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USING METAL-PLASTIC WINDOWS WITH ENERGY-EFFICIENT INSULATING GLASS UNITS IN THERMAL MODERNIZATION OF MARINE INFRASTRUCTURE FACILITIES

ВИКОРИСТАННЯ МЕТАЛОПЛАСТИКОВИХ ВІКОН З ЕНЕРГОЕФЕКТИВНИМИ СКЛОПАКЕТАМИ ПІД ЧАС ПРОВЕДЕННЯ ТЕРМОМОДЕРНІЗАЦІЇ НА ОБ'ЄКТАХ МОРСЬКОЇ ІНФРАСТРУКТУРИ

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Abstract. The article considers the use of metal-plastic windows with energy-efficient insulating glass in the process of thermal modernization of administrative and public buildings of marine infrastructure facilities. The purpose of the study is to obtain data on the heat flow densities in different types of insulating glass units depending on the temperature drop typical for the climate zone of the southern Ukraine. Mathematical modeling is employed to obtain temperature fields on the outer surface of the insulating glass units. The densities of heat flow through various types of insulating glass units are studied experimentally. Analytic dependencies of the heat flow density on the temperature drop through the window structure are obtained.
Keywords: thermal modernization; marine infrastructure facility; energy-efficient insulating glass unit; heat flow density.

Анотація. Виконано аналіз зменшення теплових втрат під час заміни звичайних склопакетів на енергоефективні у світлопрозорих конструкціях споруд об'єктів морської інфраструктури. Проведено експериментальне дослідження густини теплового потоку через різні типи склопакетів. Отримано аналітичні залежності густини теплового потоку від температурного напору через віконну конструкцію.
Ключові слова: термомодернізація; об'єкти морської інфраструктури; енергоефективні склопакети; густина теплового потоку.

Аннотация. Выполнен анализ уменьшения тепловых потерь при замене обычных стеклопакетов на энергоэффективные в оконных конструкциях сооружений объектов морской инфраструктуры. Проведено экспериментальное исследование плотностей теплового потока через различные типы стеклопакетов. Получены аналитические зависимости плотности теплового потока от температурного напора через оконную конструкцию.
Ключевые слова: термомодернизация; объекты морской инфраструктуры; энергоэффективные стеклопакеты; плотность теплового потока.

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Problem statement. According to the Strategy for the Development of Seaports of Ukraine until 2038 and the Mykolaiv Sea Port Development Plan for the short-term (until 2018), medium-term (until 2023) and long-term (until 2038) perspective [1, 2], one of the main objectives and development trend of the marine infrastructure of Ukraine is to provide for comprehensive development and increasing competitiveness of the port industry, as well as to ensure the adequate maintenance, efficient management and use of strategic port infrastructure facilities. Realization of these objectives is impossible without enhancing the energy efficiency of the entire complex of marine infrastructure facilities.

The rise in gas prices and, consequently, the heating costs for administrative and industrial buildings makes the issue of thermal modernization quite relevant. One of the thermal modernization techniques is the replacement of regular insulating glass units (IGU) in translucent window structures with energy-efficient ones [3]. The energy-efficient glass permits radiation of the visible spectrum, but has a low emission factor in the infrared range. Thus, windows with such type of glazing have an increased heat transfer resistance [4].

Increasing the efficiency of the operation of marine infrastructure facilities and reducing the operating costs are impossible without the introduction of energy-saving technologies. This is why obtaining data on the efficiency of replacement of IGUs with energy-efficient ones is relevant and requires a detailed study.

Latest research and publications analysis. Thermal resistance of translucent structures is mainly increased with the help of low-emissivity glass, which permits radiation of the visible spectrum but has a low emission factor in the infrared range. The study of characteristics of low-emissivity glass carried out on the basis of the Institute of Engineering Thermophysics of NAS of Ukraine [4, 5] has confirmed its high efficiency. Meanwhile, publications [6, 7] lay out the methodological foundations for the implementation of thermal modernization of buildings and assessment of its efficiency.

The state building standards have been reformed in 2007 and extended in 2013. Currently, they establish requirements for the thermal insulation of buildings. In particular, the minimum allowable heat transfer resistance of translucent structures is equal to 0.6 $m^2 \cdot K/W$ in residential and public buildings and ranges from 0.18 to 0.45 $m^2 \cdot K/W$ for industrial facilities depending on the purpose of a certain building [8].

The most common IGU types used in administrative and public buildings of marine infrastructure enterprises are the conventional double-glazed 4M1-16-4M1, the double-glazed 4M-16-I4 with low-emissivity glass, and the double-glazed 4M-16Ar-I4 with argon filling [9]. These types of insulating glass units are of a low cost and commonly used to replace conventional wooden windows. At the same time, thermotechnical characteristics of these IGU types may actually vary across manufacturers, since they deliberately enhance particular properties for the purpose of advertising and better sales, which leads to discrepancies when establishing the efficiency of their use [4].

THE ARTICLE AIM is to obtain data on the density of heat flows passing through different types of insulating glass units taking into account the temperature drop values typical for Ukraine in order to estimate the reduction in heat losses when replacing regular IGUs with energy-efficient ones.

Basic material. Table 1 lists the values of heat transfer resistance for the most widespread types of insulating glass units of various configurations [8].

As shown by empirical data, the heat transfer resistance remains practically unchanged when increasing in the spacer width (the distance between the panes). However, at the spacer width increase up to 50-60 mm, the heat transfer resistance of the IGU begins to decrease. Thus, an increase in air gap can actually boost the heat transfer resistance by ~10% [7].

An IGU's heat resistance is substantially enhanced through the use of low-emissivity glass with a special silver heat-saving coating. The i-glass has a soft sprayed coating that provides the necessary level of protection against harmful radiation and a high thermal resistance. The only serious drawback of i-glass is the short service life, which does not exceed 10 years.

To analyze the efficiency of use of a particular glazing option, it is necessary to obtain data on the densities of heat flows passing through different types of insulating glass units and take into account the temperature drop values typical for Ukraine. For this purpose, an experimental stand has been created on the basis of the laboratory of the Department of Technical Thermal Physics and Ship Steam-Generating Plants of the NUOS. It was utilized to study the three most widespread IGU types: the conventional 4M1-16-4M1, the energy-efficient 4M-16-I4, and the energy-efficient 4M-16Ar-I4 with argon filling [6, 7].

The general view of the experimental model is shown in Fig. 1. The structure of the stand is rendered in the diagram of Fig. 2.

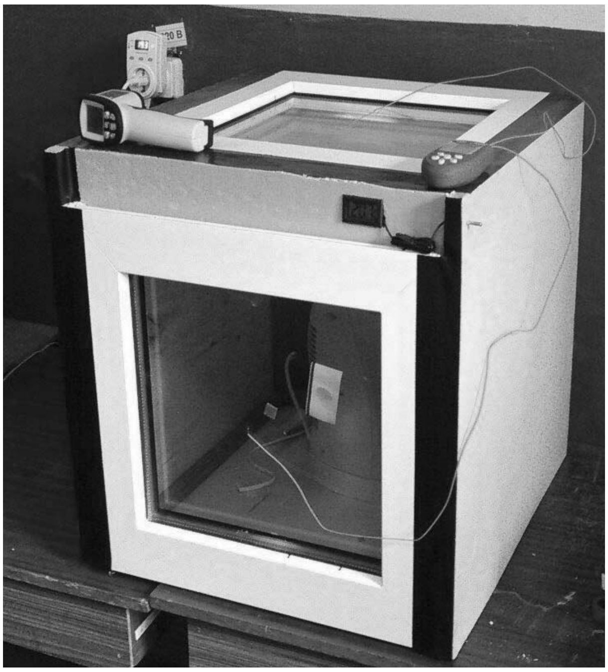


Fig. 1. General view of the experimental model

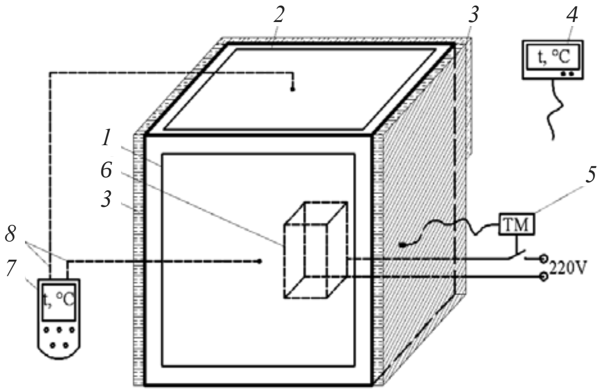


Fig. 2. Structure of the experimental stand:
1 — window no. 1; *2* — window no. 2; *3* — heat insulation; *4* — digital thermometer; *5* — thermostat with a remote sensor; *6* — electric heater; *7* — dual-channel digital thermometer; *8* — thermocouples

The experimental stand consists of an experimental model of a cubic shape. Two of its faces have the form of the metal-plastic windows *1*, *2*, the electric heater *6* is introduced into the model through another face, and the rest of them are insulated with polystyrene slabs *3*. The first metal-plastic window has the glass pane 4P-16-I4 (*1*), and the second window is equipped with

Table 1. Heat transfer resistance of insulating glass units

Number of chambers in the unit	Glazing options	Gas composition between IGU panes, %		Heat transfer resistance, m²·K/W	Market price, USD/m²
		Air	Argon		
1	$4M_1$ - 16 - $4M_1$	100		0.32	10
1	$4M_1$ - 16Ar - 4i		100	0.59	12
1	$4M_1$ - 16Ar - $4M_1$		100	0.66	13.7

the unit 4M1-16-4M1 (*2*). Both feature the 3-chamber profile OpenTeck Standart 60. In the course of the study, the 4M-16-I4 unit of the first window number (*1*) was replaced with the 4M-16Ar-I4 unit. The electric heater is connected to the mains via the thermostat *5* with a remote sensor, which is put inside the model to maintain a constant temperature. The external air temperature is measured using the digital thermometer *3*.

The temperatures of the glass surfaces are measured in different points and averaged with the help of the dual-channel digital thermometer *7* using thermocouples *8* secured on the glass surface.

The experimental study has been accompanied with mathematical modeling of the operation of the insulating glass units employed in the experimental stand.

The computer model solved the problem of thermal conductivity in solids and gases, as well as natural convection in the inner space of the IGU. The model features the continuity, motion, and energy equation in the following form:

$$\frac{\partial \rho}{\partial t}+\frac{\partial(\rho u_i)}{\partial x_i}=0.$$

$$\frac{\partial(\rho u_i)}{\partial t}+\frac{\partial(\rho u_i u_j)}{\partial x_j}+\frac{\partial P}{\partial x_i}=\frac{\partial}{\partial x_j}(\tau_{ij}+\tau_{ij}^R)+S_i .$$

$$\frac{\partial(\rho H)}{\partial t}+\frac{\partial(\rho u_i H)}{\partial x_i}=\frac{\partial}{\partial x_i}(u_j(\tau_{ij}+\tau_{ij}^R)+q_i)+\frac{\partial P}{\partial t}-$$

$$-\tau_{ij}^R\frac{\partial u_i}{\partial x_j}+\rho\varepsilon+S_i u_i+Q_H .$$

The layout of the IGU elements and the calculation input data are displayed in Fig. 3.

The air velocity modeling results for the IGU air space are given in Fig. 4. The modeling allowed obtaining the patterns of temperature distribution on the external glass $t_{ext.IGU}=f(x, y)$ (Fig. 4) and air velocity distribution in the IGU air space (Fig. 5).

By analyzing the obtained air velocity distribution patterns, one can conclude that the air velocity in the IGU chamber is higher than that of argon due to its greater heat conductivity (λ_{air} = 0.0244 W/m·K, λ_{Ar}=0.0165 W/m·K) and smaller density (ρ_{air}=1.204 kg/m^3, ρ_{Ar} = 1.7839 kg/m^3) under normal conditions. In turn, this leads to an increase in heat flow.

In engineering calculations, heat flow density is calculated with account for the average temperature at the glass surface. Therefore, the temperature on the glass surface shall be averaged in the subsequent calculations to validate the modeling adequacy.

The latter is also proved by comparing the modeled temperatures on the IGU's outer surface with those measured during the experiment (Fig. 6). The error does not exceed 2%, which is why the obtained temperatures can be used for further calculations of the densities of heat flow passing through insulating glass units.

The heat flow through an IGU between two media (air in the room and outdoors) is generally calculated via the heat transfer equation:

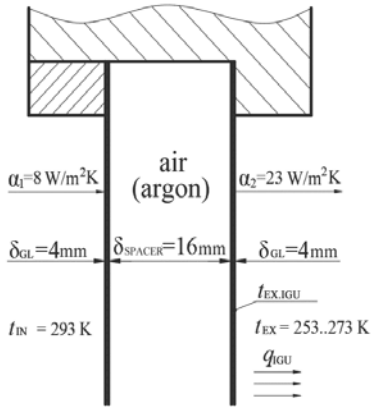
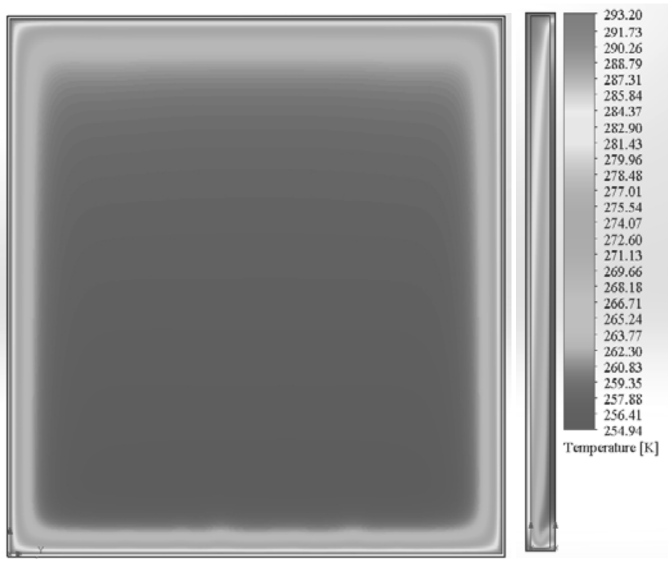
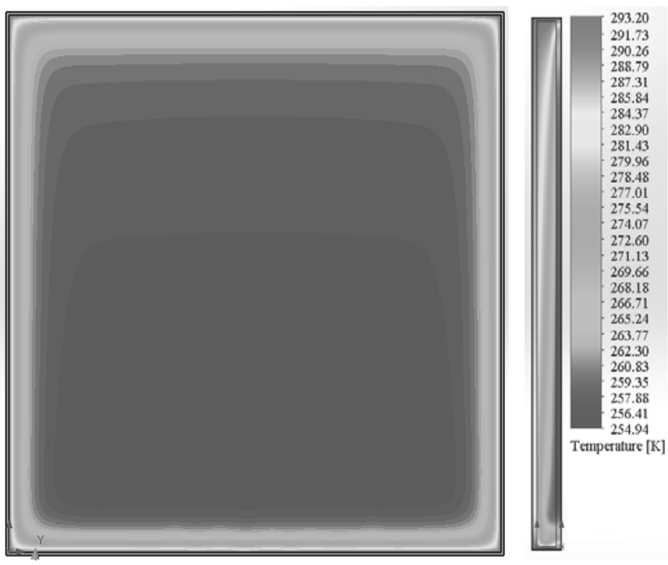


Fig. 3. Design diagram of the insulating glass unit



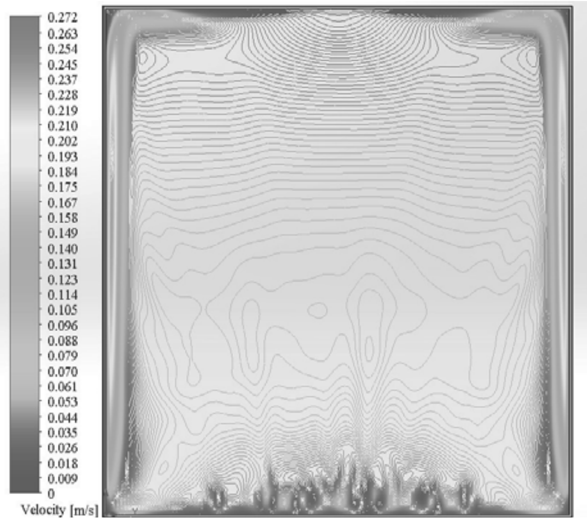
a



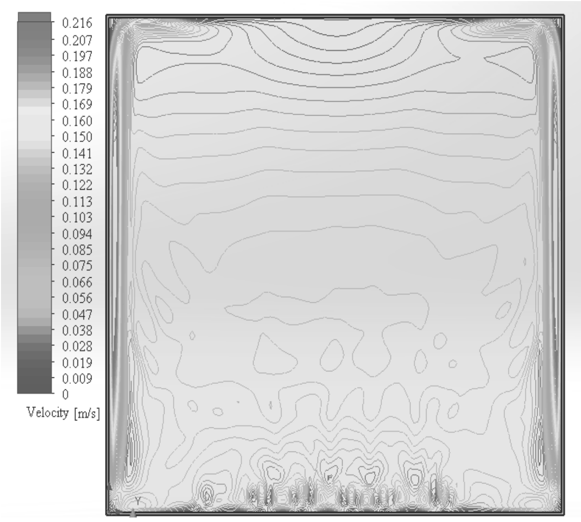
b

Fig. 4. Temperature distribution pattern for the external glass at Δt = 40:

a — air; *b* — argon



a



b

Fig. 5. Air velocity distribution pattern for the IGU air space at Δt = 40:
a — air; *b* — argon

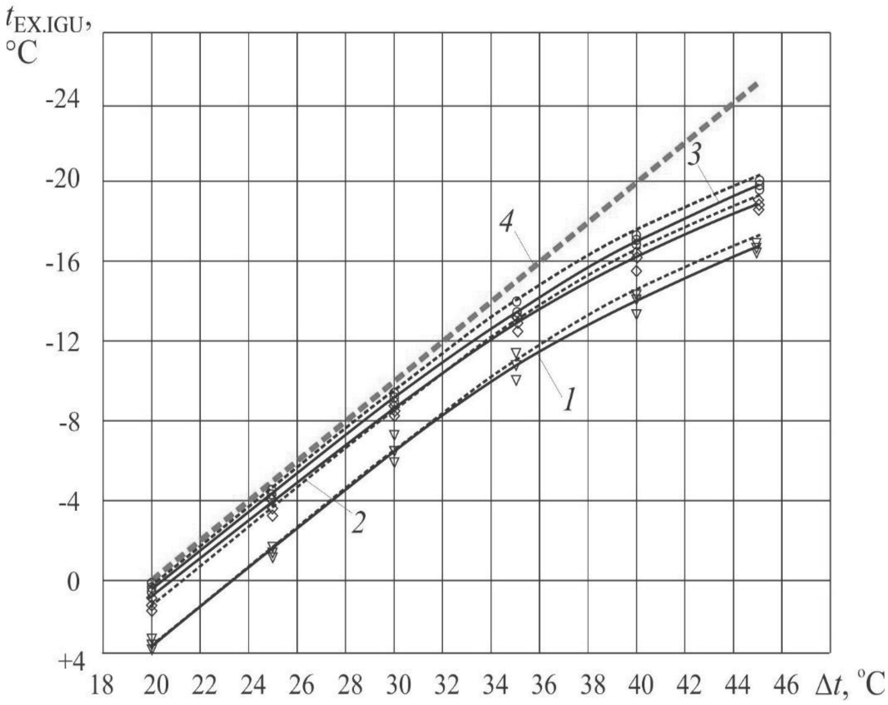


Fig. 6. Dependency of the temperature on the IGU's outer surface on the difference between the external and internal air temperatures: *1* — IGU 4M1-16-4M1; *2* — IGU 4M-16-I4; *3* — energy-efficient IGU 4M-16Ar-I4; *4* — external air temperature

$$Q_{IGU} = \frac{1}{R_{\Sigma IGU}} \cdot F_{IGU} \cdot (t_{IN} - t_{EX}),$$

where $R_{\Sigma IGU}$ is the reduced heat transfer resistance of the insulating glass unit, m²·K/W; F_{IGU} is the area of the translucent part of the unit, m²; t_{IN} is the internal air temperature, °C; t_{EX} is the external air temperature, °C.

Meanwhile, the density of heat flow from the glass surface to the external air (air outdoors) can be calculated as follows:

$$q_{IGU} = \alpha_2 \cdot (t_{EX}^{IGU} - t_{EX}),$$

where α_2 is the coefficient of heat transfer by convection from the glass surface to the outside air, W/m²·K.

The study results are presented in Fig. 7 in the form of a graph showing the dependency of the heat flow density q_{IGU} on the temperature drop Δt.

Physical modeling of heat exchange through insulating glass units with the help of the regression analysis allowed obtaining dependencies for the calculation of heat

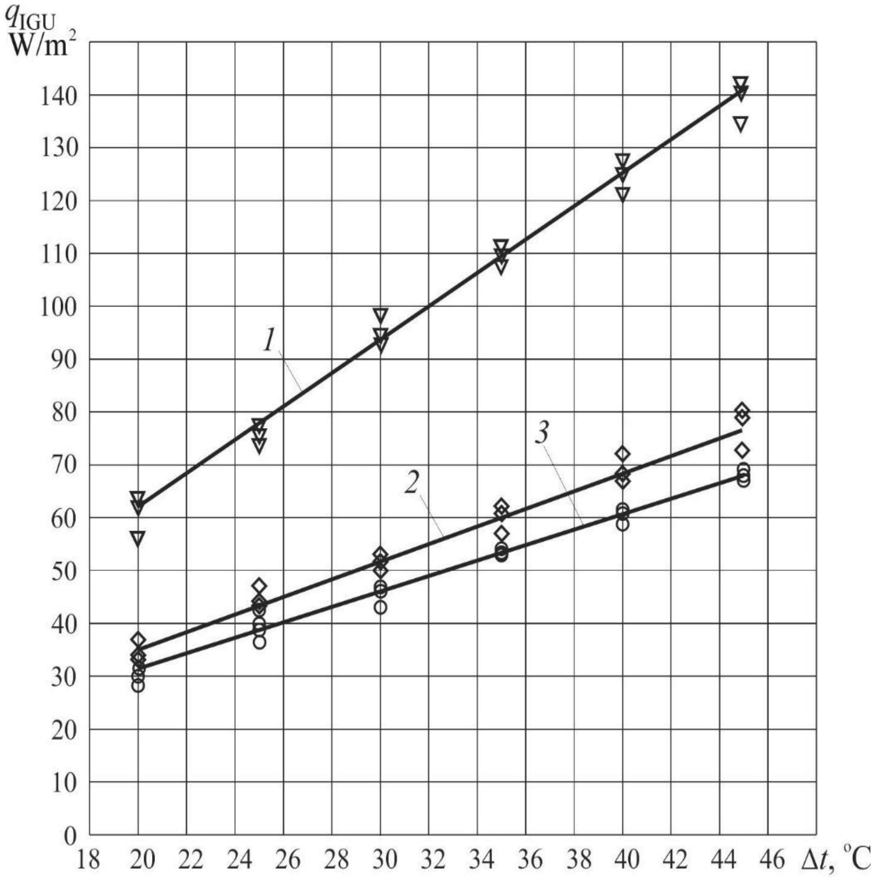


Fig. 7. Dependency of the density of heat flow through the IGU on the temperature difference: *1* — IGU 4M1-16-4M1; *2* — IGU 4M-16-I4; *3* — energy-efficient IGU 4M-16Ar-I4

flow density in the temperature drop range of 20 < Δ*t* < 45 °C. They are as follows:

– insulating glass unit 4M1-16-4M1: ;

– insulating glass unit 4M-16-I4: ;

– insulating glass unit 4M-16Ar-I4: .

Given the linear nature of the dependencies in the range under consideration, these formulas can be recommended for a wider temperature drop range as well.

CONCLUSION. The mathematical modeling and experimental study resulted in obtaining theoretical dependences of heat flow density on temperature drop in the range of temperature pressures 20 < Δ*t* < 45 °C for the conventional insulating glass unit 4M1-16-4M1 and the energy-saving units 4M-16-I4 and 4M-16Ar-I4. These dependencies can be applied to calculate heat loss through translucent structures during thermal modernization of marine infrastructure facilities.

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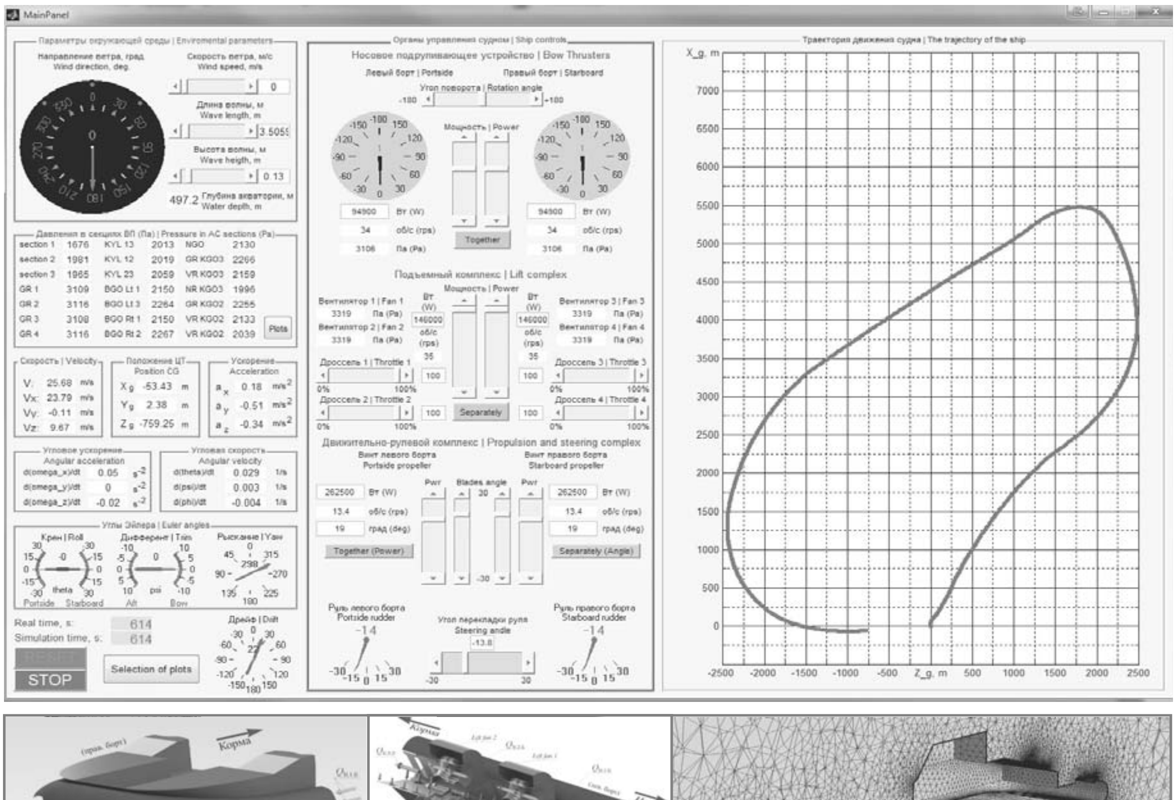

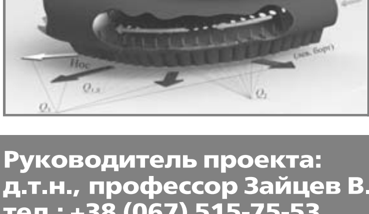

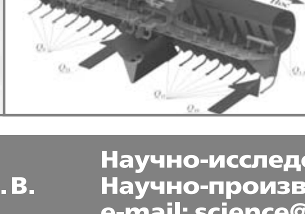

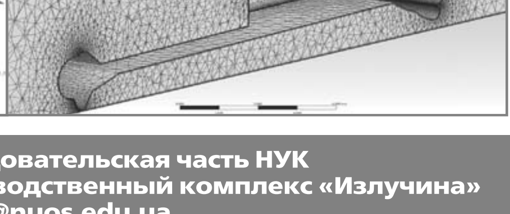

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