Experimental Determination Of The Optical Properties Of Glass

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Abstract
The article supplemented the well-known method of experimental determination of the light absorption coefficient and developed a new method according to the patent of UA No. 101462 for the joint determination of two optical properties of glass at once: light absorption and light reflection coefficients. In the known method, the light absorption coefficient is determined on the basis of measurements of the transmittance of two glass samples of different thicknesses. In the framework of the development of the known method, the article proposes, in addition to light transmission, also to determine the reflection coefficient. In the new method for the joint determination of two optical characteristics of glass, it was sufficient to measure the transmittance of glass of only one thickness.

Keywords: *glass, light absorption coefficient, coefficient of reflectivity, method of two samples of identical thickness, method of two samples of different thickness.*

I. INTRODUCTION

Knowledge of the optical properties is very important: both window glass used in construction [1] and optical glass used as transparent insulation of solar collectors [2], etc. The quality of optical glass is very important for the efficient operation of solar collectors, because, for example, the light transmission of their transparent insulation is included in the criterion of exergetic efficiency in the second degree [3]. An analysis of this criterion shows that the optical losses in the solar collector are two times more valuable than the heat losses from the absorber through thermal insulation.

Quality of window glass is determined by the fact that it must transmit a maximum of sunlight, and precisely due to high light transmission, and not due to the surface area of the windows, since windows are a significant source of heat loss from the room into the environment, i.e. source, which makes up about a third of the total heat loss from the structure.

Currently, such optical properties of glass as the absorption and reflection coefficients are determined by various independent methods. However, different methods of determination, due to their characteristics, can give different values of the optical parameters when testing the same sample. For example, the reflection coefficient of window glass is determined based on its dependence on the refractive index n: which substantially depends on the wavelength of the incident radiation and is determined at $\lambda = 0.547$ μm (for window glass n = 1.52 – 1.53). In this case, the reflection coefficient ρ of direct sunlight or daylight, and even more so the light from an incandescent lamp (in accordance with the DSTU method) will be significantly different, since these light sources have different spectral composition of radiation. Therefore, the most correct approach is the joint determination of both parameters within the framework of a unified mathematical model of light transmission of glass and with one light source. For example, using the expression of such an experimentally easily determined property as the light transmission of glass, depending on the thickness of the sheet, its reflection and absorption. This method of joint determination of several parameters (constants of a mathematical model) is the so-called indirect measurement method [4]. In the framework of such a method, its results will be devoid of a methodological error caused by different spectral composition of light.

II. OVERVIEW

Light-transmitting glass (window and display) is produced mainly in two types: sheet window and display. Sheet window glass is produced with a thickness of 2 - 8 mm and, depending on the quality indicators, there are three grades: the highest category, 1st and 2nd grade. Display glass is available in a thickness of 5.5 – 10 mm. Moreover, unlike window glass, it is polished, thermopolized and unpolished.

The quality of window glass is mainly determined by its optical properties, some of which are regulated by regulatory documents: SNIPs (DBN) [5] and state standards GOST (DSTU) [6].

Table 1. Regulatory data on light transmission of sheet glass

Type of glass	Issue, GOST	Thick-ness, mm	Light- passing, one and two glasses	
Window glass	111-78 -//-	2-2,5 3-4 5-6	0,87 0,85 0,84	– 0,72 0,71
Display glass:				
Unpoli-shed	5380-77	6,5	0,84	0,71
polished	13454-77	5,5-6,5 8	0,87	0,76
- // -	-//-		0,85	0,72
Thermo-polized	7138-78	3-7	0,87	0,75

The standards regulate the transmission of light **τ** by both window and optical glass for solar collectors. Both of these qualities are mainly determined by the chemical composition of the glass. The green color of the glass cut is determined by the presence of iron ions in it: divalent (ferrous) Fe^{2+} and trivalent (oxide) and Fe^{3+}, which increases the absorption coefficient in the layer, and the main influence on the absorption is exerted by the concentration of iron ions $\mathbf{C}_{Fe}$ in the acid form (specific absorption coefficient **χ** decreases with increasing concentration of Fe^{2+}, э = $\chi/\mathbf{C}_{Fe}$). For various glasses, the light absorption coefficient **χ** varies from 0.04 cm^{-1} (for highly transparent glasses) to 0.32 cm^{-1} (for weakly transparent glasses). For window glass, χ = 0.16 cm^{-1}. In accordance with Bouguer's law, light absorption of glass depends on **χ** as follows: $\alpha = exp(-\chi\delta)$.

An increase in the concentration of lead ions in the glass increases the refractive index n of the glass and, accordingly, value of its reflectivity, since $\rho = [(n - 1)/(n + 1)]^2$. For ordinary window and display windows, the refractive index is assumed to be 1.52 – 1.53. In this case, the reflection coefficient from one glass surface is 4.3 – 4.4%. And from two surfaces of the sheet 8.5 – 8.8%. In addition, the quality of surface treatment (e.g. polishing) affects the light transmission of glass.

Optical glass on the cut is almost colorless. It is produced in the following categories: 000, 00, and 0, as well as 1, 2, 3, and 4. Optical absorption **α** of optical glass is not more than 0.2 – 3.0% by category, respectively.

To date, three main characteristics of optical glass have been adopted: the refractive index n_e for λ_{Hg} of the green line of mercury (since the refractive index is characterized by dispersion, i.e., depends on the wavelength: $n_e = f(\lambda)$. For example, for glass crown does not change in range 1.47 – 1.67). The wavelength of the green line of mercury λ_e = 0.546 μm. In addition, glass is characterized by an average dispersion Δn in the range between the blue and red cadmium lines and the dispersion coefficient ν_e.

Experimentally, the absorption coefficient is usually determined by measuring the attenuation of light as it passes through a plane-parallel plate (a sheet of glass, transparent plastic, or a polymer film). In this case, it is necessary to take into account the role of reflection from both surfaces of the plate. If multiple reflections from two surfaces [7] are neglected, for the flow passing through a plate of thickness δ an approximate expression of light transmission is obtained:

$$\tau = (1-\rho)^2\cdot\alpha = (1-\rho)^2\cdot exp(-\chi\delta), \quad (1)$$

where **α** - is the light absorption of glass,
$\alpha = exp(-\chi\delta)$.

The standard method for determining the optical properties of glass [8] does not at all use a mathematical model of the passage of light through glass. The standard procedure does not provide for the direct receipt of either the reflection coefficient of one glass face **ρ**, or the light absorption coefficient in the layer **χ**. Instead, for some reason, their estimates are determined by the formulas: $\tau=\tau_э\cdot(I_\tau/I_э)$ and $\rho = \rho_э\cdot(I_\rho/I_э)$ using the test data of the reference sample. The theoretical foundations of a standard method for determining properties of glass are unclear.

A known method for determining the optical properties of glass based on this formula, the so-called "method of two samples" of different thicknesses. The known method includes two experiments to determine the light transmission of two samples (τ_1 and τ_2) of a glass sheet (transparent plastic or polymer film) with a thickness of: δ_1 and δ_2, respectively. By conducting two experiments, the values of τ_1 and τ_2 of samples of different thicknesses are measured and a system of two equations with two unknowns is obtained:

$$\begin{cases} \tau_1 = (1-\rho)^2\cdot exp(-\chi\delta_1) \\ \tau_2 = (1-\rho)^2\cdot exp(-\chi\delta_2) \end{cases} \quad (2)$$

As a result of solving this system of equations with respect to **χ**, the experimental value of the glass absorption coefficient is obtained:

$$\chi = (\delta_2 - \delta_1)^{-1}\cdot ln(\tau_1/\tau_2) \quad (3)$$

In a similar way, the spectral absorption coefficient of window glass was determined as applied to solar collectors in [9]. The authors present the results of a study of the glasses of two factories with a rather large difference in the content of iron oxide. The spectral characteristics of the glasses were measured on a Specord-75-IR instrument. To increase the accuracy and reduce the error in the obtained results, the measurements were performed on glass samples of three thicknesses (3, 5, and 8 mm). By processing the spectral transmission curves of glasses of three thicknesses, a family of lines was obtained, each line of which corresponds to a specific wavelength and is constructed from three points (respectively, glass thickness) with common beginning at $\delta = 0$.

A disadvantage of the known method is that for its implementation it is necessary to have two samples of different thicknesses, and in real conditions samples of only one thickness are often available, for example, in cases where products from translucent material of only one thickness are produced or delivered (sheets of glass or transparent plastic, as well as polymer film). In addition, the known method does not provide for determining the coefficient of reflection of light from the surface ρ, which is also necessary when calculating the light transmission of one glass τ or a double-glazed unit.

Moreover, the use of an approximate model for describing the light transmission of a glass sheet (1) leads to an incorrect formula for the light transmission of glass packets. In this case, the transmittance of the glass unit is erroneously defined as a simple product of the transmittance of the glasses making up the package [10]:

$$\tau_{1N} = \tau_1 \times \tau_2 \times \ldots \times \tau_N. \quad (4)$$

III. RESEARCH RESULTS

A. Development of the well-known method for determining the optical properties of glass, the "two thickness method".

An exact solution to the problem of determining the transmittance τ of a glass plate taking into account multiple rereflections [11] gives the following expression:

$$\tau = (1-\rho)^2 \cdot \alpha / (1 - \rho^2 \cdot \alpha^2) \quad (5)$$

If we write this dependence in the form of reduced light transmission of glass **T**, then taking into account the fact that $\alpha = exp(-\chi\delta)$ we get :

$$\mathbf{T} \equiv \tau/\alpha = [(1-\rho)^2]/[1 - \rho^2 \cdot exp(-2\chi\delta)], \quad (6)$$

whence the limit of the obtained expression for $\chi\delta \to 0$, which is typical for glass:

$$lim\mathbf{T} = lim(1-\rho)^2/[(1-\rho^2 \cdot exp(-2\chi\delta)]\big|_{\chi\delta\to 0} = (1-\rho)/(1+\rho) \quad (7)$$

Now we can write the limiting expression for the light transmission:

$$\tau = [(1-\rho)/(1+\rho)] \cdot exp(-\chi\delta) \quad (8)$$

A comparison of the two formulas shows that the approximate expression for τ without taking into account multiple reflections gives an slightly underestimated result.

The system of equations for the light transmission of two samples of different thicknesses will have the following form:

$$\begin{cases} \tau_1 = [(1-\rho)/(1+\rho)] \cdot exp(-\chi\delta_1) \\ \tau_2 = [(1-\rho)/(1+\rho)] \cdot exp(-\chi\delta_2) \end{cases} \quad (9)$$

As a result of solving the system of equations, the expression obtained for the absorption coefficient of the glass χ coincides with the previously obtained result (3), and for the reflection we obtain a new expression:

$$\rho = [(\tau_1/\tau_2)^m - \sqrt{(\tau_1 - \tau_2)}]/[(\tau_1/\tau_2)^m + \sqrt{(\tau_1 - \tau_2)}], \quad (10)$$

where τ_1 and τ_2 are the light transmission of glass with a thickness of δ_1 and δ_2, respectively, and $m = (\delta_1 + \delta_2)/2(\delta_2 - \delta_1)$.

In addition to the reflection coefficient ρ from this formula, one can also determine the average integral value of the refractive index n by the formula:

$$\bar{n} = (1 + \sqrt{\rho})/(1 - \sqrt{\rho}) \quad (11)$$

EXAMPLE 1

If we assume, that the transmission data τ of the glasses shown in Table 1, are obtained in accordance with the DSTU, then based on these transmission data of one glass and a package of two glasses, then, using the above formulas, we can calculate the limiting values of the optical parameters of these glasses. Let us consider the case when τ_1 = 84% and τ_2 = 71%, which is typical for two cases: window glass with a thickness of 6 mm and glass case polished glass with of 6.5 mm.

Substituting these values in the formulas for window glass, we obtain that the reflection coefficient (10) is ρ = 0.041 (4.1%) and the absorption coefficient (3) is $\chi = 0.154$ cm^{-1}, which is very close to that adopted for window glass (4.3% and 0, 16 cm^{-1}). For display glass, this substitution gives the same value for the reflection coefficient and a slightly lower value for the absorption coefficient $\chi = 0.142$ cm^{-1}.

B. Development of a new method for the joint determination of the optical properties of glass

The light transmission τ_N of a packet of N sheets of glass of the same thickness δ relative to the normal light flux in the general case [12, 13] is determined from the formula:

$$\tau_{1N} = \{(1-\rho)/[1 + \rho(2N-1)]\} \cdot exp(-\chi N\delta) \quad (12)$$

Thus, measuring the transmission of one sheet ($\tau_1 = E_1/E_o$), two ($\tau_{12} = E_2/E_o$) of glass and solving the system of two equations with two unknowns obtained for τ_1 и τ_{12}:

$$\begin{cases} \tau_1 = [(1-\rho)/(1+\rho)]\cdot exp(-\chi\delta) \\ \tau_{12} = [(1-\rho)/(1+3\rho)]\cdot exp(-2\chi\delta) \end{cases} \quad (13)$$

get a quadratic equation for ρ, as a result of the solution of which we obtain the formulas of the reflection coefficient ρ of light from the surface of the sample and the coefficient χ:

$$\rho^{-1} = 2\sqrt{[\tau_2/(\tau_{12} - \tau_1^2)]} - 1 \quad (14)$$

$$\chi = (\delta)^{-1}\cdot ln[(\tau_1)^{-1} - \sqrt{\{(\tau_1)^{-2} - (\tau_{12})^{-1}\}}]$$

EXAMPLE 2

As part of the methodology for testing solar collectors described in GOST 28310-89, Appendix 2 (mandatory), optical glass “000” was tested, a sheet of which was used as a transparent insulation of the collector. The light transmission of glass relative to direct solar radiation was determined using the thermoelectric actinometer M3 (No. 192970 D/551) produced by the “Meteopribor” plant, Tbilisi. The light transmission of one sheet of glass with a thickness of 3.5 mm was 85.7%, and the light transmission of a packet of two parallel layers of such glass was 74.6%. Using the formulas given above, the reflection coefficient ρ of light from the glass surface and its absorption coefficient χ were calculated. As a result, it was found that for glass ρ = 0.063 (6.3%), and χ = 0.072 cm^{-1}. Thus, optical glass, having a low absorption coefficient, reflects quite a lot of 6.3% due to the high value of the integral refractive index of direct solar radiation, which is:

$$\bar{n} = (1 + \sqrt{\rho})/(1 - \sqrt{\rho}) = 1{,}67.$$

IV. CONCLUSIONS

The light transmission of a glass or a glass packet depends on two optical parameters (reflection and light transmission coefficients), therefore, the problem of their experimental determination should be formulated as a method for the joint determination of these parameters (i.e., an indirect measurement method).

The possibility of using three types of light fluxes (from an incandescent lamp, direct solar radiation, and diffuse daylight) to determine the glass absorption coefficient in DSTU at once is incorrect, since they all have a different spectrum, and accordingly, the integral values of the obtained optical properties will differ from each other.

The reflection coefficient of glass in the known method of two samples (glass thicknesses) should be determined on the basis of the same measurements of glass transmittance as the absorption coefficient - according to the formula obtained for the first time in this paper, and not be calculated from the uncertain value of the "refractive index for the green line of mercury".

The article developed a new method for the joint determination of the optical properties of glass (reflection and light transmission coefficients), for the implementation of which it is quite enough to have glass samples of the same thickness, which often takes place in real conditions. A patent of Ukraine No. 101462 was obtained for this method of determining glass parameters [14].

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