STUDY OF ENERGY-EFFICIENT CHARACTERISTICS OF TRANSPARENT ENCLOSING CONSTRUCTIONS OF SOLAR DRYERS BASED ON GLASS UNITS

Serhiy Korobka[1], Mykola Tolstushko[2], Igor Stukalets[1], Viktor Sheichenko[3], Nataliya Tolstushko[2]
[1]Lviv National Environmental University, Ukraine;
[2]Lutsk National Technical University, Ukraine;
[3]Poltava State Agrarian University, Ukraine
korobkasv@ukr.net, tmmtno@gmail.com, igorstukalets@gmail.com,
vsheychenko@ukr.net, nataleksa1978@gmail.com

Abstract. The article deals with the completed research, which is aimed at solving a scientific and applied problem. It consists in the development and justification of optimal modes of operation of the solar dryer to increase the energy efficiency of the fruit drying process under conditions of small volumes of raw material processing by reducing heat loss in enclosing constructions, in particular in glass units. Transparent enclosing constructions based on double-glazed windows of types 4M1-16(Ar)-4i; 4M1-8(A)-4M1-12(A)-4M1 and 4M1-8(Ar)-4M1-12(Ar)-4i are proposed to be used to reduce heat loss in the constructions of the drying unit. The structure and parameters of glass units have been studied. Analysis of the heat resistance of window structures was carried out from the point of view of the theory of heat transfer. Comparison of heat transfer indicators of external enclosing elements has been completed. The level of optical losses in glass units of various designs was estimated. A comparison of the heat transfer resistance index used for the enclosing constructions of solar dryers has been carried out. The parameters of the gas filling, the distance between the panes, as well as the features of the passage of visible and infrared radiation through the glass and low-emission coating were taken into account. Innovative approaches to increase the thermal resistance of modern window constructions such as 4M1-16(Ar)-4i, 4M1-8(A)-4M1-12(A)-4M1, 4M1-8(Ar)-4M1-12(Ar)-4i were presented. Optical component of light flux in relative units using an actinometer and a luxmeter was estimated. This allowed us to investigate the effectiveness of various design and technological solutions. In addition, the studies help improve the penetration of solar energy through the transparent coating of the air solar collector to the absorber and reduce reflection, which allows to increase its energy characteristics.

Keywords: solar dryer, glass unit constructions, heat transfer resistance, heat loss, heat transfer coefficient.

Introduction

Helio dryers are proposed to be used to increase the efficiency of the fruit drying process [1; 2]. Currently, there is a wide range of helio dryer designs that differ in complexity [3]. In addition, considerable practical experience has been accumulated in the use of solar energy for drying fruits and vegetables [4]. Helio dryers with a thermal accumulator and flat mirror concentrator are shown in Fig. 1.

The helio dryer, as shown in Fig. 1, is equipped with transparent enclosing structures made on the basis of double-glazed windows, which makes it possible to simplify the design and has a number of advantages and disadvantages. The advantages include improved energy efficiency due to reduced heat loss, increased use of solar energy and improved control of the temperature inside the dryer. Double-glazed windows also provide high transparency for solar radiation, which increases the drying efficiency. The disadvantages include the high cost of such materials compared to other options for enclosing structures, as well as the need for regular maintenance to maintain high thermal insulation and transparency of double-glazed windows. In addition, double-glazed windows can be sensitive to mechanical damage and external conditions, which can affect the durability of the structure [5].

A detailed analysis of the parameters and operating modes of the air solar collector, in particular, a comparison of the efficiency of various structures, including the use of additional components, was carried out in the works [6-9]. The influence of multilayer glass systems, such as double-glazed windows, on the thermotechnical characteristics and energy efficiency of the helium dryer is not taken into account. The influence of multilayer glass systems, such as double-glazed windows, is not taken into account in the thermal characteristics and energy efficiency of the helio dryer.

Consequently, this allowed us to determine the research directions to improve the energy efficiency of the helio heater structures equipped with transparent enclosing elements based on double-glazed windows.

a)

b)

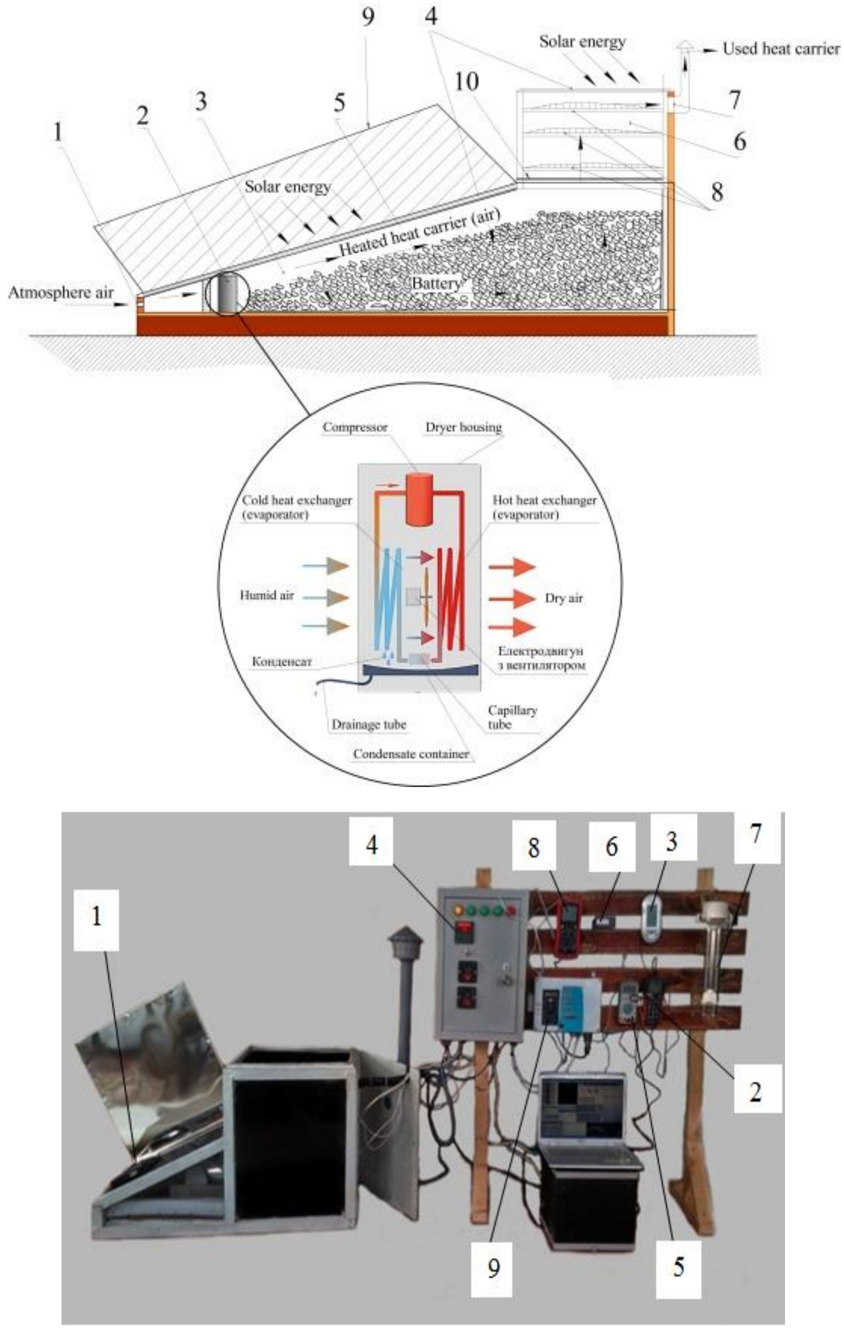

Fig. 1. **Structural and technological scheme of the helio dryer with a thermal accumulator and flat mirror concentrator (a) and a general view of the experimental installation (b):** 1 – input channel; 2 – coolant moisture dryer; 3 – air duct; 4 – air manifold; 5 – heat accumulating material (TAM); 6 – drying chamber; 7 – exhaust duct; 8 – sieve; 9 – flat mirror concentrator; 10 – flap [10]

Materials and methods

The purpose of the research is to increase the efficiency of using drying units by reducing heat loss in double-glazed windows with transparent enclosing structures.

The following tasks were completed to achieve this goal:

1. determine the influence of the chamber thickness and its gas filling on the value of the heat transfer coefficient;
2. experimentally determine the temperature values and optical losses of various designs of solar dryers.

The heat transfer coefficient of the outer wall of the helio-dryer, α_{ex} = 23 W·(m^{-2}·K^{-1}), and the inner surface is used during engineering calculations. Empirical dependencies of natural convection are applied to the zone of contact with the solar collector. Combined coefficient α_{in} = 8.6 W·(m^{-2}·K^{-1}), with temperature modeling of the wall at 21 ºC inside and 15 ºC outside for glazing 0.5 m high and 0.7 m wide for other areas. It is assumed that the temperature of the helio collector is equal to the air temperature in the drying chamber (21 ºC), and the thickness of the double-glazed window in the helio collector is 0.1 m at the initial research stage.

A specialized laboratory stand was developed and installed to study heat transfer processes through a translucent structure with electric heating (Fig. 2).

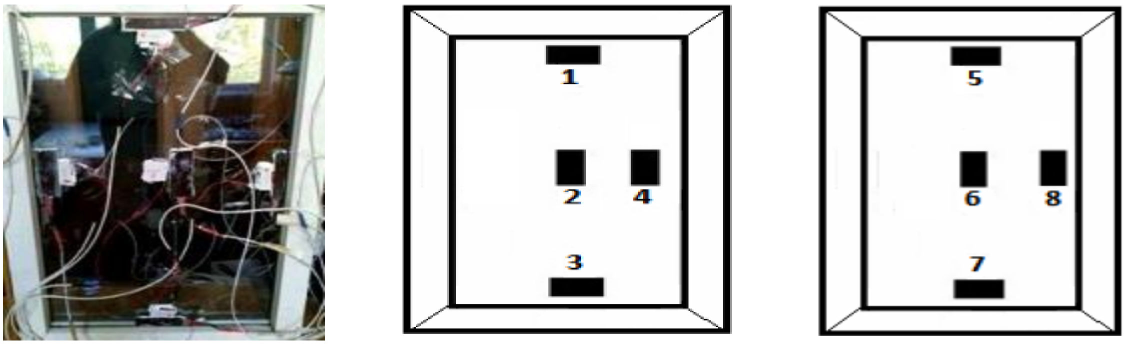

Fig. 2. **Photo of the installed heat flow and temperature sensors on the surface of the transparent enclosure structure of the 4M1-16(Ar)-4i helio dryer and a diagram of their placement with built-in temperature sensors**

The research stand is equipped with various types of thermal sensors (Pt-1000, TXK-123, Pt-100) installed in certain areas of the double-glazed window and the internal environment of the helio dryer, which ensures accurate measurement of temperature characteristics at key points of the structure. The collection and processing of temperature and thermal data was carried out using a mobile measuring complex with a PT-1002 device and analog-digital converters LabVIEW USB-6008/6009, which provided digital data transmission and mathematical processing through LabVIEW and SolidWorks. Therefore, this methodology will allow us to evaluate not only the thermotechnical characteristics of structures, but also their impact on the energy efficiency of the drying process.

Results and discussion

The double-glazed window is a separate element of the transparent enclosing structure of the helio dryer. Several sheets of glass separated by a spacer frame are sealed around the perimeter to form an insulated chamber. It is filled with dry air or heavy inert gas with less thermal conductivity (most often argon). But the chambers do not vacuum. Glass sheets are deformed inevitably with a violation of tightness under the influence of excessive atmospheric pressure. A fixed distance between the sheets is provided by hollow distance frames, preferably made of aluminum or galvanized steel, less often of plastic. The cavities of the frame are filled with silica gel to dry the air, thereby preventing fogging of the inner surface of the chamber in the cold season.

Double-glazed windows are divided into single-chamber, consisting of two sheets of glass, two-chamber - from three and multi-chamber depending on the number of chambers. Additional chambers increase the heat and sound insulation of the double-glazed window, but the weight of the window leaf and the load on the hinges simultaneously increase and the light of transmission decreases. One- and two-chamber double-glazed windows are the most common in Ukraine. Three or even four-chamber double-glazed windows, which retain heat better, but pass sunlight worse, are used in cold climate zones. Therefore, increasing the thermo-resistance of double-glazed windows by increasing the number of chambers is undesirable, since the natural illumination of the helio-dryer decreases.

The thickness of double-glazed windows depends on the number of sheets and chambers: the thickness of the glass is 4 mm, and the gaps between the sheets make up a standard row of 8, 10, 12 and 16 mm. “Double-glazed window formula” is recorded in the form of a set of numbers and letters with indexes through a dash. If we take into account only the geometric parameters, then a single-chamber double-glazed window with an interval of 16 mm is recorded with a set of 4-16-4. Letters with indexes mean a kind of glass and its additional covering: for example, a record of 4M1-12-4M1 means a single-chamber double-glazed window made of standard sheet (window) glass and a chamber thickness of 12 mm. The order of glazing is calculated from the outer surface of the double-glazed window.

The main characteristics of the double-glazed window are transparency and heat transfer resistance. They are regulated by state building codes. According to SBC V.2.6-31:2006 the thermal insulation properties of double-glazed windows are determined as part of window blocks and are characterized by heat transfer resistance, that is, thermal resistance averaged over the entire section of the double-glazed unit. It is determined during tests in the climatic chamber according to the method given in USS B V.2.6-17-2000. Qualitatively made double-glazed windows must correspond to the calculated values of the reduced heat transfer resistance given in the SBC V.2.6-31:2006 for the temperature difference from + 20 ºC to -20 ºC (see Table 1). The heat transfer resistance may be different under other temperature conditions. It is known that the deterioration of their properties relative to the calculated values occurs mainly due to shortcomings in the opaque parts from the experience of operating window blocks. Therefore, the results of direct testing of intact double-glazed windows without a frame are always better or at least not worse than in the unit.

Table 1

Reduced heat transfer resistance of double-glazed windows

Number of cameras	Glazing options	Gas storage of chambers, %			Heat transfer resistance, $м^2 \cdot K \cdot W^{-1}$
		Air	Krypton	Argon	
1	4M1-16-4M1	100	–	–	0.32
1	4M1-16-4i	100	–	–	0.59
1	4M1-16-4i	–	–	100	0.66
2	4M1-6-4M1-6-4M1	100	–	–	0.42

Note: M1 – sheet standard; i – energy-saving with soft coating

To reduce heat loss due to radiation, modern double-glazed windows are made of so-called energy-saving low-emission glass with a special three-layer metal-oxide coating, several atomic layers thick. It freely passes only short-wave (visible) sunlight inside the drying chamber and does not emit long-wave thermal radiation from inside the installation at the same time. Instead, it prevents excessive heating by reflecting back the solar rays of the infrared portion of the solar spectrum in summer.

The optical component of the heat transfer resistance of the double-glazed window can be estimated by comparing the intensity of the streams of free sunlight with those passed through double-glazed windows of different designs. Rays can be replaced with an incandescent lamp simulator in the absence of the sun. Features of the passage of visible and infrared rays through glass and low-emission coating are used.

Design and operation of the laboratory stand. One of the tasks of the article is a comparative assessment of the features of the passage of visible and infrared rays through the glass and the low emission coating of the studied double-glazed windows with different structural and technological designs. Separate double-glazed windows with different designs and a specially made glass plate with glued several double-glazed windows of elongated rectangular shape were taken to perform the research.

The optical component of the heat transfer resistance of a double-glazed window can be estimated by comparing the intensity of streams of free sunlight passed through double-glazed windows of different designs. The flows of the visible range are recorded by a luxmeter, and the infrared, together with the visible, a heat flow meter, for example a pyranometer, an actinometer or another wide-range measurement device.

The experimental stand is equipped with the necessary tools in accordance with the requirements of the user and the task for the work. This will allow the study of optical and thermotechnical characteristics of double-glazed windows (Table 2).

Table 2

Optical component measurement results

Number of cameras	Double-glazed window formula	Luminous flux in relative units		Heat transfer resistance, $m^2 \cdot K \cdot W^{-1}$
		Actinometer q, $W \cdot m^{-2}$	Luxmeter I, Lux	
-	Air	720	1358	-
1	4M1-16(A)-4M1	750	1458	0.35
1	4M1-16(Ar)-4i	850	1658	0.56
2	4M1-8(A)-4M1-12(A)-4M1	820	1570	0.52
2	4M1-8(Ar)-4M1-12(Ar)-4i	800	1490	0.90

A rectangular table frame structure with guide inserts is the basis of the stand design. A glass plate of a suitable size with glued double-glazed windows to be compared is fixed in the insert.

Bracket for attachment of replaceable working members is mounted in the upper part of the frame in the middle across the structure. This is done in accordance with the stage of the research, as well as the electrical equipment for turning on the power of light sources. The general view of the laboratory stand prepared for experimental studies is shown in Fig. 3 and 4.

Therefore, the possibility of using transparent enclosing structures based on double-glazed windows of types 4M1-16(Ar)-4i, 4M1-8(A)-4M1-12(A)-4M1 and 4M1-8(Ar)-4M1-12(Ar)-4i has been established. The conducted analysis of their structure and technical characteristics made it possible to investigate heat resistance using the principles of measuring the optical component (intensity of the light flux) using an actinometer (from 720 $W \cdot m^{-2}$ to 850 $W \cdot m^{-2}$) and a luxmeter (from 1358 Lux to 1658 Lux). The heat transfer characteristics of the external enclosing elements were also compared, the numerical data of which are presented in Table 2. The level of optical losses in double-glazed windows with different design solutions was estimated and it was established that the most effective option for the manufacture of transparent enclosing structures is a double-glazed window of type 4M1-8(A)-4M1-12(A)-4M1.

Fig. 3. **General view of the laboratory stand for comparative studies of the permeability of infrared and visible rays**

Fig. 4. **General view of the laboratory stand for comparative studies of the permeability of visible flux rays for each type of double-glazed windows**

Data for plotting the temperature (Fig. 5) and thermal distribution (Fig. 6) under the conditions of stabilized double-glazed window temperature (20 ºC) and external air temperature of -15 ºC were obtained during the experiment with sensors installed on the double-glazed window of the solar dryer.

Studies have shown an uneven distribution of heat flow on the surface of the double-glazed window with maximum values in the upper part (up to 350.5 $W \cdot m^{-2}$ inside) and minimum in the lower part (up to 147.3 $W \cdot m^{-2}$ outside). The temperature distribution on glazing revealed vertical unevenness, where the highest average temperatures were observed in the upper part (up to 60.4 ºC inside and 21.6 ºC outside), and the lowest in the lower part (up to 51.8 ºC and 19.3 ºC, respectively).

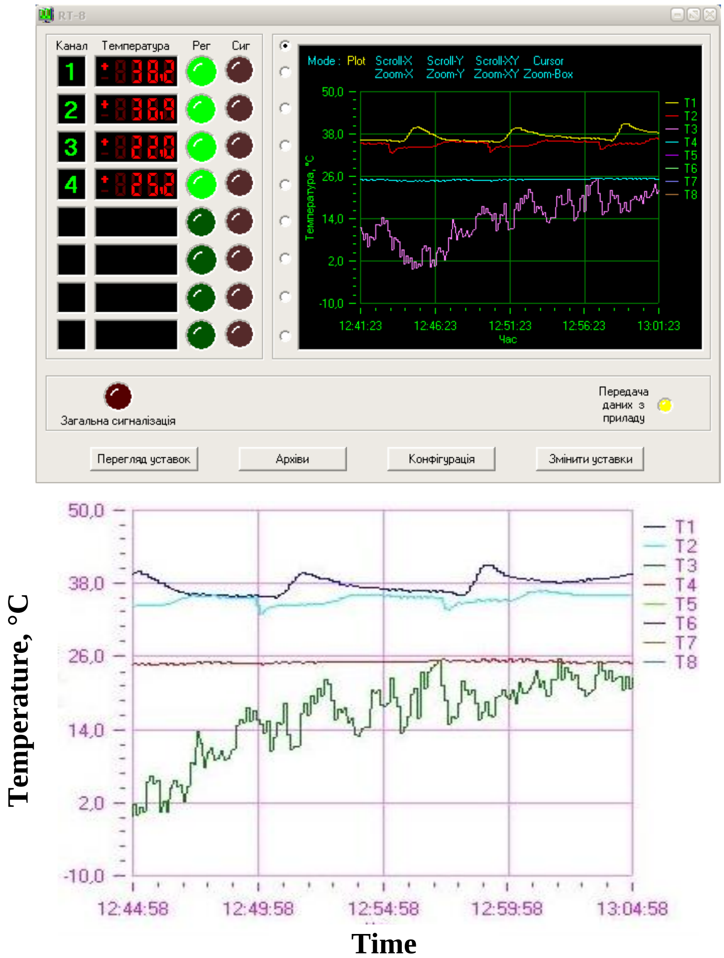

Fig. 5. **Distribution of temperature on the inner and outer surfaces of the translucent energy structure of the 4M1-16(Ar)-4i helio-dryer from March 17 to 21, 2025, under the condition that the temperature is maintained by the thermostat at 20 °C**

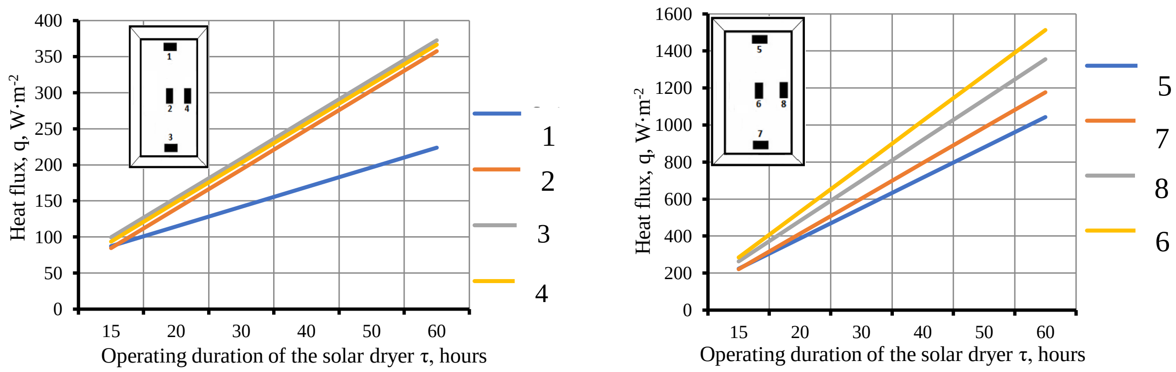

Fig. 6. **Distribution of the heat flux density on the inner and outer surfaces of the translucent energy structure of the 4M1-16(Ar)-4i solar dryer from March 17 to 21, 2025, under the condition of maintaining the temperature by the thermostat at 20 °C**

A mathematical model was developed to verify the reliability of the experimental heat transfer data through a double-glazed window with electric heating. The results are compared with the experimental temperature and thermal characteristics of the helio dryer design. The corresponding graphic materials are shown in Fig. 7 for Q = 90.7 W, t_{tn} = 17 °C.

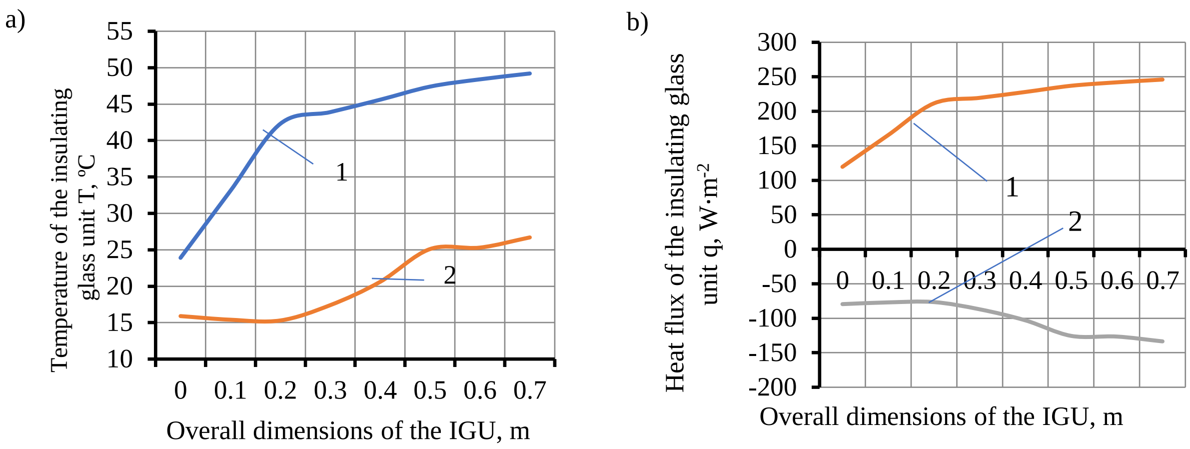

Fig. 7. **Validation of experimental results on the temperature distribution (a) and heat flux density (b) on the surfaces of the translucent energy structure of the 4M1-16(Ar)-4i solar dryer:** 1 – glass with built-in heating; 2 – opposite glass without a heating element

The functional layer with metal ions on the inner surface of energy-saving glass performs the role of a thermal barrier, reducing the loss of infrared radiation and heat from the helio dryer.

Thus, the study of heat transfer through a single-chamber energy-saving design showed high accuracy of numerical modeling, confirmed by experimental measurements of temperature and heat flow.

Conclusions

1. The dependencies of the value of the heat transfer coefficient, inverted to the thermo-resistance, on the thickness of the chamber and its gas filling are installed. It is noted that under the conditions of filling with heavy inert gases, the size of the chambers can be reduced to 6 mm, which will reduce the material capacity of double-glazed windows, respectively.
2. The range of the change in the heat transfer resistance (Table 2) of transparent enclosing structures based on double-glazed windows 4M1-16(Ar)-4i, 4M1-8(A)-4M1-12(A)-4M1 and 4M1-8(Ar)-4M1-12(Ar)-4i is determined based on measuring the optical component of the intensity of the light flux using an actinometer and luxmeter.
3. It is noted that double-glazed windows 4M1-8(A)-4M1-12(A)-4M1 are characterized by the lowest level of optical losses. Manufacturers of double-glazed windows 4M1-16(Ar)-4i and structures made of materials like PVC, fiberglass, wood and aluminum are guided by increasing the tightness and thermal insulation, achieving high heat transfer resistance. It depends on the double-glazed window, which provides the necessary level of energy efficiency for the helio dryer due to the use of energy-saving K-glass with a low-emission coating, having a heat transfer resistance $R = 0.55$ m²·°C·W^{-1}.

Author contributions

Conceptualization, S.K.; methodology, S.K. and I.S.; software, M.T. and N.T.; validation, M.T. and N.T.; formal analysis, S.K. and M.T.; investigation, S.K., M.T., I.S. and V.S.; data curation, M.T. and N.T.; writing – original draft preparation, S.K.; writing – review and editing, S.K. and I.S.; visualization, M.T., V.S. and N.T. All authors have read and agreed to the published version of the manuscript.

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