Angle dependent solar transmittance of collector glazings

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Abstract - The angle dependent change in transmittance - the incident angle modifier (IAM) - for solar radiation of surface structured and unstructured glass sheets was measured in the range of $\alpha = 0°$ to 70° relative to normal incidence by a new laboratory based equipment. The surface structures examined are embossed inverted truncated cones which are arranged in a rhombic or in a quadratic grid. Unstructured glass shows a decrease of the transmitted intensity down to 78 % at an angle of 70° compared to normal incidence. This behaviour of transparent materials is well known and can be explained by Fresnels theory. Surface structured glass qualitatively shows the same behaviour for the change in solar transmittance but the decrease is much stronger with increasing angle. Depending on the orientation of the structured surface relative to the light source and the detector the relative transmittance was observed to be higher up to an angle of 65° if the structure faces the light source. For the whole measured range, i.e. up to an angle of 70°, the IAM of the quadratic structured glass remains at lower values than the one of the rhombic structured glass. In case of the rhombic structure the relative transmittance was observed to depend also on which diagonal the rotation axis of the incident radiation corresponds to.

1. INTRODUCTION

The energy efficiency of solar thermal collectors and solar cells is determined by their design. In solar thermal collectors the design includes the solar absorber with the piping, the housing of the absorber with the thermal insulation and the glazing. The application of the glazing is in order to improve the efficiency and for protecting the absorber and the insulation.

In order to avoid unacceptable and bothering mirror effects as well as to impede a clear view inside the collector at least one side of the glass sheet is macroscopically structured in many cases. So, the transmittance of electromagnetic radiation through the glass is not only influenced by the chemical composition and the thickness of the glass but also by the geometrical shape, the dimension of this shape and its orientation relative to the suns movement.

Under normal conditions each glass surface reflects about 4 % of the solar radiation because of natural reasons (Feynman, 1988; Born & Wolf, 1980). Thus, in solar thermal collectors at least 8 % of the suns radiation is lost by reflectance due to the application of one glazing sheet in front of the absorber. With increasing angle of incidence, the reflection losses are coming up to 27% at 70°, whereas the absorptance of the bulk material still remains below 2%, in case of low-iron glass is used. This means, that the surface of the glass is of major interest.

The aim of this work is to show the change in transmittance in dependence to the angle of the incident radiation (incident angle modifier = IAM) for different structured and unstructured glasses which are applied in solar thermal collectors. The angle dependant relative transmittance of the glasses with the structured surface facing the light source or the detector was measured, too.

2. EXPERIMENTAL

The schematic of the experimental configuration for the measurements is shown in Fig. 1. Glass samples with a minimum size of 8 x 8 cm^2 and a maximum size of typical collector glazings can be measured. For light source an LTI-AMKO Xenon high pressure lamp equipped with a elliptical mirror is used. The spectral range of this lamp is 280 - 2500 nm with the highest spectral density in the range of 790 - 1020 nm. In the second focal point of the elliptical mirror a diffusor is placed in order to a get a homogenous light beam. To avoid heating of the integrating sphere a stop aperture with a diameter of 4 cm is installed in front of it, in Fig. 1 named 'aperture'.

The integrating sphere has a diameter of 7 cm and is made of PTFE. Its aperture has a circular opening of 1.6 cm in diameter. As the sphere has only one opening, the transmittance measurements have to be performed with the so called substitution method, leading to an overestimation. However, as only the ratio of transmittance at angle α to normal transmittance are considered (i.e. the IAM), the values reported are not affected by the sphere error any more.

The transmitted radiation was detected by a thermally compensated thermopile of DEXTER RESEARCH (Type 1SC) or a silicon photo diode, respectively. The homogeneous spectral sensitivity of the thermopile ranges from the UV to the far IR. While the range of the photo diode is 280 - 1000 nm with it's maximum sensitivity at 800 nm. All values reported here are based on measurements with the photodiode.

In addition the spectral near normal direct-hemispherical transmittance and reflectance of the unstructured glass samples was measured with a Bruker FTIR spectrometer. Basing on these measurements and on values reported in literature [Ealing], the spectral variation of the index of refraction n was estimated to be within [1.48 – 1.54] and the extinction coefficient K was estimated to be within [0.5 – 4.0] m^{-1} in the spectral range of 400 nm to 1800 nm. This range covers more than 91 % of the AM1.5 hemispherical solar irradiance [ISO 9845-1]. Calculations of the IAM using Fresnel's theory show that the influence of this bandwith of the material properties onto the IAM will be less than 0.5 % up to an incidence angle of 70°.

To determining the geometrical shape of the structured glass surfaces the topography was measured with an optically working 3D surface profiler, Fig. 2. For sample 1 we used glass with embossed truncated cones arranged in a rhombic grid. with the dimensions of 1 mm (Fig

2a and insert of Fig. 3a). For an other sample 2 the cones embossed are arranged in an orthogonal and almost quadratic grid with the dimensions in the range of 0.9x0.9 mm^2 (Fig. 2b and insert of Fig. 3b). The deepness of the embossed cones is little less than 0.1 mm for both samples.

The two samples were measured with the light source illuminating the structured side ('structure outside') as well as the smooth side ('structure inside') of the glass pane. The light source was moved around axis $A_j(i)$ (j = r, q with r = rhombic, q = quadratic; i = 1, 2).

In order to be able to exclude a different behaviour of the IAM caused by different material properties, the structure of both glasses was removed by abrading and polishing. This unstructured glass samples are assumed to be invariant to different axis $A_j(i)$.

3. RESULTS AND DISCUSSION

In Fig. 3 the measured IAM data for the different glasses are shown. For both samples a comparison is given in between the resulting measurements with the structure removed and Fresnel's theory (with n = 1.51, K = 2 m^{-1}). As can be seen the accordance of the measured values and the theory is excellent. Both materials are showing the same angular dependency within the uncertainty of the measurement. The loss in transmittance is moderate up to an angle of 70° were the IAM still is above 78%.

Up to an angle of 40° the difference of the IAM of the glasses is marginal, independently if the surface is structured or not. Above 40° the IAM is almost linear decreasing with an increasing angle of incidence in case of the quadratic structured glass with the structure facing the detector ('structure inside'). The same linear dependency is observed with the rhombic structure facing the detector, but at angles above 50°.

For both samples the IAM is significantly higher if the structure is oriented to the light source for angles up to approximately 65°. At an angle of about 63° to 67° the curves for the structure inside intersect the curves for the structure outside in the range of 70% for both structures and both orientations of the axis of rotation.

For the quadratic structured glass there is only a small difference measured if the light source is moved around the longitudinal axis $A_q(1)$ or the diagonal axis $A_q(2)$, respectively (Fig. 3b). Astonishingly, the difference is much more pronounced in case of the rhombic structured glass (Fig. 3a). Based on symmetry considerations of the axis $A_r(1)$ and $A_r(2)$ this behaviour was not expected.

4. CONCLUSIONS

The angle dependent relative transmittance of solar radiation of glazings for solar thermal collectors was measured. The transmittance is higher for glass with an unstructured surface compared to a roll embossed inverted cone like structured surface. If the structure faces the light source the IAM is higher compared to the IAM with the structure facing the detector up to a certain angle. A slightly higher transmittance is reached by moving the light source around the shorter diagonal axis of the rhombus.

As for energy conversion the absolute value of the angle dependant solar transmittance is of more interest than a relative value as the incident angle modifier, a new apparatus will be set up including an integrating sphere with 2 sample ports. Furthermore, the broadband detector will be replaced by a spectrophotometer. With this modifications it will be possible to measure the angle dependant solar transmittance even of spectrally non flat materials, such as plastics or coated glass sheets.

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REFERENCES

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Figure captions

Fig. 1: Schematic of the experimental setup.

Fig. 2: Surface topography of a rhombic a) and a quadratic b) surface structured glass.

Fig. 3: Relative transmittance versus angle of incidence (IAM) of rhombic a) and quadratic b) structured glass sheets.

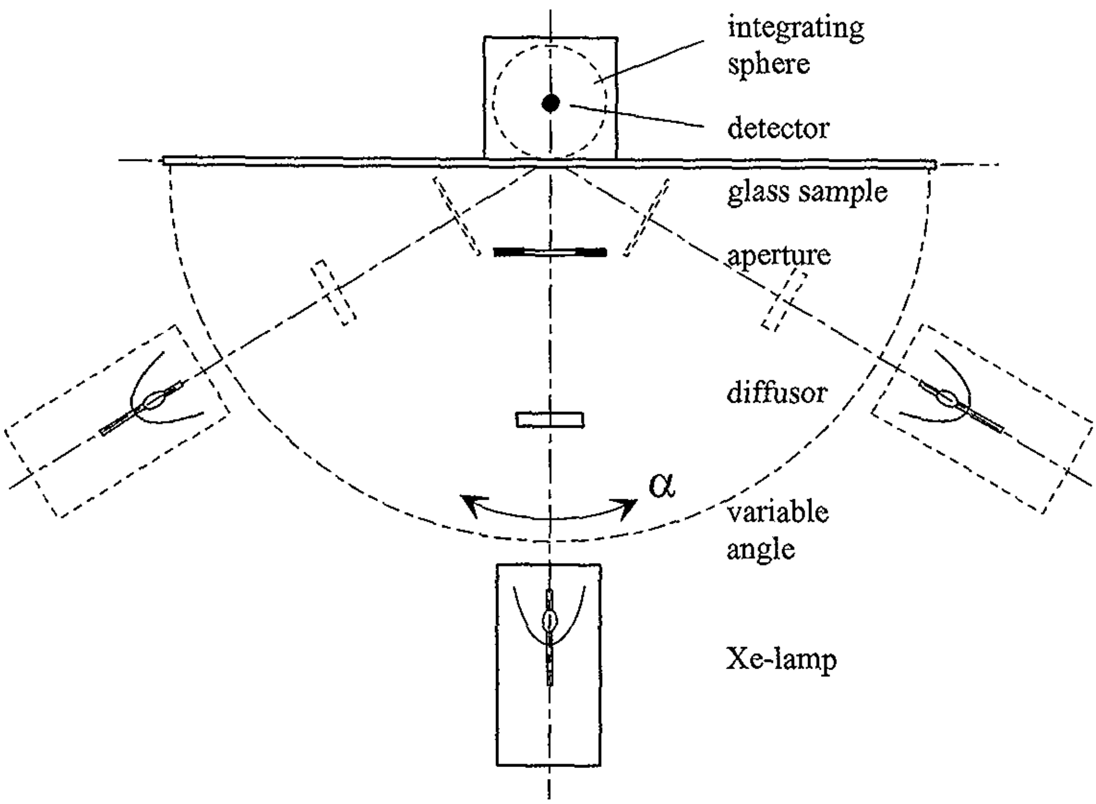


Fig. 1: Schematic of the experimental setup.

Fig 1

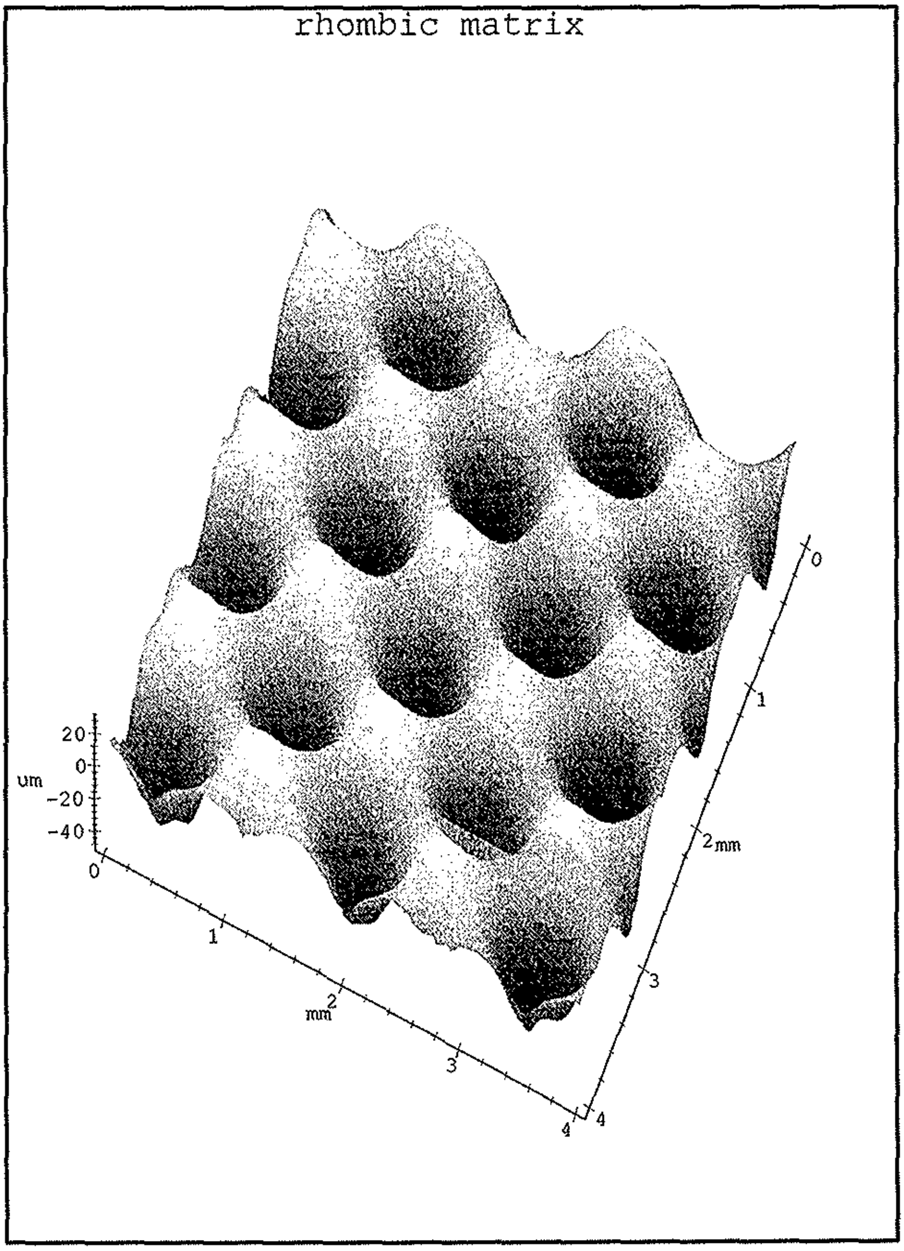

rhombic matrix
20
0
um
-20
-40
0
1
mm 2
3
4
0
1
2 mm
3
4

Fig 2a

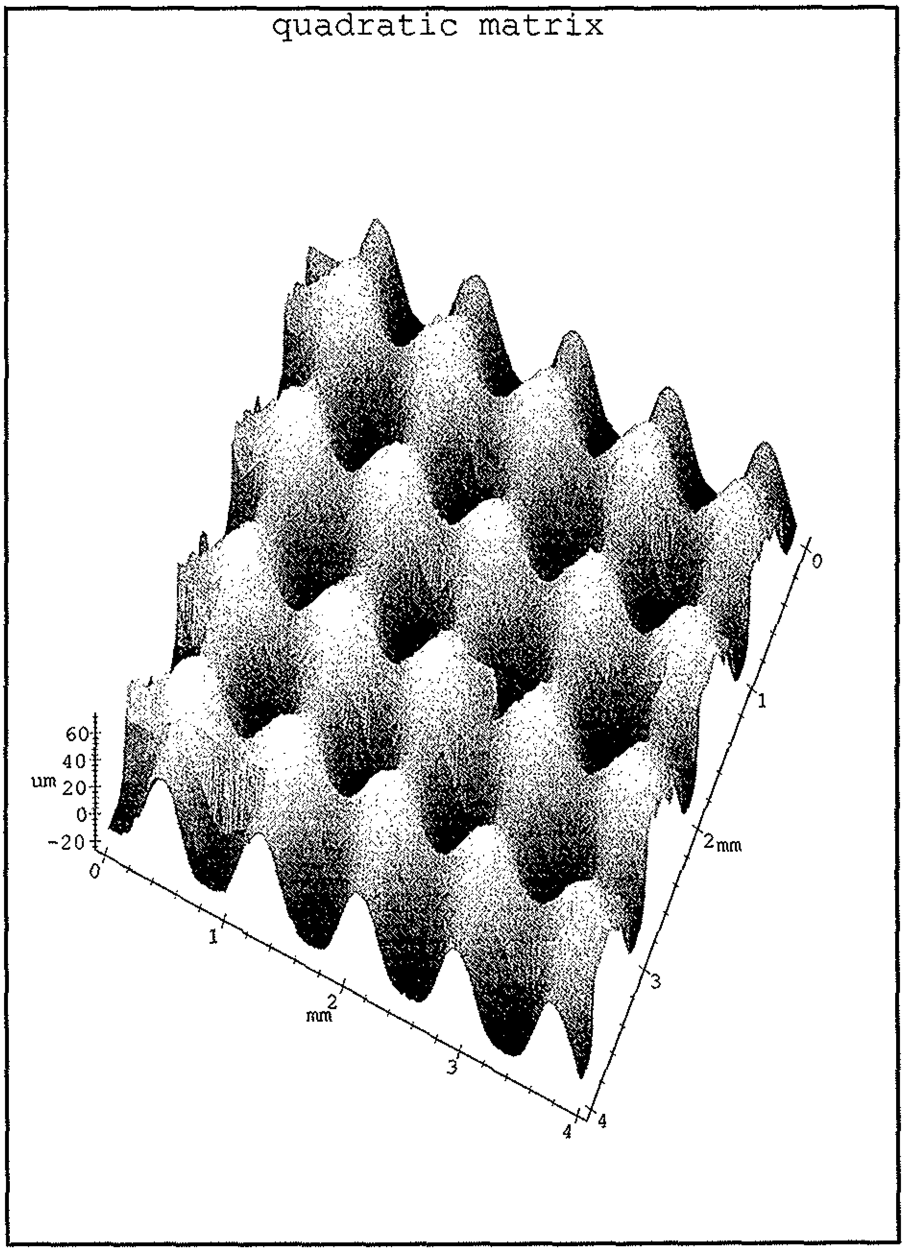
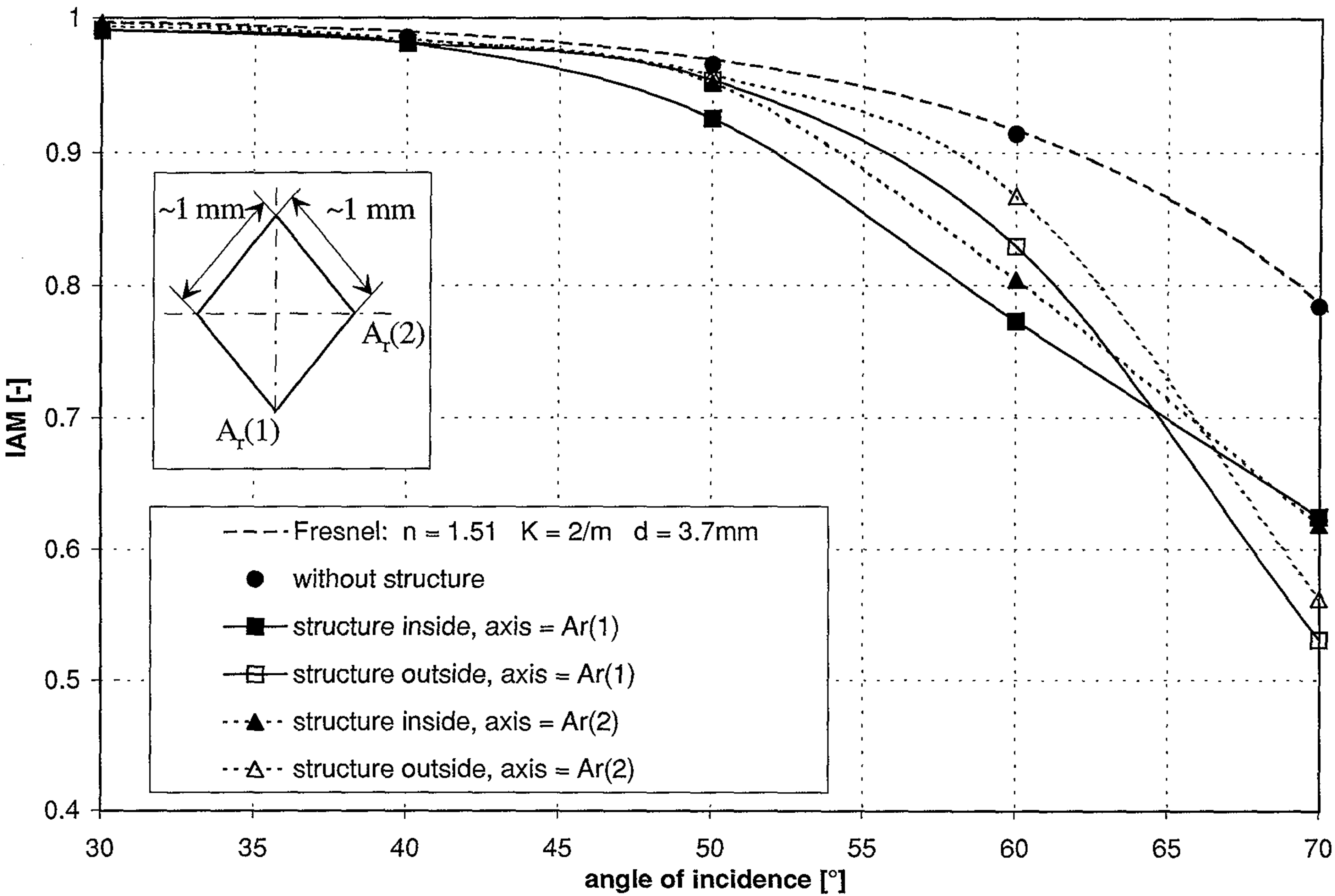

quadratic matrix
60
40
um 20
0
-20
0
1
2
mm
3
4
0
1
2mm
3
4

Fig 2b



IAM [-]
angle of incidence [°]
~1 mm
~1 mm
Ar(1)
Ar(2)
Fresnel: n = 1.51 K = 2/m d = 3.7mm
without structure
structure inside, axis = Ar(1)
structure outside, axis = Ar(1)
structure inside, axis = Ar(2)
structure outside, axis = Ar(2)

Fig 3a

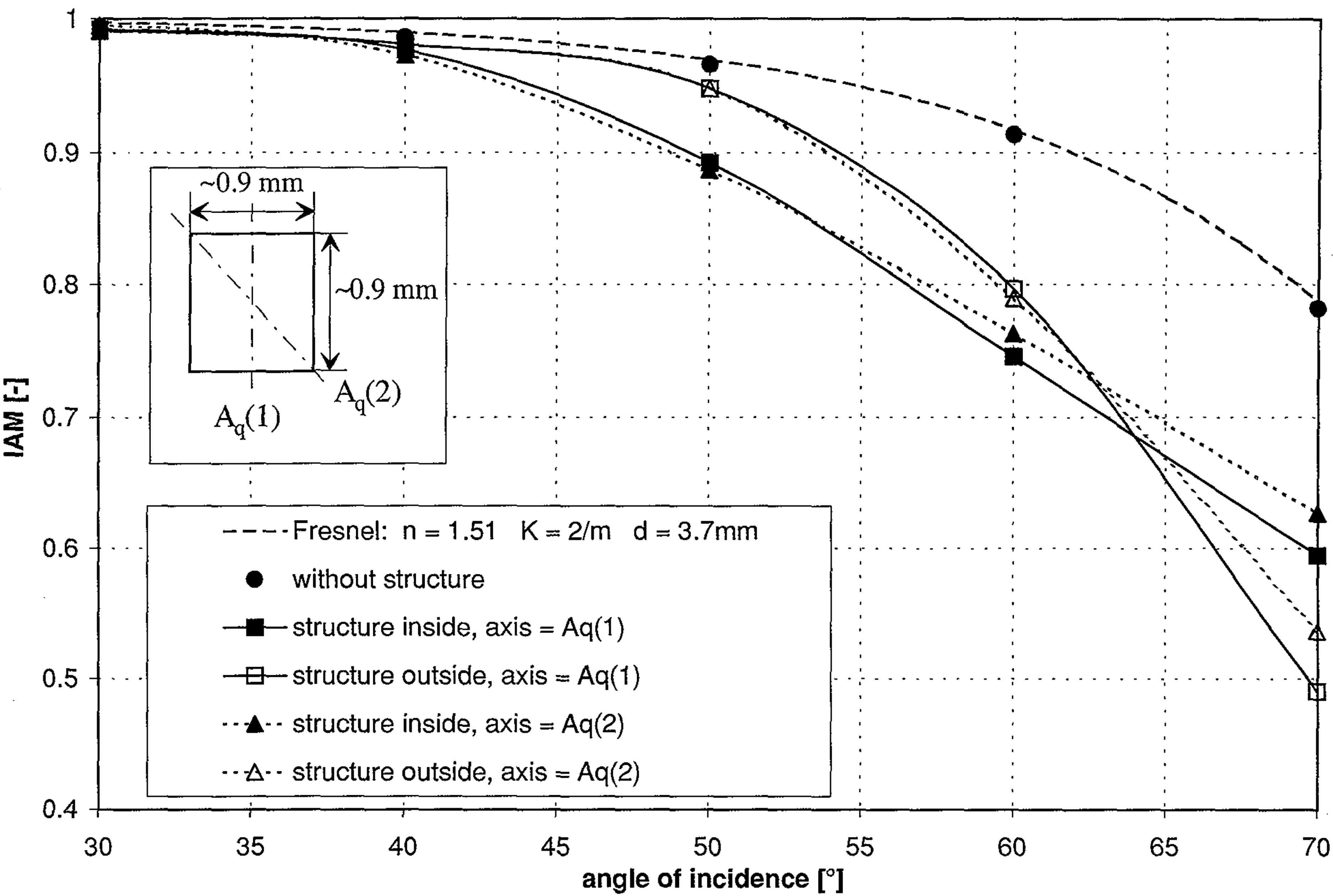

~0.9 mm
~0.9 mm
Aq(1)
Aq(2)
Fresnel: n = 1.51 K = 2/m d = 3.7mm
without structure
structure inside, axis = Aq(1)
structure outside, axis = Aq(1)
structure inside, axis = Aq(2)
structure outside, axis = Aq(2)
IAM [-]
angle of incidence [°]
1
0.9
0.8
0.7
0.6
0.5
0.4
30
35
40
45
50
55
60
65
70

Fig 3b