a function of the measured conductivity at 10 °C. The observed trend is in agreement with theoretical predictions, since conductivity is expected to increase and basicity to decrease with bond strength. Note that according to the last column of table 1 in [5] basicity numbers are computed using a weighted average of cation–oxygen bond strength. The observed narrow spread of $\lambda$ values is consistent with the narrow range of basicity numbers.

According to [4 and 6], thermal conductivity can be computed from composition and is an additive property, particularly if a narrow composition range, such as the one typical of industrial soda–lime–silica glass, is considered.

In order to verify the possibility of predicting conductivity from the chemical composition, the two following examples were selected:

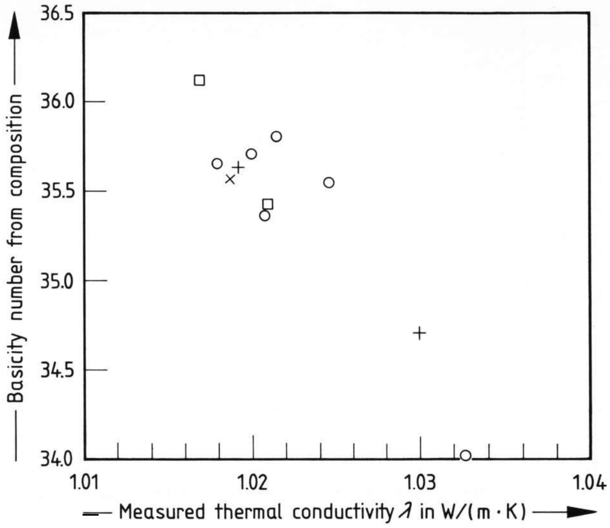

Figure 2. Basicity number versus measured thermal conductivity at 10 °C for different coloured float glasses. ○ = clear, × = grey, + = bronze, □ = green.

a) The coefficients suggested by Ratcliffe [7] were used to calculate conductivity at 0 and 100 °C; from those, the values predicted for 10 °C were obtained by linear interpolation and compared with the values measured experimentally at 10 °C.

b) The coefficients suggested by Ammar [8] were used to calculate conductivity at 30 °C; the results were compared with the experimental values at 30 °C (obtained by linearly interpolating the values measured at 10 and 50 °C).

A comparison between the measured and calculated values as already described is plotted in figures 3 and 4. In both cases a similar trend is observed: In spite of the relatively large scatter and of the difference in absolute values between predicted and measured conductivities (which can probably be explained by the fact that the equipment used to calculate the coefficients was not as accurate as the one used in the present case), the empirical equations predict a range of values as narrow as the one actually measured, as shown by table 3.

Another possibility of theoretically predicting conductivity suggested by Ratcliffe [7] is based on a simple equation of the type:

$$\lambda = a/\varrho + b \qquad (1)$$

where $\lambda$ is the thermal conductivity, $\varrho$ the measured density and $a$ and $b$ are constants which vary with temperature. For 0 °C Ratcliffe suggested 2.09 and 0.17; for 100 °C the constants are 2.30 and 0.21. It is interesting to note that the values of conductivity predicted with the same procedure at 0 and 100 °C, for Pyrex glass, are in agreement within 0.7 % with the values given in [3].

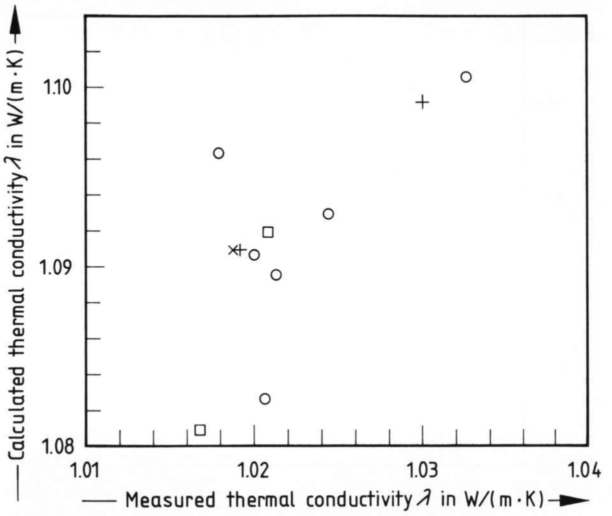

Figure 3. Thermal conductivity at 10 °C calculated from the composition according to Ratcliffe [7] versus measured thermal conductivity for different coloured float glasses. ○ = clear, × = grey, + = bronze, □ = green.

Table 3. Range of measured and theoretically predicted conductivities (in W/(m K))

| | average value | maximum value | minimum value | spread 1) in % |
|---|---|---|---|---|
| experimental results | | | | |
| at 10 °C | 1.022 | 1.033 | 1.017 | 1.6 |
| calculation procedure | | | | |
| at 10 °C from composition [7] | 1.091 | 1.100 | 1.081 | 1.7 |
| at 30 °C from composition [8] | 1.109 | 1.118 | 1.099 | 1.7 |
| at 10 °C from density [7] | 1.019 | 1.025 | 1.012 | 1.3 |

1) Computed as (maximum − minimum)/(average · 100).

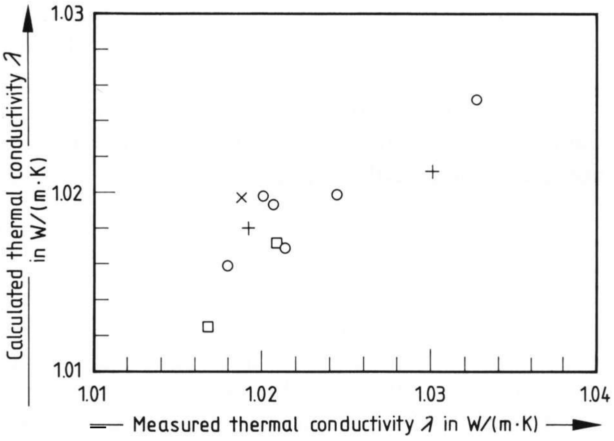

Figure 5. Thermal conductivity at 10 °C calculated from the measured density according to Ratcliffe [7] versus measured thermal conductivity for different coloured float glasses. ○ = clear, × = grey, + = bronze, □ = green.

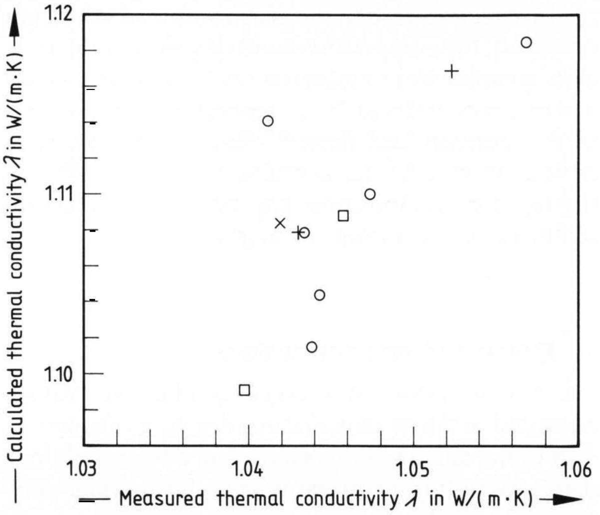

Figure 4. Thermal conductivity at 30 °C calculated from the composition according to Ammar [8] versus measured thermal conductivity for different coloured float glasses. ○ = clear, × = grey, + = bronze, □ = green.

Table 4. Interpolated values of the constant $A$ and of the coefficients $p_i$ allowing to predict conductivity at 10 °C from the composition according to equation (2)

| | | |
|---|---|---|
| constant $A$ in W/(m K) | | 2.371 |
| coefficients $p_i$ in W/(m K) for the oxides | $SiO_2$ | −1.062 |
| | $Al_2O_3$ | +0.449 |
| | $Na_2O$ | −1.952 |
| | $K_2O$ | −3.939 |
| | $CaO$ | −1.905 |
| | $MgO$ | −3.318 |
| | $SO_3$ | −2.480 |
| | $Fe_2O_3$ | −1.687 |

After computing the values at 0 and 100 °C from density for each sample, a value predicted for 10 °C was obtained by linear interpolation and compared with the corresponding experimental values. As can be seen in table 3, the agreement with the values calculated from the density is better than that with the calculation procedures based on the chemical composition. A plot of measured versus calculated values is shown in figure 5. The trend again is quite similar to the ones observed for the predictions based on the composition. In particular, again a narrow spread is predicted, as shown by table 3.

Finally, a statistical multiple regression programme was used to calculate the coefficients allowing to predict conductivity at 10 °C from the chemical composition with a linear equation of the type:

$$\lambda = A + \sum p_i x_i \,, \tag{2}$$

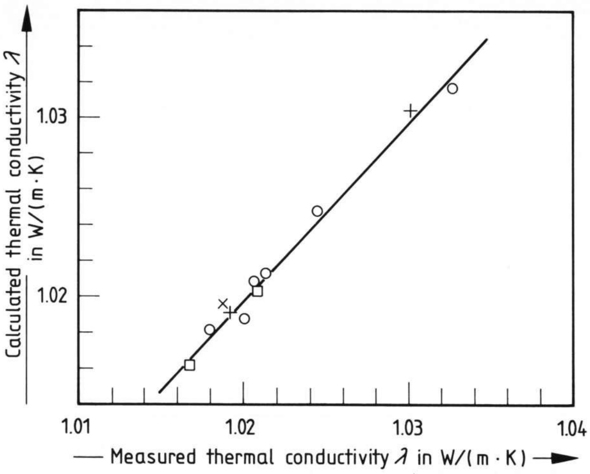

Figure 6. Thermal conductivity at 10 °C calculated from the measured composition according to equation (2) versus measured thermal conductivity for different coloured float glasses.
○ = clear, × = grey, + = bronze, □ = green.

where $A$ is a constant, $p_i$ are the coefficients for each oxide, $x_i$ are the mass fractions of each oxide, $\lambda$ is the calculated conductivity in W/(m K).

The coefficients obtained (neglecting components with $x_i < 0.001$) are reported in table 4.

In figure 6 a comparison between measured and calculated values is plotted. As can be seen, the agreement is significantly improved as compared to figures 3 to 5. On the basis of such mathematical simulations and of the composition ranges reported in table 2, it has been established that:

- the observed net scatter of $\lambda$ is moderate partly because of the substantial stability of the float glass composition and partly because the effects of variations of one component are compensated by others,
- in spite of the large relative variations of the concentration of colouring oxides, their practical influence on the room temperature conductivity is negligible.

In summary, it can be concluded that the moderate spread observed between the 11 float glass samples examined is confirmed by predictions based on both composition and density.

A further consideration is the possible influence of modified surface layers (due to the float process itself, to weathering, or to surface coatings for solar control and thermal insulation). Calculations were run to simulate the effects of surface layers with a different composition. As can be seen from table 5, even if the extent of the modification is exaggerated for the sake of argument by increasing the thickness and by attributing extreme values to the surface layer, in each case the influence on the thermal conductivity is within 1 %, i. e. within the range measured on the float glass sample.

Table 5. Influence of modified surface layers on conductivity

| modified surface layer | modelled as | conductivity variation for 4 mm float in % |
|---|---|---|
| bottom surface of float | 1 µm with 2 % $SnO_2$ and dealkalization;<br>$\lambda$ = 1.2 W/(m K) | 0.004 |
| strong dealkalization on top surface of float | 0.5 µm pure $SiO_2$;<br>$\lambda$ = 1.3 W/(m K) | 0.003 |
| coating for solar control and/or thermal insulation | 0.05 µm Au;<br>$\lambda$ = 240 W/(m K) | 0.3 |
| high-$T$ low-$\varepsilon$ coating | 1 µm $SnO_2$;<br>$\lambda$ = 30 W/(m K) | 0.7 |

In conclusion, conductivity values of 1.02 W/(m K) at 10 °C can safely be suggested for soda–lime–silica glass for the building industry, regardless of the colour.

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