

Spot Landing: Determining the Light and Solar Properties of Fritted and Coated Glass

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The use of ceramic fritted architectural glazing is becoming increasingly popular. “Fritted glass”, which is also known as “enamel glass”, is defined as glass with a surface covering made of glass frit¹ that is applied by a printing method and fused to the glass substrate at elevated temperatures. The enamel coating may be continuous or consist of a discontinuous pattern such as spots or stripes. Functional thin-film coatings on glass have been used in standard glazing units for many years to improve thermal insulation or for solar control. Specification of light and solar properties for these standard glazing types is well-defined and can be calculated on the basis of the algorithms specified in EN 410:2011 or ISO 9050:2003. This is not the case for glazing that incorporates fritted glass, alone or in combination with functional thin-film coatings. The paper initially describes the different printing options for fritted glass and the fundamental principles of functional thin-film coatings. When glass surfaces are coated with glass frit, it is essential to note that the light-scattering coatings transmit and reflect incident radiation not only directly but also diffusely. The same applies when functional thin-film coatings are combined with frit coatings. Suitable measurement methods to collect the scattered radiation, measured transmittance and reflectance spectra, and the calculation of light and solar properties on the basis of the EN 410:2011 standard are presented. At the same time, the limits of this standard and the need for its extension are demonstrated.

Keywords: Fritted glass, printing on glass, technical data, frit print, screen printing, digital ceramic printing, spectral data, measurement procedures

1. General Remarks

Wherever glass is installed in the building envelope, not only those requirements relating solely to design must be met, but also certain functional specifications relating to building energy and acoustic performance must be provided, such as thermal transmittance coefficients, total solar energy transmittance coefficient (“g value”), acoustic insulation etc. This means that the relevant technical data for these products must be made available by the glazing manufacturer not only for the widely used, thin-film-coated, non-printed glass but also for printed glass (with or without a thin-film coating), which is prepared by applying a glass/ceramic frit with a printing method such as those presented by Maniatis and Elstner (2016).

2. Manufacturing and Frit Application Processes

To help the reader understand which printing process is suitable for which products and why the relevant optical properties can often be very different in different cases, initially some of the frit application processes will be described. The most frequently used methods to apply the frit for the enamel coating on the glass substrate include: digital printing, screen printing, roller coating and “curtain” coating processes. The enamel coating is, as a rule, applied on the “air side” of the float glass pane (that is to say, on the opposite side to the “tin side”: that surface of the pane which had come into contact with the bath of molten tin during float glass production). Then, during the tempering process involved in manufacturing thermally toughened safety glass (TSG) or heat-strengthened glass (HSG), the ceramic coating is fired and fuses to the glass. In a guideline prepared by the German Bundesverband Flachglas (2014), these printing processes are described as follows.

2.1. Digital Printing

The ceramic frit ink for digital printing is applied directly onto the glass surface using a similar method to that of an inkjet printer, with the thickness of the ink coating being variable. The applied frit thickness is less than in the roller-printing, “pouring curtain” or screen-printing processes and, depending on the colour chosen, the coating appears either opaque or translucent. A high printing resolution of up to 720 dpi is currently possible. Barely visible stripes in the printing direction are typical for this production process. The nature of the process makes these unavoidable. Where the digital printing process is used, the pane edges generally remain free of frit but can display a slight bulging or beading of frit in the arched area, so that, if the enamelling process is to be appropriate to the application envisaged, note must be taken beforehand of any such edges as may remain uncovered and subject to weathering. The print edges

¹ Frit: a durable mixture of glass and ceramic particles, which may act as pigments.

are straight in the printing direction and slightly serrated transverse to the printing direction. Frit spray mist along the print edges can occur. With spot, hole and text motifs, the print edges show a serration which can, like the frit spray mist, only be discerned on close inspection. The digital printing method is particularly suitable for complex multi-colour repeated designs or images, less so for single-colour and whole-surface printing.

2.2. Screen Printing

In contrast to the other processes described, it is possible with screen printing to apply the frit paste across either the whole or just a part of the pane surface. On a horizontal screen-printing table, the paste is applied to the glass surface through a narrow-mesh screen using a squeegee; in this process, the applied paste thickness is influenced by the mesh width of the screen and the thread diameter. The applied paste thickness is less than in the roller-coating, "curtain" coating or screen-printing processes and, depending on the colour chosen, the coating appears to be either opaque or translucent. Typical for this manufacturing process is the residual visibility (depending on the colour chosen) of faint stripes or bands both in the direction of printing and also in the perpendicular direction, as well as occasionally occurring spots of slight fogging. The pane edges remain free of paste during screen printing as a rule, but can have a slight paint bead in the arressed area, making it necessary to specify clean edges if required by the intended application. Using this process, it is possible to print several colours: for example, so-called double screen-printing, in which two different colours are overlaid, such that the colour seen depends on the surface being viewed. Tolerances, e.g. for equal coverage over different areas, must be clarified with the manufacturer. Printing of selected patterned (i.e. structured) glass types is possible, but must always be clarified with the manufacturer.

2.3. Roller Coating

The flat glass pane is passed underneath a fluted rubber roller that applies the frit slurry to the glass surface. This ensures a regular, even and homogeneous distribution of the slurry across the entire surface of the pane. Typically, it is possible to see the ribbed impression from the roller if the pane is examined closely (on the printed side). Normally, however, these "ribs" are barely perceptible when the glass is observed from the front (i.e. looking in through the uncoated glass surface). Roller-coated enamelled glass panes are, as a rule, not suitable for installation in positions in which they will be visible from both sides, so that such applications must always be discussed with the manufacturer beforehand. A so-called "starry sky" (with very small pinhole defects) can occur in the enamel. Due to the nature of this application process, a certain "enamel overrun" is possible along all edges of the pane; this overrun can be slightly corrugated, especially along the longitudinal edges (viewed in the direction of movement of the roller unit). However, the edge surface will generally remain free of frit. The installation situation must therefore be agreed upon beforehand with the manufacturer.

2.4. "Curtain" Coating

The pane of glass is run horizontally through a so-called "pouring curtain" in such a way that its entire surface becomes covered with slurry. By adjusting the slurry quantity and the throughput speed, the thickness of the applied slurry layer can be controlled within a relatively large range. However, slight unevenness in the spout lip creates the risk of causing stripes of varying thickness in the longitudinal direction (pouring direction). Using this type of glass for visual-contact purposes certainly requires prior agreement with the manufacturer. Where this process is used, the "slurry overflow" at the edges is significantly greater than in the case of the roller-coating process and can only be avoided with great expense and effort. If slurry-free visible edges are required, this must be specified in the purchase order.

2.5. Further Processing and Overview

The frit/medium blends need to possess different viscosities for each different application process. Thus, for the roller coating process, for example, more fluid and less viscous slurries (i.e. with a larger organic fluid component) need to be chosen. As a result, each different application procedure will require a different drying time. After application of the frit, the printed pane is first dried (at a temperature of approx. 170 °C to 190 °C). Then the pane is thermally toughened and at the same time the enamel coating is fired onto the surface of the glass. As already mentioned, different thicknesses of this enamel coating will result depending upon the manufacturing process chosen (see Fig. 1).

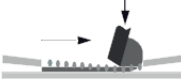
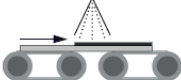

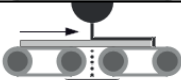
Method	Symbol	Thickness [μm]
Digital Print	-	15 – 20
Screen Print		25 – 35
Spraying		10 – 250
Roller Coating		50 – 150
Curtain Coating		150 – 350

Fig. 1 Enamel-printing application processes with resulting median coating thicknesses after firing (adapted from Krampe, 2013).

The currently available frits are available in a large number of colours, including those in the RAL and NCS colour charts. The manufacturers of such frits provide recommendations on the products and percentages to be applied in order to achieve a specific enamel colour. Up to four different additives are used, in different proportions.

3. Detailed Description of Screen Printing

The process which is currently most frequently employed for decorating glass façades is the screen-printing process. As already described, the paste is applied to the glass through a narrow-mesh screen in this process. However, in order to be better able to gauge the paste and the thickness of the enamel coating, certain parameters must be documented, because the alteration of a single parameter, or switching from one printing processor to another, can already be enough to change the thickness of the frit coating and thereby the relevant technical data for the fritted glass. Since the factor exerting the greatest influence on the quality of printing, quantity of paste and reproducibility of design is always the screen mesh, the following geometrical mesh parameters, as illustrated in Fig. 2, are decisive according to (Spirig and Sefar, 2017):

- Number of threads n in $[\text{cm}^{-1}]$ or $[\text{inch}^{-1}]$
- Thread diameter d in $[\text{mm}]$
- Plain weave (PW) or twill weave (TW)
- Mesh aperture width W in $[\text{mm}]$
- Mesh thickness D in $[\text{mm}]$
- Screen aperture a_o in $[\%]$
- Theoretical paste volume V_{th} in $[\text{cm}^3/\text{m}^2]$

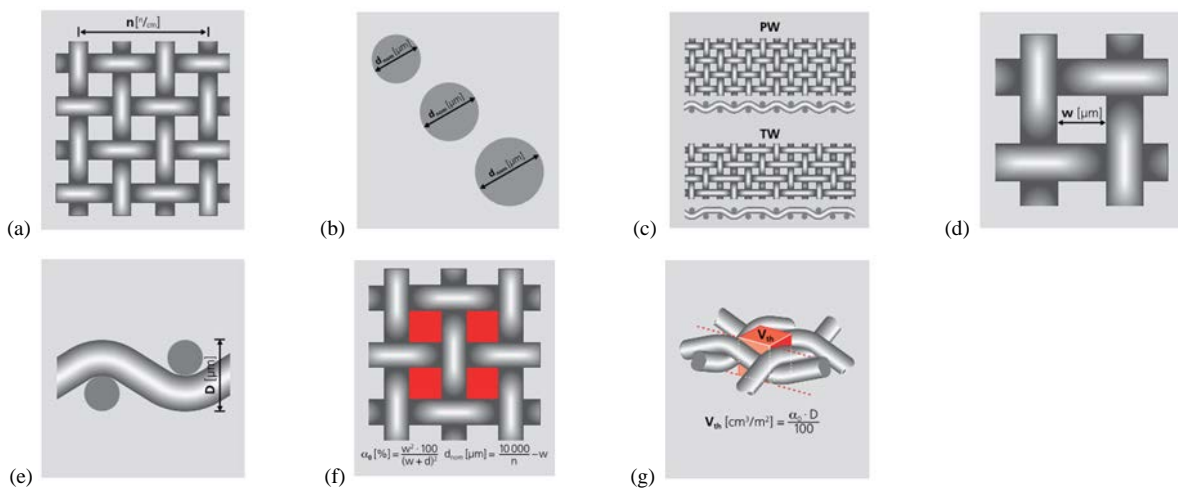


Fig. 2 Parameters of mesh geometry and their definition (adapted from Spirig and Sefar, 2017). (a) Number of threads n , (b) thread diameter, (c) weave type PW (plain weave) or twill weave (TW), (d) mesh aperture width W , (e) mesh thickness D , (f) screen aperture a_o , (g) theoretical paste volume V_{th}

As mentioned above, the designation of each respective screen must be appropriately documented, to permit correlation between the technical data established for the printed glass pane and the paste application. Since very often the technical data provided are those for panes printed across only a part of their surface, a screen must be used which is generally suitable for this type of printing and which is used by the manufacturer of the enamelled glass for partially

printed glass panes. Primarily, it is important that the design is reproduced faithfully in the printing process, with straight edges and smooth curves. In the past, the designations “68 T” or “48 T” were often used to specify the screen. The number in these designations indicates the number of threads per cm. The current designation is of the form “68 - 55 WPW”, which in this example indicates 68 threads per centimetre horizontally and vertically; a thread thickness of 55 μm ; W stands for white (as the colour of the mesh); PW indicates the weave “Taffeta 1:1” (plain weave). This is the manner in which the threads are interwoven. It should also be noted that the paste application along with the particular shade of printing colour can be different depending on the manufacturer of the printed glass. Adjusting and matching the colour to achieve the desired result in each case is imperative here. Thus, for example, two identical colours according to the RAL colour-matching system may not in fact be so when they are produced by two different manufacturers. This is due to different paste-manufacturing formulae, different lots and types of raw materials used, the firing process, the parameters used in tempering, etc.

4. Technical Data

In glazing, solar-control coatings are usually applied onto Position #2 of an insulating glazing unit to achieve the best possible g value. Since printing on glass can be used not only for design purposes but also to improve g values, it makes sense to print the frit onto the same position. In addition, if the type of enamel is suitable, the frit can also be applied to Position #1 so as to achieve the best possible solar-control effect. The total solar energy transmittance g (“g value” or solar heat gain coefficient SHGC or “solar factor”) describes the total fraction of solar radiation that is transmitted directly or as heat after absorption by the glazing. The g value is the sum of the direct solar-energy transmittance τ_e and the secondary heat transfer coefficient toward the interior q_i (referring to absorbed solar radiation that is transferred by long-wave radiation and convection). The g value is expressed in [%]. It can either be measured calorimetrically (Kuhn, 2014) or calculated on the basis of the optical data for the individual panes (e.g. the transmittance and reflectance spectra for a coated pane). If one first applies an enamel coating (i.e. made of fired frit) and then a low-e coating, the U_g value will change only very minimally compared to the case without the enamel or not at all, as the low-e coating still essentially determines the surface properties. If, however, the frit is applied on top of the coating, then the U_g value will be worse (i.e. will be higher), since the resultant enamel, consisting essentially of glass, displays a similar emissivity to that of an uncoated glass surface. Furthermore, it is to be noted that the g value will not automatically become lower when the printing coverage is increased, i.e. with an increase in the proportion of the glass surface that is screen-printed. For example, if dark colours are printed, an increase in the printing coverage results in an increase in absorptance and thus secondary heat emission, which may be so large that the g value also increases in total. This can occur especially in single glazing or in multiple-glazing units displaying a high U value.

The g value of glazing can be altered in the following ways:

- Increasing absorptance by using tinted instead of clear float glass
- Coating with selectively reflecting or selectively absorbing coatings
- Combination of absorbing glazing with selectively/non-selectively reflecting coatings
- Elements installed in the cavity, e.g. blinds, films or textiles
- Switchable glazing (e.g. electrochromic glazing)
- Integration of solar-thermal or photovoltaic elements with a view to utilizing solar energy
- Changing the position of a coating
- Changing the glass thickness
- Treatment of the glass surface in some way, e.g. by screen printing

A synoptic summary of these and other possible ways of altering the g value for various solar-control building components can be found in (Kuhn, 2017).

5. Measurement of the Spectral Data of Coated and/or Printed Glass

To determine the technical data for printed glass panes, it is first necessary to measure their transmittance and reflectance spectra, using a spectrometer. Whereas in the case of “classic” low-e and solar-control thin-film coatings, which do not scatter the incident radiation, a small so-called “integrating sphere” (diameter: up to 150 mm) suffices as a transmittance and reflectance detector, in the case of glazing which scatters transmitted and reflected radiation – e.g. fritted glazing of the sort described above – a significantly larger integrating sphere must be used and/or a greatly altered geometrical configuration for the incident light. An integrating sphere is a sphere with a white, diffusely reflecting coating on its interior surface which, ideally, permits an equally sensitive recording of all the light rays striking its interior regardless of the direction from which they come. This is necessary for also the scattered radiation to be detected. A number of measurement procedures for light-scattering solar-shading attachments which are also relevant for the measurement of light-scattering glazing are listed in EN 14500:2018; the performance requirements and classifications based on these measurements are to be found in EN 14501:2018.

5.1. Integrating Spheres for Optical Measurements of Light-Scattering Glazing

The basic problem of optically measuring light-scattering glazing is that the combination of light scattering and multiple reflections significantly increases the cross-section of the transmitted or reflected light beam as compared to that of the incident light beam (see Fig. 3). Since solar-control glazing typically has glass thicknesses of at least 6 mm, this lateral shift of the light beams means that a significant proportion of the transmitted or reflected radiation may well “miss” the integrating sphere aperture, which typically has a diameter of only 25 mm, and thus not be recorded (Polato, 2003).

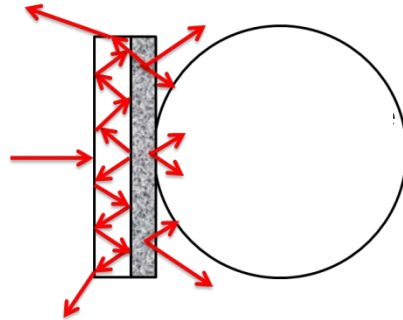


Fig. 3 Radiation laterally shifted after incidence on a light-scattering coating on an otherwise transparent glass pane. In the case where the incident beam is narrow and the aperture is too small, only a fraction of the transmitted radiation will enter the integrating sphere.

A solution to this problem with transmittance measurements is provided by using a measurement beam with a cross-section significantly larger than the aperture of the integrating sphere (“over-radiating the aperture”). In this way, lateral losses are compensated by lateral gains, as illustrated, for example, by Platzer (1992) and Milburn (1994). To measure reflectance, one option is to use a so-called “Edwards” sample holder, which is located within the integrating sphere. Where this configuration is used, all reflected beams which leave the glass pane through the radiated surface are recorded by the integrating sphere. In this case, the distance between the spot of light on the sample and the sample edge should be several times greater than the sample thickness. To simultaneously meet the geometrical conditions noted above and the usual requirement of “minimal perturbation” of the spherical geometry e.g. by apertures, larger integrating sphere diameters must be selected: in the case of the measurement results presented below, the “large” integrating spheres have a diameter of 620 mm, while the diameter of the “small” integrating sphere is 220 mm.

5.2. Measurement Results for Screen-Printed Fritted Glass from Integrating Spheres of Different Sizes

Figure 4 shows the spectra obtained at Fraunhofer ISE from measurements using two integrating spheres of different diameters (as specified above) for 6 mm low-iron glass panes which had been screen-printed with fritted coatings in the colours, RAL 9010 white, RAL 7037 dusty grey and RAL 9005 black.

The light and (solar) energy transmittance and reflectance values listed in Table 1 were calculated by weighting and integrating the solar spectra as stipulated in EN 410:2011 (Tables 1 and 2). The data clearly indicate that for the white screen-printed pane, the values measured using the smaller integrating sphere are more than 0.1 less than those measured using the larger integrating sphere.

Table 1: Transmittance and reflectance values according to EN 410:2011 for 6 mm low-iron glass panes with white, dusty-grey or black screen-printed coatings, using integrating spheres of diameter 220 mm (small) and 620 mm (large). The figures shown in parentheses are the results of measurements made using the small sphere, which are clearly too low in the cases of the white and the grey fritted glass. T = transmittance (= τ in EN 410), R = reflectance (from the glass side), R' = reflectance (from the screen-printed side), nh = normal-hemispherical, L = light, e = (solar) energy. Only the first two digits after the decimal point are significant. The third digit is used only to indicate very small differences.

Screen-Printing Colour	T _{nh,L} [-]	T _{nh,e} [-]	R _{nh,L} [-]	R _{nh,e} [-]	R' _{nh,L} [-]	R' _{nh,e} [-]
White	0.320	0.337	0.572	0.479	0.623	0.523
White (small sphere)	(0.218)	(0.244)	(0.398)	(0.347)	(0.567)	(0.459)
Dusty Grey	0.035	0.099	0.207	0.198	0.237	0.227
Dusty Grey (small sphere)	(0.031)	(0.090)	(0.179)	(0.173)	(0.231)	(0.215)
Black	0.000	0.004	0.047	0.050	0.076	0.079
Black (small sphere)	(0.000)	(0.004)	(0.047)	(0.050)	(0.076)	(0.079)

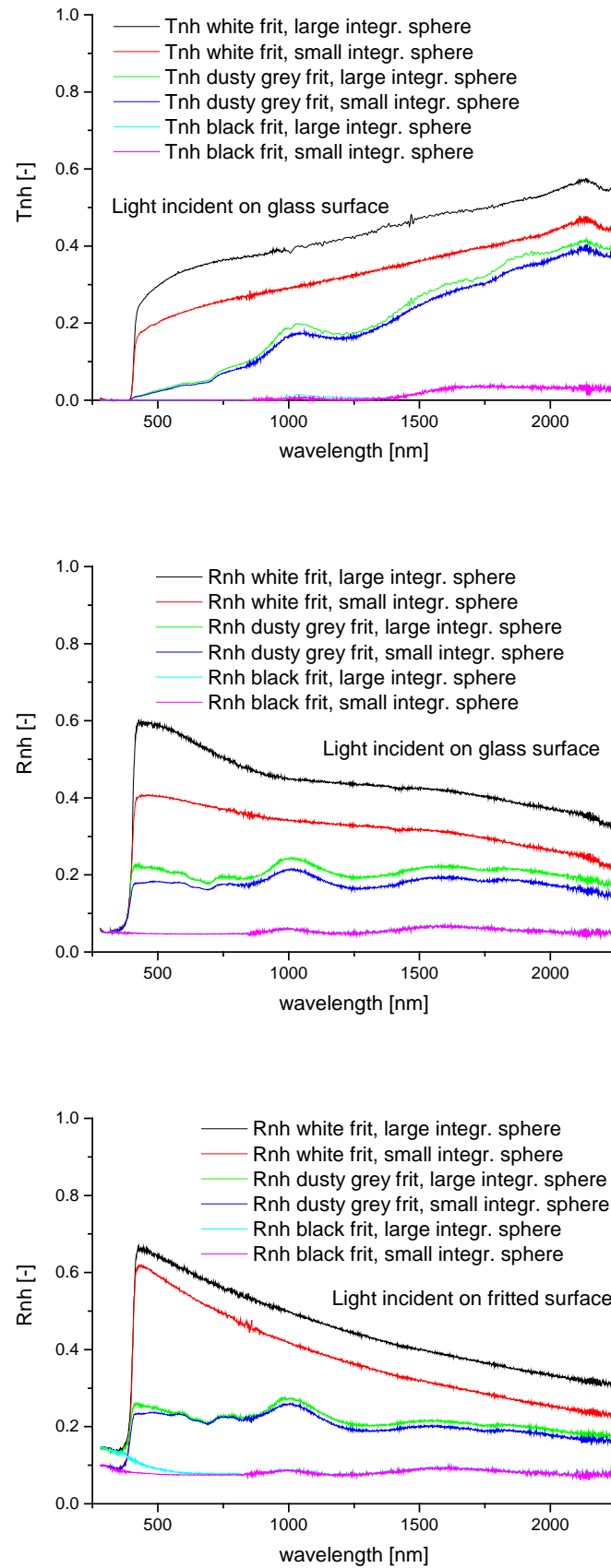


Fig. 4 Spectra for normal-hemispherical transmittance (Tnh; upper graph) and reflectance (Rnh; middle and lower graphs) for 6 mm low-iron glass panes screen-printed with white, dusty-grey and black frits, measured using integrating spheres of diameter 220 mm (small) and 620 mm (large). The measurement results obtained with the “small” integrating sphere are clearly too low in the cases of the white and grey fritted glass. In the case of the black fritted pane, the results obtained with the two spheres are almost identical.

5.3. Measurement Results for Thin-Film-Coated Glass with and without Fritted Layers

Whereas “classic” thin-film-coated solar-control glazing can be measured optically without difficulty at normal incidence using integrating spheres of typically small dimensions, thin-film-coated, fritted glass must be measured using an integrating sphere of sufficiently large dimensions, as described above, due to the light scattering. Figure 5 shows the normal-hemispherical transmittance and reflectance spectra measured in this way for 8 mm low-iron glass panes with the same type of solar-control thin-film coating, which is sputtered either directly onto the usual glass pane or onto the layer of white, dusty-grey or black screen-printed enamel. By comparing the upper graphs in Figures 4 and 5 respectively, the transmittance spectra can be qualitatively interpreted as the product of the spectra for two consecutive filters, namely the screen-printed and the solar-control coatings. For qualitative understanding of the reflectance spectra, it is helpful to divide them at a wavelength of around 800 nm at the end of the visible spectrum and to consider the visible and the near-infrared (NIR) spectral ranges separately. In the case where the glass pane is illuminated from the glass side (see the middle graphs of Figures 4 and 5), the light beam strikes first the glass, then the screen-printed layer, and finally the solar-control coating. Within the visible range, where the solar-control coating has high transmittance, the reflectance of the fritted panes with or without the solar-control coating is similar. In the NIR range, on the other hand, where the fritted panes have higher transmittance than in the visible region, the reflectance of the fritted panes is significantly higher with the NIR-reflective solar-control coating than without it. When the glass pane is illuminated from the coated side, the high reflectance of the solar-control coating is the dominating effect in the NIR range; here, hardly any radiation penetrates through to the enamel layer. Within the visible spectral range, however, the highly transmissive solar-control coating allows reflection by the enamel layer to be effective.

The same qualitative effects were observed in the transmittance and reflectance spectra for glass panes with the same three fritted coatings but a different solar-control coating (25/17). For this reason, the corresponding spectra are not shown here. However, Table 2 documents the light and (solar) energy data for transmittance and reflectance according to EN 410:2011 for both solar-control coatings and for the three frit colours (white, dusty grey and black). For each solar-control coating, all transmittance and reflectance values increase as the screen-printed colour changes from black through grey to white. Conversely, absorptance values increase as the screen-printed colour changes from white through grey to black – as, indeed, was intuitively to be expected.

Table 2: Transmittance and reflectance values according to EN 410:2011 for 8 mm low-iron glass panes with a solar-control coating, with and without a screen-printed, fritted layer, measured using an integrating sphere of 620 mm diameter. The results are shown for two different solar-control coatings, with the designation 70/37, for example, indicating a coating which, in a double-glazed solar-control glazing unit, results in $T_{nh,L} = 0.70$ and $g = 0.37$. T = transmittance, R = reflectance (from the glass side), R' = reflectance (from the coated side), nh = normal-hemispherical, L = light, e = (solar) energy. Only the first two digits after the decimal point are significant. The third digit after the point is used only to indicate very small differences.

Screen-Printing Colour	Solar-Control Coating	$T_{nh,L}$ [-]	$T_{nh,e}$ [-]	$R_{nh,L}$ [-]	$R_{nh,e}$ [-]	$R'_{nh,L}$ [-]	$R'_{nh,e}$ [-]
None	70/37	0.758	0.393	0.081	0.395	0.087	0.439
White	70/37	0.152	0.078	0.534	0.487	0.315	0.527
Dusty Grey	70/37	0.022	0.013	0.185	0.194	0.151	0.457
Black	70/37	0.012	0.006	0.046	0.055	0.068	0.429
None	25/17	0.262	0.173	0.643	0.682	0.339	0.531
White	25/17	0.073	0.048	0.566	0.501	0.378	0.539
Dusty Grey	25/17	0.005	0.006	0.186	0.196	0.349	0.528
Black	25/17	0.004	0.003	0.046	0.054	0.335	0.521

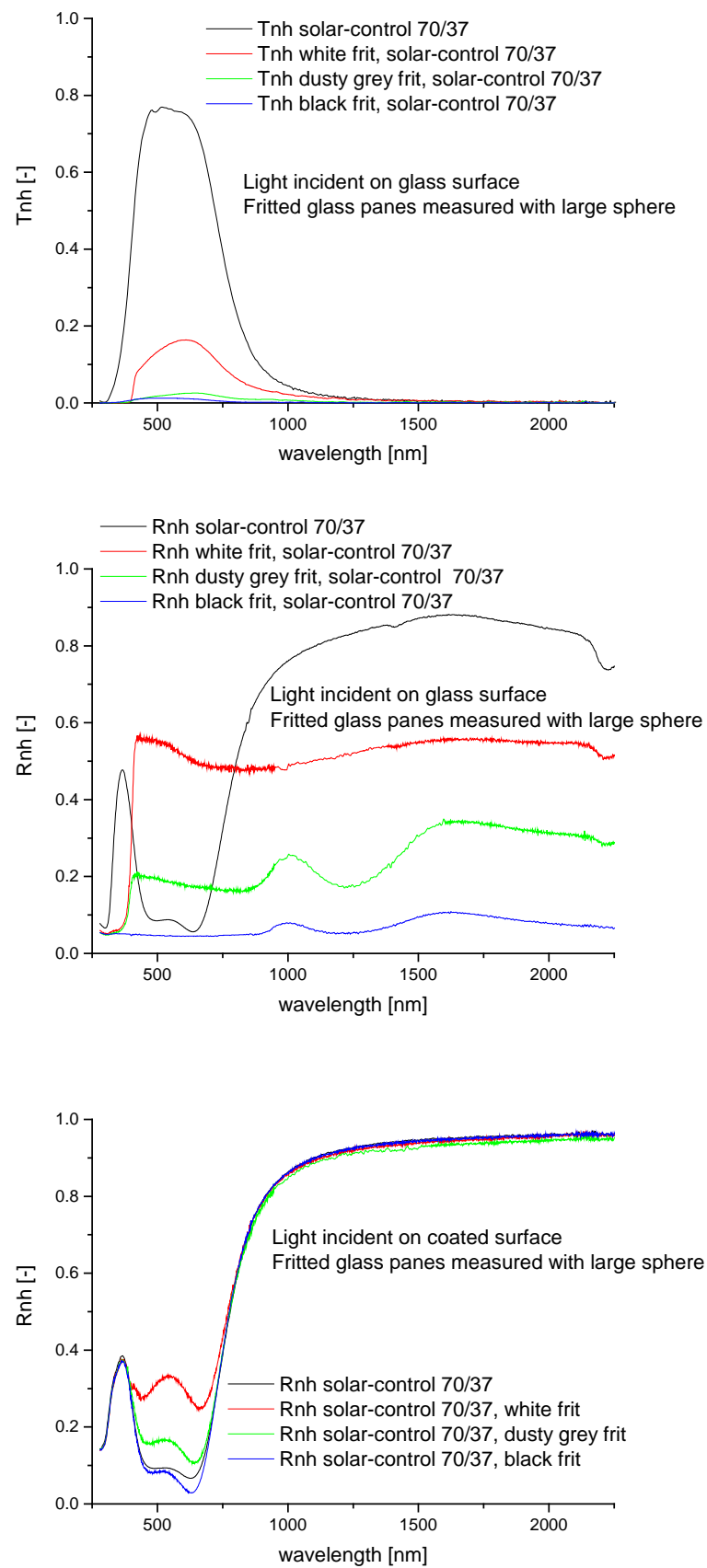


Fig. 5 Spectra for normal-hemispherical transmittance (Tnh; upper graph) and reflectance (Rnh; middle and lower graphs) for 8 mm low-iron glass panes with white, dusty-grey and black fritted coatings combined with a thin-film solar-control coating. An integrating sphere of 620 mm diameter was used for the measurements.

6. Determination of Further Technical Data for Printed and Coated Glazing according to EN 410 and its Limits

From the integrated values for normal-hemispherical transmittance and reflectance given in Tables 1 and 2, the g and q_i values for an individual glass pane can be calculated according to the methods specified in EN 410:2011. The method (also described in EN 410:2011) of weighting by relative surface areas for calculating the technical data of a partially printed glass pane – with or without a thin-film coating – is a well-established approach, provided the enamel layer is on one surface only of the pane in question. As soon, however, as both surfaces of a glass pane are completely or partially printed, this method of weighting by relative surface areas is no longer sufficient, since it is fundamentally unable to take the spatial relationship of the two printed surfaces of the pane into account.

The EN 410:2011 standard is formulated for the case where normally incident radiation continues, in transmission, without any change in direction and after reflection, in exactly the opposite direction. In the case of light-scattering panes within multiple glazing, where this condition is not met, differences must be expected between the results measured directly for such multiple-glazed units and the values calculated according to EN 410 on the basis of the normal-hemispherical spectra of the single glass panes. In the case, however, of strongly absorptive screen-printed frits and low-angle light scattering, it can be expected that these differences will be minimal. The magnitude of the difference can be calculated using bi-directional scattering distribution functions (BSDF) for the individual panes, which can either be measured experimentally or be calculated theoretically with the help of material models and ray-tracing. The “four-flux” model, which treats diffuse and direct radiation separately in calculating both transmittance and reflectance, and which is applied, for example, in ISO 15099:2003, must be ranked, in terms of its accuracy, somewhere between the approach prescribed in EN 410:2011 and ray-tracing calculations based on bi-directional scattering distributions. It is to be expected that such methods will be used increasingly often in future. Meanwhile, however, it already represents a significant advance if the spectra of single light-scattering panes are measured, as described above, with integrating spheres that are, in fact, large enough for the task.

Attention must also be explicitly drawn here to the fact that the procedure described in Annex B of EN 410:2011 for calculating the optical properties of laminated glass is not valid in the case where a light-scattering enamel frit is to be found “inside” the laminate (i.e. where the enamel layer is located between the glass substrate and the laminating interlayer). The equations proposed in Annex B were derived applying the assumption that the coatings involved would not be light-scattering; they no longer apply in cases where the direction of radiation is altered as a consequence of scattering or light redirection.

7. Summary

After a description of various techniques by which glass frit is applied to glass panes by printing, and of the specific characteristics of these techniques, the metrological determination of the normal-hemispherical transmittance and reflectance spectra of fritted and coated glass was discussed. An important aspect here is the use of integrating spheres, the apertures of which are “over-radiated” and large enough to capture laterally shifted light, without the spherical geometry being significantly perturbed by the apertures. In this way, it is possible to determine the light and solar properties of individual fritted glass panes with the enamel on one side only – with or without a thin-film solar-control coating – reliably in accordance with the approaches specified in EN 410:2011, as has been demonstrated here using specific data measured on panes of this type. With regard to geometrically more complex glazing, however, there remains a need for further research which, in all likelihood, will involve recourse to bi-directional scattering distribution functions.

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