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A Portable Technology for Measuring Haze Levels in Thick Laminated Glass Panels

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Abstract

Increasing security concerns and a trend towards larger glass panels are driving the adoption of thicker laminate glass panels in prominent architectural works worldwide. However, the polymeric materials used in these laminates can lead to haze, a detrimental optical defect that impairs transparency perception, particularly when used in thick, multi-layer laminates. This work presents a novel technology capable of accurately and robustly measuring haze in glass laminates of arbitrary thickness, based on using computer vision to measure changes in contrast when viewing a standard mask through the material under controlled diffuse lighting conditions. Unlike previous approaches, this technology can be employed on installed glasses without requiring exposed edges for double-sided measurements, making it suitable for on-site work. The experimental evidence provided indicates that its precision and robustness are adequate for quality control.

Keywords

Haze, laminate, hazemeter, thick, transparency perception

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1. Introduction

Glass has become an increasingly prominent material in modern architecture, valued for its association with quality, cleanliness, and the ability to create open, visually connected spaces. This trend necessitates the use of thicker laminated glass elements for structural purposes. However, thicker formats pose challenges during lamination. Slower cooling times, often associated with larger formats, can introduce optical changes in the laminating polymer, leading to haze and a perceived reduction in clarity.

While established standards exist for quantifying haze in thin plastic sheets used in packaging, these are not applicable to thick laminated glasses used in architectural applications. The subjective nature of haze perception, further influenced by varying lighting conditions, can lead to disputes regarding the acceptability of the final product.

Given the significant cost of these architectural glass elements, a standardized method for haze measurement is crucial. This requires a defined technology and protocol for objective haze quantification. However, establishing a standard also necessitates linking these objective measurements with human visual perception under various conditions.

To address this need, this work presents our efforts towards defining such a standard. We propose a new technology for haze measurement and describe an initial prototype for its implementation. The prototype's performance is evaluated through experiments where (relatively thin) glass laminates are measured using a conventional hazemeter. Finally, we discuss the potential of this technology as a practical tool for haze determination in thick architectural laminates.

This research was conducted for a retail brand that also provided the samples used in the experiments presented below.

2. Understanding haze

2.1. The physical phenomenon

Haze is an optical parameter that quantifies the scattering of visible light as it passes through a transparent material. According to the International Lighting Vocabulary (International Commission on Illumination, 2011), transmittance haze is defined as the "reduction in contrast of objects viewed through it", while most established standards consistently define haze as the percentage of transmitted light that deviates from the incident beam by more than 2.5°.

Traditionally, the concept of haze has been applied to polymeric sheets used extensively in packaging and specific glass applications, such as automotive windshields to measure a kind of distortion caused by the scattering of light as it passes through an otherwise transparent material. However, it is important to distinguish between haze and clarity in optical characterization, both of which being visual phenomena caused by diffraction in transparent materials.

Haze involves scattering only a portion of the light rays, but those scattered deviate at high and random angles. Conversely, a lack of clarity arises from interactions that scatter a significant portion of the light, primarily at small angles (see Molloy et al. 2023).

The particular type of scattering responsible for haze originates from either Mie or Rayleigh scattering, depending on the dominant size of the microstructures causing it (Molnár et al. 2020):

Rayleigh scattering is responsible for the blue sky and occurs when light interacts with particles smaller than its wavelength. It scatters light of different colors unevenly, leading to tonal shifts.

Mie scattering, by contrast, is caused by particles larger than the wavelength, Mie scattering produces a white, more uniform type of scattering.

In glass laminates, the microstructures responsible for haze are believed to be micro-crystals formed during the cooling process (Moreau 2020). The growth of these crystals is known to be directly linked to the laminate's cooling time.

2.2. Visual impact

The visual perception of haze on laminated windows is a complex phenomenon that can significantly impact the viewing experience. Nonetheless, it is useful to contrast its effects to those of clarity.

Let us consider an observer looking at the background through a hazy window. The distortion introduced by Mie scattering (the likely cause of haze in most cases) leads to a type of distortion where the image remains recognizable and quite sharp to the observer, while its contrast is noticeably diminished (see Fig 1).

Note that, in contrast, a lack of clarity would distort the background image due to significant edge blurring. In this case, while contrast might be partially preserved, the scattered light from bright areas minimally overlaps with the rays from darker regions, resulting in a blurred image.

One of the most noticeable effects derived from this type of phenomenon is the creation of a plastic-like feel. This contradicts the intention of making the shop appear exclusive and of high quality, instead conveying low-quality and giving the scene a slightly worn-down appearance. This is perceived by some brands as an inacceptable impact.

The issue becomes more pronounced with abundant ambient light, especially when looking out from a darker interior. The contrast between the bright outside and the dim interior exacerbates the hazy appearance of the laminated windows, detracting from the clarity that one would normally expect.

Moreover, the effect is most clearly manifested when looking at dark areas through the glass, which appear more greyish than they would under normal viewing conditions. This is due to the scattering of light caused by the haze, which reduces the contrast and makes dark areas appear lighter.

Interestingly, the perception of haze is not particularly dependent on distance or perspective. Whether close up or far away, the hazy appearance remains relatively consistent, indicating that it is a property of the material itself rather than a result of viewing conditions.

Furthermore, the haze does not typically show obvious inhomogeneities. Instead, it presents as a uniform effect across the surface of the glass, further contributing to the plastic-like feel.

Finally, it’s worth noting that the measured haze (according to the standards) appears to be highly correlated with the perceived loss in contrast perceived by humans, as our experiments with volunteers indicate (see Fig. 2). This suggests that the standards for measuring haze are effective in capturing the human perception of this phenomenon, providing a useful tool for assessing the visual impact of haze on laminated windows.

Fig. 1: Effects of haze on the background. In the image,
the effect is amplified as the background is seen through two layers of hazy glass.

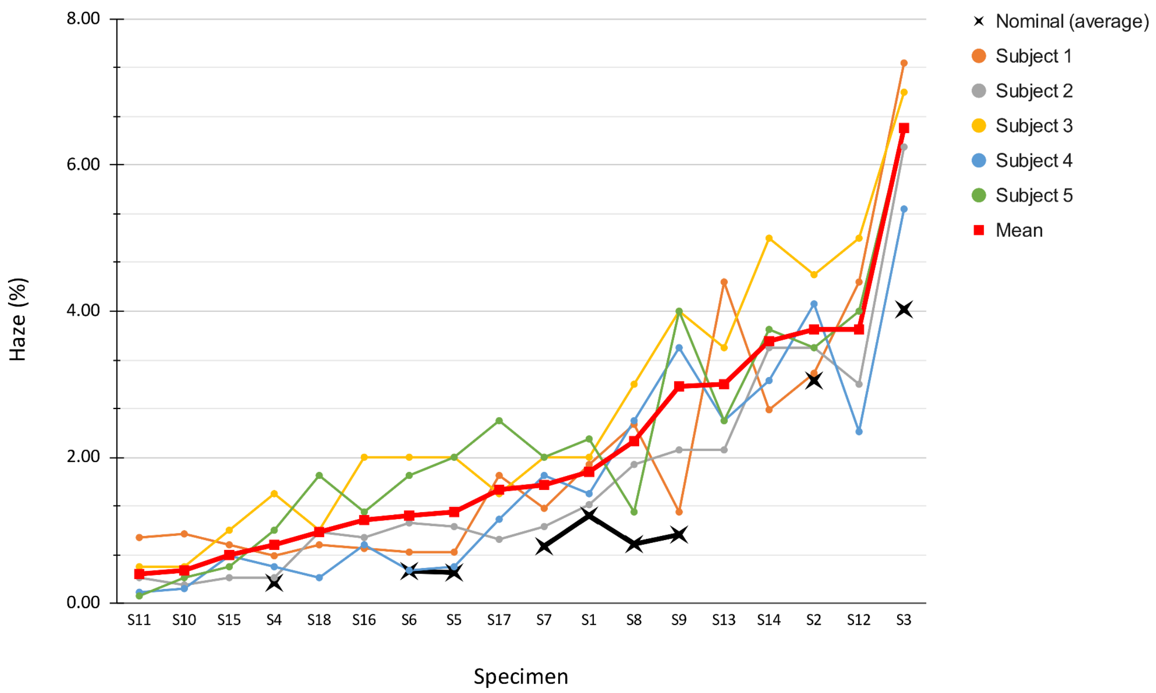

Fig. 2: Perceived haze values as recorded by the 5 subjects that took part in a visual perception experiment.
The values reported here are the average of the two values corresponding to the two different times each specimen was evaluated by each user. Only a subset of the sample had measurements attached to it (obtained with a conventional hazemeter). Note how the average of all human perceived haze values is correlated with the nominal haze values, although biased to higher values.

3. Limitation of existing hazemeter technologies

The investigations described in this paper were motivated by the lack of a convenient haze-measuring technology adapted to its use for thick glass laminates. In this section we explain the main reason that explains the inadequacy existing technologies that are well adapted to measuring haze in the industry for some transparent materials.

3.1. Haze according to standard

There are several standards currently used in the haze measurements with application mostly in the plastics industry, all of which agree on the definition of haze as the relative intensity of light scattered to an angle of more than 2.5 degrees when a collimated light ray passes through the transparent sheet of material. All the above standards agree on the use of an integrating sphere as a measurement method for haze according to this definition (see Molloy et al. 2023).

While there exist several variants of the basic procedure, its fundamental characteristics are captured in the diagram represented in Fig. 3. According to the ASTM D1003 norm (ASTM International 2013), four different intensity measurements are to be taken: T1 (incident light), T2 (transmitted light), T3 (scattered light by the empty apparatus), and T4 (scattered light by the whole system). Here we will assume that T_3 = 0 simply to make the explanations simpler. The procedure for determining each of the remaining values goes as follows: The incident light intensity is determined by closing port B in the integrating sphere with a lid having similar highly reflective properties as the rest of the sphere's inner coating. The integrating sphere spreads the light homogeneously within it, allowing one to derive the incoming intensity by measuring it only at location C, where the light detector is placed. By opening the lid at B, the collimated light ray passes through the sphere without intercepting any wall. Thus, the reading at C, T_3 should now be small or, in our idealized case, exactly equal to 0. Next, we perform two analogous measurements, but this time with the specimen placed right in front of the entrance port A. This permits the measurement of T_2 and T_4, obtained respectively with the lid at B closed and open respectively. The haze measurement is computed from the previous quantities as in Eq. 1.

$$H = \frac{T_d}{T_t} = \frac{\frac{T_4}{T_1}}{T_4 - \frac{T_3 T_2}{T_1}} = \frac{T_2}{T_1}, \tag{1}$$

where T_t represents the luminous transmittance and T_d the diffuse luminous transmittance (part of the transmitted light that is scattered by more than the conventional 2.5°).

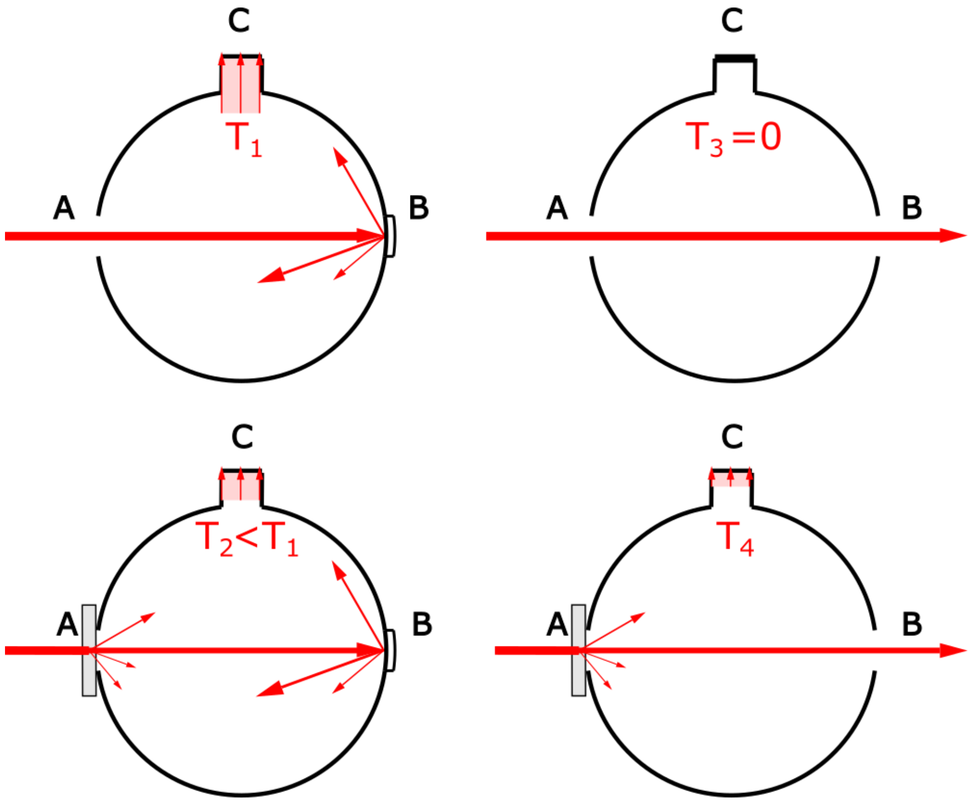

Fig. 3: The diagram illustrates the simplified geometry of an integrating sphere as defined by standards for measuring transmittance haze. A is the entrance port, B is the exit port and C is the detection port. The red arrows represent light rays. The quantities T_1 and T_3 are determined without a specimen at A (top figures). The quantities T_2 and T_4 are obtained with the specimen placed in front of port A. Note that $T_2<T_1$ is expected, as the transmittance of the specimen is typically lower than that of air, leading to less light entering the spheric cavity.

3.2. Limitations of conventional hazemeters

While there are previous studies pointing out some limitations of the standard haze measurement techniques, even for thin sheets (see Molloy et al. 2023), here we argue that their most important limitation is related to their invalidity for thicker materials, such as the laminates we are interested in.

Separating the specimen from the entrance has a similar effect to increasing the specimen thickness. When the specimen is far enough from the entrance, some of the scattered light misses the entrance port, resulting in an underestimation of haze (see Fig. 4).

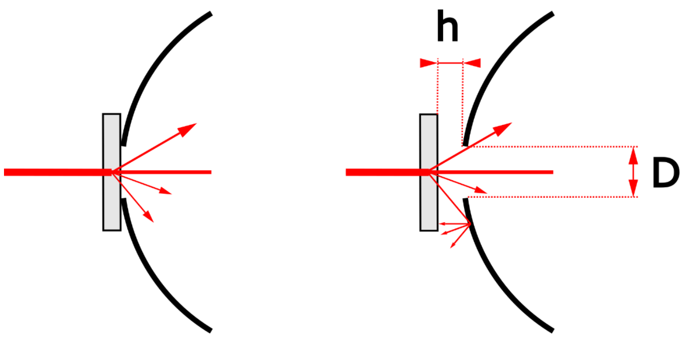

Fig. 4: Illustration of the main reason for the failure of the integration sphere-based methods to deal with thick specimens, where some or all of the haze-generating surfaces may be relatively far away from the entrance port, leading to some losses (scattered light that never enters the integrating sphere) and thus to a systematic underestimation of haze for thick specimens. In the figure, the distance h of the haze-generating surface and the entrance port, as well as the entrance diameter D are specified.

We illustrate this limitation by running a simple ray-tracing simulation of the system represented in Fig. 3. A large number of collimated rays is sent in the direction orthogonal to the specimen (represented as a single sheet of material), which is placed at varying distances from the aperture of the integrating sphere (which is assumed to work ideally). The haze is simulated by including a certain probability that a given ray will suffer a scattering event. The scattering direction is based on a simplified Rayleigh scattering where the wavelength dependence is ignored.

In Fig. 5, we plot the corresponding value of haze as the separation (normalized by the entrance port diameter) increase. It is clearly seen that once this separation is larger than about 10% of the port diameter (what could be assimilated to a thickness of about twice this value), the error in the haze measure becomes significant. Given that thicknesses well over 50 mm are commonly used, we conclude that the integrating sphere method is not suitable for measuring thick glass laminates, given that common values for the entrance diameter are well below this value.

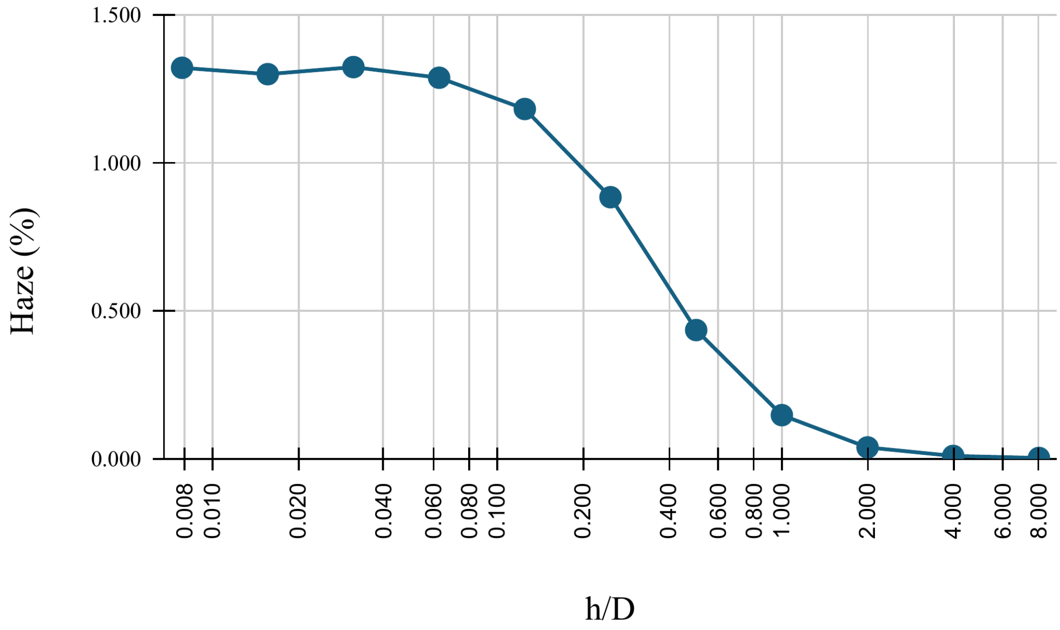

Fig. 5: Haze as a function of distance from the specimen to the integrating sphere entrance port. Note that the measurement saturates to a value of around 1.3%, a moderate value compatible with values commonly seen in situ.

4. Proposed solution

4.1. Restrictions and design criteria

Let us briefly list the particularities of the system of interest that crucially determine the most important restrictions to the optical problem at hand:

- **Overcoming Thickness Limitations:** Traditional haze measurement techniques, such as those using an integrating sphere, are designed for thin materials. However, the glass panels we aim to measure often reach a thickness of up to 80mm. Our proposed method is specifically designed to overcome this limitation and accurately measure haze in these thicker specimens.
- **Handling Variable Laminate Structure:** The haze-causing material within the glass panels is not uniformly distributed. This results in multiple interfaces that can cause refraction effects. Unlike standard methods, our solution is robust enough to handle these variations, eliminating the need for exhaustive testing of all possible combinations.
- **Sensitivity to Low-Haze Values:** Even at haze values around 1%, the effect is noticeable to the naked eye, especially when viewing the background on sunny days from indoors. Our method improves upon standard techniques by being sensitive to such low haze values.
- **Adaptability to Various Optical Conditions:** Our proposed method offers the significant advantage of being able to measure in a range of lighting conditions. This is particularly useful when in situ measurements are required, making our solution resilient to changes in ambient lighting conditions.
- **Portability:** Given the necessity to measure panels installed in situ, portability is an indispensable requirement. Our proposed method is designed with this in mind, offering a practical solution for on-site measurements.

4.2. Working principle

Our method for measuring haze in thick glass laminates is based on Michelson's for the measurement of contrast (Eq. 2). This principle has been previously employed in portable technology for measuring haze in thin films, as documented by Busato et al. (2021). In our approach, we extend this principle to accommodate the unique challenges presented by thick glass laminates. Thus, since the more haze there is, the lower the contrast we take as our haze-like quantity 1-M.

$$M = \frac{I_{max} - I_{min}}{I_{max} + I_{min}}, \tag{2}$$

where I_{max} and I_{min} are the maximum and minimum values of the intensity of light (in greyscale values) averaged over the two areas over which the contrast is being analysed. In our case, we used the average value of the intensity in the central part of the peak corresponding to the central dot as the maximum and the average in a sufficiently flat area in the dark region plateau; see Fig. 7.

The core idea of our method is to simulate real-world conditions by producing diffuse light and allowing this light to scatter in the material. The scattered light is expected to reduce the contrast in a sharply contrasted light/dark background scene in a predictable way due to the light scattering that produces the well-known hazy effect. By quantifying this loss in contrast, we obtain an objective measure of haze. This approach is inspired by the condition as that the human eye experiences when looking through a relatively distant glass to a far-away dark background (which will look significantly less dark if the glass is very hazy).

To normalize the signal, we use the intensity of a central dot from which we derive the transmissivity. This allows us to account for variations in lighting conditions and ensure that our measurements are robust and reliable and is consistent with Eq. 1.

4.3. Prototype design

The basic principle on which we base our design is very simple: we strive to emulate the most salient effect on human visual perception, which is the relative loss in contrast that is observed, especially when observing a dark are in the background. For that, we plan to use the arrangement shown in Fig. 6, where the basic configuration of the proposed design is shown.

In the figure, the light rays are schematically represented as red arrows, roughly indicating their intensity by their size. As shown by using a lens to collimate the light coming from the central part of the mask (where we measure the contrast), we strive to make the system robust to changes in the specimen thickness and inner structure. This is similar to the visual process of observing a dark, far-away background by the human eye. By having little direct light, we avoid a localized halo around the inner light dot. The results are calibrated to a specimen with known haze.

Note that such a system can be turned into a portable system quite easily, as all of its components are relatively small and already present in portable cameras.

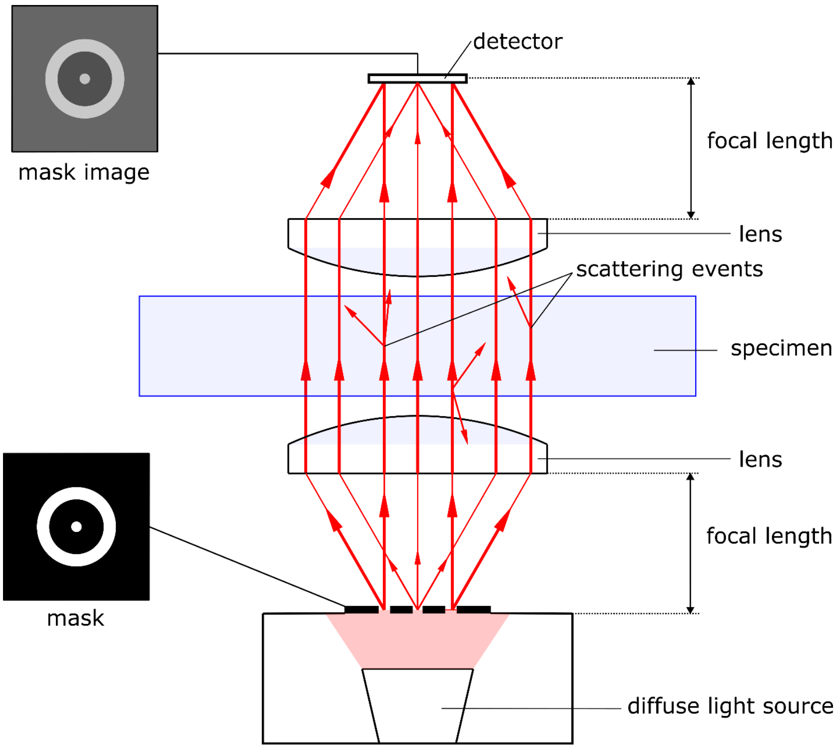

Fig. 6: Basic configuration of the proposed solution. The diffuse light turns the light areas in the mask bright. The light rays coming from a region around the mask canter are collimated between the two lenses, allowing for the distance between them to be variable. The scatter of the light as it goes through the specimen causes the reconstructed image at the detector to show less contrast. The two lenses shown are of equal size, although different combinations are also possible.

4.4. Post-processing

Once the image is generated, we measure Michelson's contrast by taking the average value of a thin slab in the darkest area (averaged over the circumference) and the integrated value of the light integrated over the light area (central dot); see Fig. 7. Both areas are automatically detected by the software.

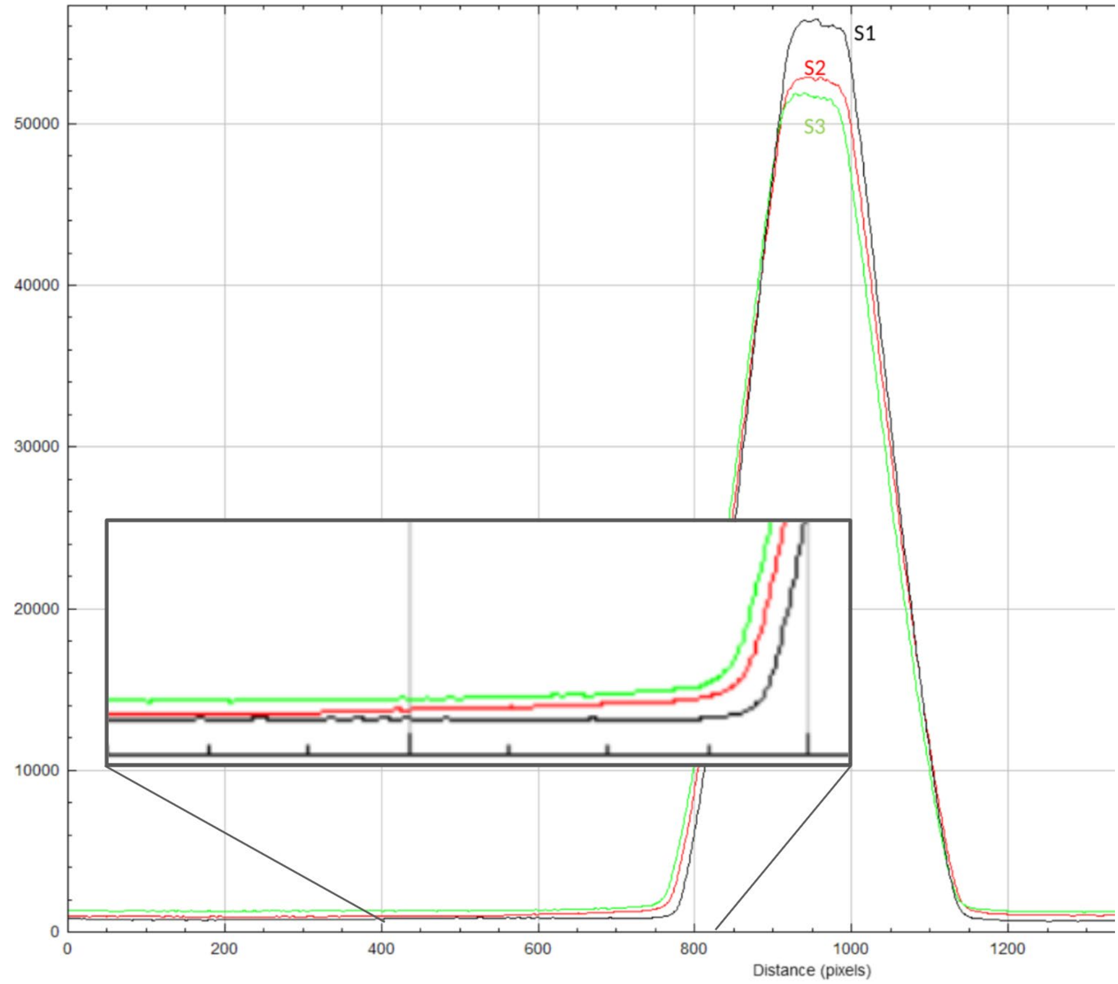

Fig. 7: Grayscale values across a diametral section of the analysed pattern for different specimens. In the figure, Specimen S1 has the highest luminosity in the central peak (highest transmittance), while also having the lowest value at the left plateau that corresponds to the dark portion of the mask. Thus, its predicted haze is the lowest according to Eq. 2.

4.5. Expected behaviour

In order to illustrate the expected qualitative behaviour of our prototype, we have run some ray-tracing simulations with a system similar to the one depicted in Fig. 6. The results, obtained using 20 million rays in 100 different orientations and 200.000 different starting positions, indicate that the system is almost perfectly linearly correlated with the standard notion of haze (with an ideal, infinitely large integrating sphere). Crucially, they are almost independent of distance, thanks to our design.

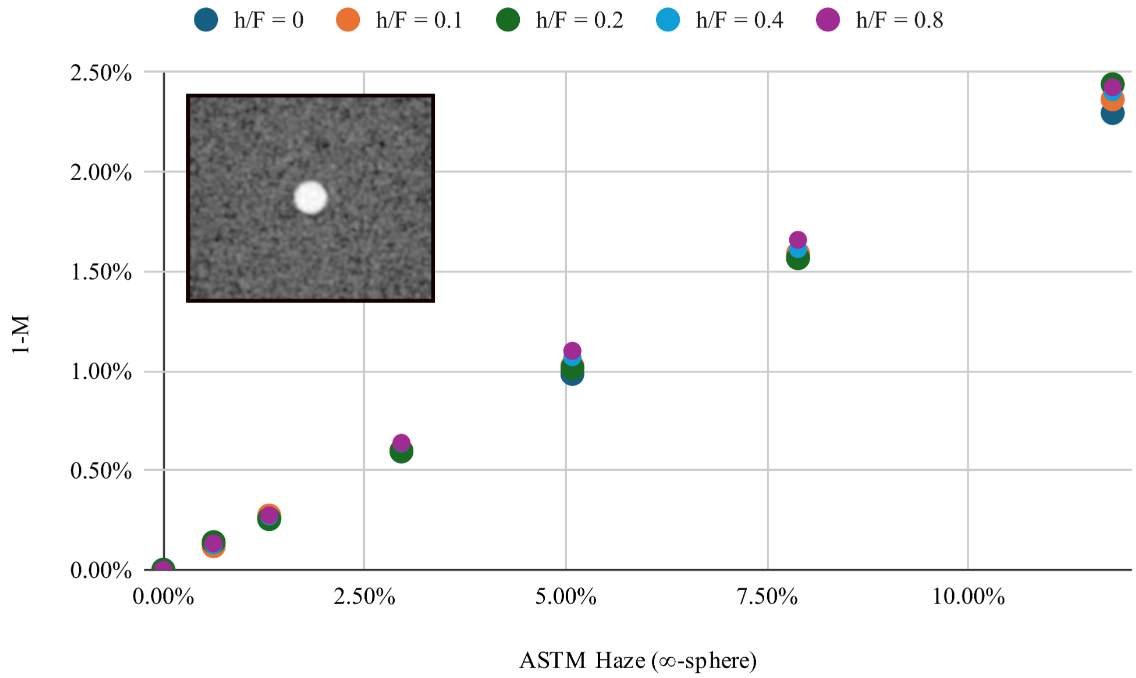

Fig. 8: Correlation between the simulated haze measure based on Michelson's contrast and the ideal ASTM Haze as defined in Eq. 1 with a very large value of h/F (F is the illumination-side focal length). Note that the correlation is almost independent of the normalized distance h/F, values across a diametral section of the pattern. The insert shows an example result of the Ray-tracing program showing the region on which the Michelson's contrast is measured.

5. Experiments

The simulations show that our concept design is very effective in quantifying haze. In this section we explore whether this behaviour is also realized in practice, based on a simple prototype built based on the design presented above. However, due to this being work in progress, at the time of writing this paper we have not yet run the simulations including the collimating lens. Nonetheless, we expect the system to work reasonably well if the distance between the light source and the camera do not become extreme.

5.1. Experimental setup

The basic configuration described above can be materialized using relatively inexpensive equipment. A black and white camera with a 25 mm optic and a backlight LED illumination system are the main equipment required. The remaining components are a 3d-printed plastic mask and a box containing the backlight to support it (see Fig. 9). The basic specifications of the various elements are summarized in Table 1.

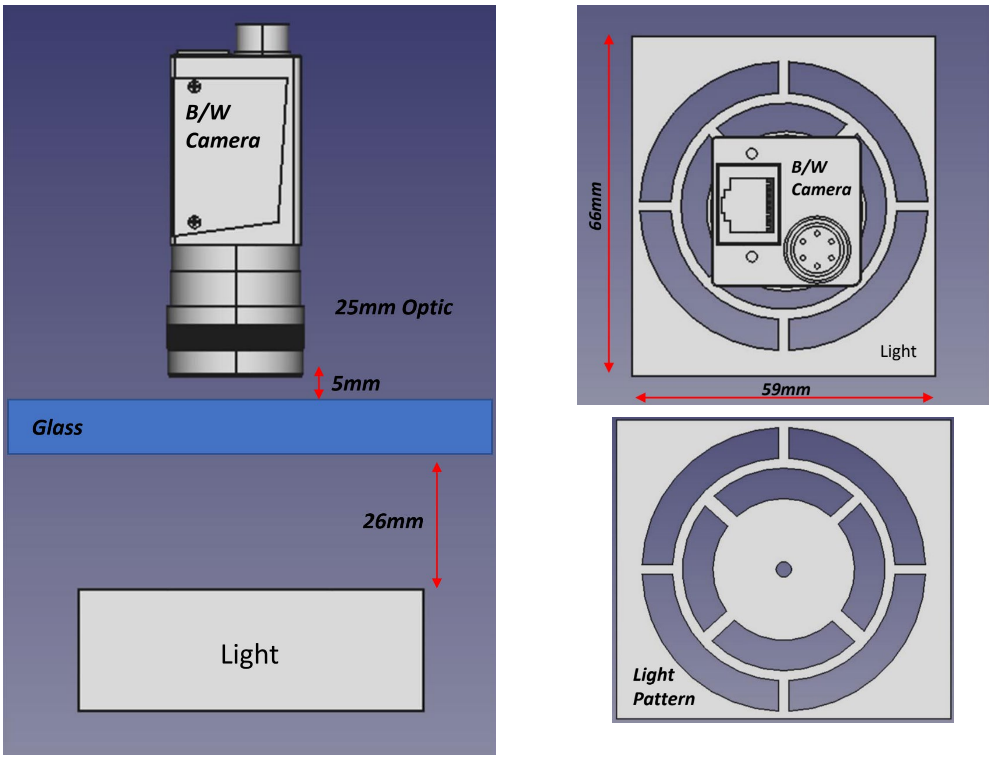

Fig. 9: Layout of the setup used in the experiments. This configuration does not include a collimating light, so we expect the setup to be sensitive to the distance between the camera and the light source.

Table 1: Equipment specifications

Component	Specifications
Camera	Basler acA 2440-20gm
Sensor	Sony CMOS IMX264 (2448 x 2048; Optical Size: 16.93 mm)
Optics	Focal length: 25 mm; max. aperture: f/1.4 (in the experiment, the aperture was set to a low value for increased robustness)
Lighting	LED backlight BKL0505A; IP rating: IP40

5.2. Reference samples

A set of 18 glass specimens were provided by the client in three different batches. Here we have pooled all these specimens together for simplicity. The setup described in the previous sub-section was tested on all of them.

The samples were examined in arbitrary order, each time making 7 measurements, each time at different point on its surface, which entailed a degree of movement in the distance camera-specimen (but not on the distance light source-specimen).

Table 2 includes all the specimens tested, including their respective thickness, cross section structure and ASTM-measured haze values (when provided by the client). Some of the latter were provided as ranges (reportedly, the ranges obtained after repeated measurements at different locations), while others only provided a single value.

Table 2: Glass laminate sample. Nominal haze corresponds to the haze value (or range) obtained with a conventional upper range hazemeter (model or specifications not disclosed by the client)

Specimen	Thickness (mm)	Structure	Nominal haze (%)
S1	7.5	2*3 low Iron+1*1.52SGX	1,1 - 1,3
S2	9	2*3 low Iron+2*1.52SGX	2,9-3,2
S3	11	2*3 low Iron+3*1.52SGX	3,51-4,54
S4	14	2*6 low Iron+1*1.52SGX	0.28
S5	15	2*6 low Iron+2*1.52SGP	0.42
S6	15	2*6 low Iron+2*1.52SGX	0.44
S7	18	2*6 low Iron+4*1.52SGP	0.78
S8	17	2*6 low Iron+3*1.52SGX	0.81
S9	18	2*6 low Iron+4*1.52SGX	0.94
S10	6	1*6	—
S11	13	1*13	—
S12	52	4*12 low Iron+3*1.52SGP5000	—
S13	30	3*8 low Iron+2*3.04SGP5000	—
S14	24	3*6 low Iron+2*3.04SGP5000	—
S15	14	2*6 low Iron+1*1.52SGP5000	—
S16	25	6 low Iron+1*1.52SGP5000 +10 low Iron+1*1.52SGP5000+6 low Iron	—
S17	21	3*6 low Iron+2*1.52SGP5000	—
S18	27	3*8 low Iron+2*1.52SGP5000	—

5.3. Results

The results of the (average) measurements obtained with our prototype are compared with their corresponding values measured with a standard hazemeter (for the specimens with reported haze) are shown in Fig. 10. Clearly, both quantities are highly correlated. We have also compared the values obtained with our design with the values obtained from the human perception experiment which, while much noisier, remain well-correlated as it can be seen in Fig. 11.

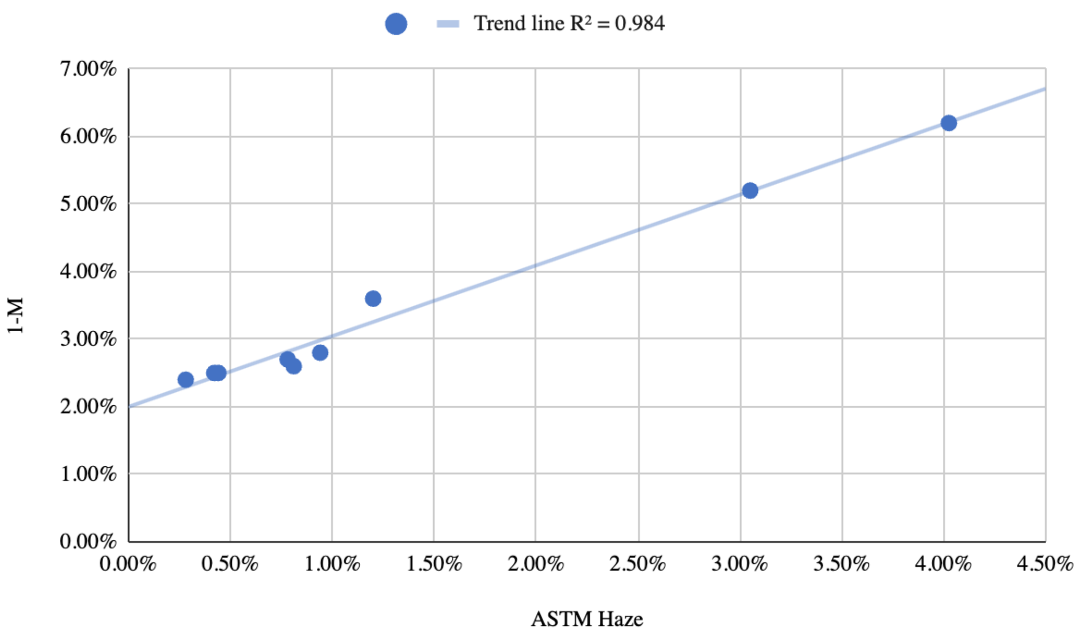

Fig. 10: Measurements of the measured Michelson's contrast-based haze values versus the reported standard values. Only specimens S1-S9, for which the haze was reported, are included.

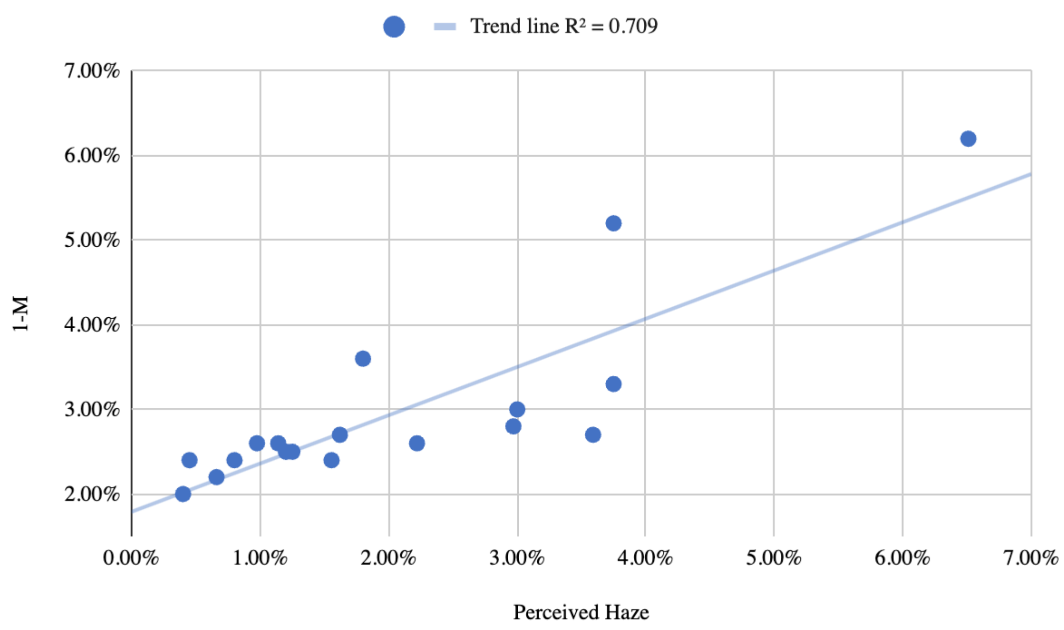

Fig. 11: Measurements of the measured Michelson's contrast-based haze values versus the mean values obtained in the visual perception experiments (see Fig. 2). All specimens in Table 2 are included.

6. Discussion and future work

We have described a technology for the quantification of haze that, unlike standard methodologies, is adequate for measuring thick slabs of laminated glass. The simple technology involved is compatible with completely portable solutions based on relatively inexpensive existing components.

Our numerical simulations and experimental results confirm that our methodology is highly correlated with the traditional ASTM measure of haze, even though the prototype used had some limitations at this stage of development. In particular, the collimating lens has not yet been added to the prototype, which is expected to harm its robustness with respect to changes in the glass thickness. Nonetheless, the results remained good for a wide range of thicknesses.

Some of the most urgent work to continue improving upon the concept presented here include a systematic sensibility study with respect to the two most important sources of (incontrollable) noise in situ: glass structure (including thickness) and ambient lighting conditions.

Furthermore, we have yet to explore the possibilities offered by more accurate numerical simulations which can help optimize various components in our design with criteria of precision and robustness. This is the subject of current work.

Finally, we must investigate the precision of this technology at the 0-1% ASTM-haze value range systematically, since in this range the signal-to-noise ratio drops and the variability increases (see Fig. 10).

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