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EXERGY ANALYSIS OF DOUBLE-CIRCUIT FLAT SOLAR COLLECTOR WITH THERMOSYPHON CIRCULATION

Waldemar Wójcik¹, Maksat Kalimoldayev², Yedilkhan Amirgaliyev^{2,3}, Murat Kunelbayev², Aliya Kalizhanova^{2,3}, Ainur Kozbakova^{2,3}, Timur Merembayev²

¹Lublin University of Technology, Institute of Electronics and Information Technology, Lublin, Poland, ²Institute of Information and Computational Technologies SR MES RK, Almaty, Kazakhstan, ³Al-Farabi Kazakh National University, Almaty, Kazakhstan

Abstract. In the present work, an exergy analysis was done of two-circuit flat solar collector with thermosiphon circulation. The article presents a mathematical model of energy and exergic analysis of flat solar collectors, as well as calculations of solar radiation efficiency, temperature, flow rate of the fluid, exergy rates and exergy loss rates are done. The significance of the results achieved is high, since experimental studies can detect inefficient components of the solar heating system. The exergetic efficiency of a dual-circuit flat solar collector with a thermosiphon circulation describes irreversibility of the process according to thermodynamic parameters. This is caused by a large degree of overheating achieved at the end of the processes of compression and evaporation, which leads to large differences in heat exchange temperature based on the heat pump cycle. The exergy efficiency value for the entire system is 70. Maximum values energy efficiency and exergy at noon, 32.5% and 2.23%, respectively. The efficiency of exergy is 4%, and the highest the loss of exergy is the difference between the absorber plates and the sun, accounting for 52.86% of the total exergy rate.

Keywords: temperature, solar energy, analysis, mathematical model

ANALIZA EGZERGETYCZNA KOLEKTORA SŁONECZNEGO DWUOBWODOWEGO Z OBIEGIEM TERMOSYFONU

Streszczenie. W niniejszej pracy wykonano analizę egzergetyczną płaskiego kolektora słonecznego dwuobwodowego z cyrkulacją termosyfonową. W artykule przedstawiono model matematyczny analizy energetycznej i egzergetycznej płaskich kolektorów słonecznych, a także obliczono sprawność promieniowania słonecznego, temperaturę, natężenie przepływu cieczy, wskaźniki egzergii i wskaźniki strat egzergetycznych. Znaczenie osiągniętych wyników jest duże, ponieważ badania eksperymentalne mogą wykryć nieefektywne elementy systemu ogrzewania energią słoneczną. Egzergetyczna sprawność dwuobwodowego płaskiego kolektora słonecznego z obiegiem termosyfonowym opisuje nieodwracalność procesu według parametrów termodynamicznych. Jest to spowodowane dużym stopniem przegrzania osiąganym pod koniec procesów sprężania i odparowywania, co prowadzi do dużych różnic w wymianie ciepła w oparciu o cykl pompy ciepła. Efektywność energetyczna całego systemu wynosi 70. Maksymalne wartości sprawności energetycznej i egzergii w południe, odpowiednio 32,5% i 2,23%. Efektywność egzergii wynosi 4%, a największą stratą egzergii jest różnica pomiędzy płytami absorbera a słońcem, stanowiąca 52,86% całkowitego wskaźnika egzergii.

Słowa kluczowe: temperatura, energia słoneczna, analiza, model matematyczny

Introduction

For water heating the power cost can be sufficiently reduced thanks to the solar energy usage. Thermosiphon solar collector is a type of a passive heater, which might be easily constructed and used without any complications. Thermosiphon thermal electric collector has been designed, constructed and tested at Dhaka University, Bangladesh [17]. Upon assessing the solar coil-type water heater the water temperature at the collector's inlet and outlet and in the reservoir were recorded during sequential hours. Maximum water temperature at the outlet from the collector accounted to 67°C, and maximum water temperature in the reservoir constituted 61°C within June-July. Based on the collected data there have been constructed and analysed various temperature graphs for different sunny time, different insulation quantity and different weather conditions. There also has been conducted the pH test to study water pH value in the water reservoir made of alumina. Thermosiphon collectors' performance depends on several physical dimensions, operating parameters and meteorological parameters. While evaluating the efficiency, the attention is frequently paid merely to the thermal effectiveness. However, the energy equalizing does not consider many internal and conversion losses factors. High thermal effectiveness does not maintain the operation high performance [15]. The article [13] presents the theoretical model of the flat solar collectors' energy and exergy analyses, through which we can study the influence of all designed parameters at the operating characteristics.

To a greater extent, upon tracking the entropy generation, the exergy analysis using the thermodynamics second law might bring to the system operation optimization [18, 23]. The denoted article pays the basic attention to the thermosiphon collector, considering its parameters in respect of the power consumption efficiency, as well, to dimensional, operational and meteorological parameters.

In the heat exchangers and solar water heaters for providing heat and hot water there widely used the serpentine tube. The system's dimensions physical parameters influence greatly at the

performance. The serpentine tubes shall be precisely designed and placed within the system. The optimal position analysis of the calculated hydrodynamics of a serpentine heat exchanger is in contact with the drain with the carrier medium and length [9]. Wang et al. [22] have shown, that the exergy efficiency changes inversely to the collector width using the «Three stage theory». Comparing to other energy analysis theories, three theories' procedures have more advantages. The three procedures give an appropriate platform for conducting an energy analysis. An exterior analysis is executed with a purpose to provide some methods for cost saving and maintaining the solar water heater's performance at the local level at the demanded degree, and at the same time, to clarify the bounded losses at operation [3]. The solar fraction and configuration are sufficiently influenced with the absorber plate thermal conductivity [12]. Gupta et al. in the article [11] denoted, that there is an optimal temperature at the air inlet and mentioned parameters for a definite system, also, they analysed the dependence of air outlet energy on the ratio of the collector's dimensions, mass flow speed per the absorber's square unit and channel depth [8, 16] through the exergy analysis recommended the thermosiphon collector's optimal operation conditions. However, they supposed the constant inlet water temperature, which was equal to the atmospheric temperature. The authors thereof did not take into consideration the pressure drop. The proposed thermosiphon collector design method is based on the minimal entropy generation, but there was neglected the exergy destruction due to the pressure drop [21]. Farahat et al. [7] presented a detailed approach to the exergy analysis and optimization and showed, that the exergy performance constitutes 3,898% in the optimal state. Exergy analysis of multiple solar thermal collectors and processors have been thoroughly considered by many researchers [14]. The next article has given the exterior balance stages [20], the thermosiphon exergy optimization for dimensional and operational results. The stage thereof and optimal outcome might be used for other similar systems. In the work [19] there has been developed the optimization tools in the MATLAB media, which is used for

defining the parameters of the exergy maximum performance. Parameters' values in the optimal state are used for studying the definite parameter impact at the system's efficiency. There has been mentioned a concise information about the exergy elimination and destruction in the works [4, 7], nondimensional exergy [2] and an exergy destruction factor [5], which can be used for forecasting such type systems performance.

1. Method of research

Double circuit flat solar collector with thermosyphon circulation has been constructed and installed at the Institute of Information and computer technologies of MES RK, Almaty, Republic of Kazakhstan: 77 degrees of East longitude and 43 degrees of Northern latitude), as it is shown on the Figure 1. The installation has tubes over the absorber plate, which act according to a thermosyphon principle (Fig. 1 and 2). A flat collector slope angle is 45°, directed to the South. Water incomes to a collector through an inlet tube from a water tank and bleeds heat from an absorber plate.

Water tank: an isolated reservoir, containing water, used for maintaining the water stream into and out of the collector. Water density change inside the reservoir creates thermosyphon activity.

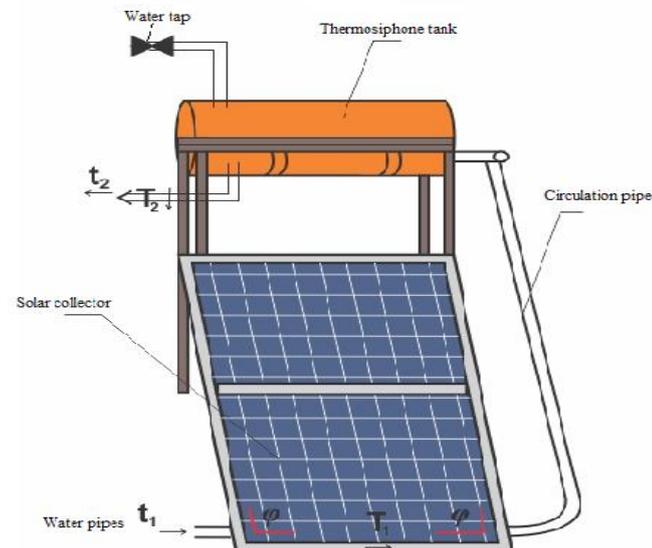


Fig. 1. General view of solar water heater

Substantiation of design technological scheme. With account of requirements to the installation's indices upgrading there has been developed the diagram of double circuit solar installation with a thermal pump (Figure 1), the installation is formed of four basic units: thermosyphon 1, solar collector 2, heat pump 3, tank accumulator 4.

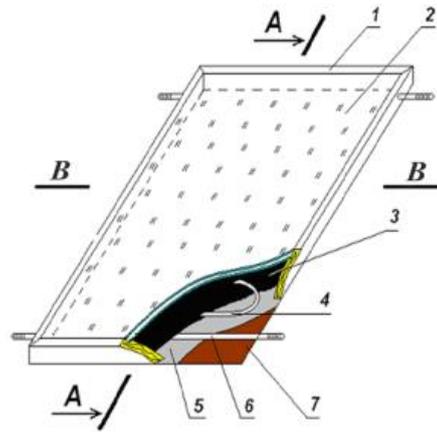


Fig. 2. Flat solar collector

Fig. 2 demonstrates the flat solar collector model. The installation's principle and novelty consists in its difference from the known designing principle, the collector contains a transparent double glazing unit 2 with reduced pressure, as well, a parametric frame 1. A wooden frame bottom 7 is made of 8 mm thickness plywood and there is fixed a heat sealing film to it 5 with foil. In the gap between a glazing unit and frame bottom there is laid a thin wall flexible stainless corrugated tube 4Ø16 mm in the coil form. Tube edges are fixed to the inlet and outlet obtrusive tubes 6.

Table 1. Technical indicators of flat solar collector

| Parameters | Value |
|---------------------------------|---------------------------------|
| Absorbing plate material | copper |
| Absorber plate dimensions | 2 m×1 m |
| Plate thickness | 0.4 mm |
| Glazing material | Hardened glass |
| Glazing dimensions | 2 m×1 m |
| Glazing thickness | 4 mm |
| Insulation | Foam plexus (foam polyurethane) |
| Collector's decline angle | 45° |
| Absorber's thermal conductivity | 401 W/(m K) |
| Insulation thermal conductivity | 0.04 W/(m K) |
| Transmission-absorption factor | 0.855 |
| Visual sun temperature | 4350 K |
| Atmospheric temperature | 303 K |
| Irradiation intensity | 1000 W/m ² |

1.1. Substantiation of design-technological scheme

Due to the necessity of upgrading the installation's operational specifications we have developed a principle diagram of double circuit solar collector with a heat pump (Fig. 3).

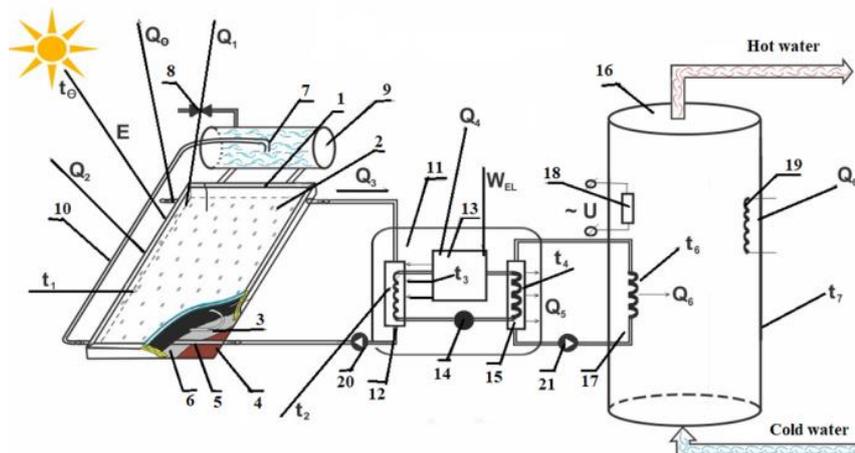


Fig. 3. Functional diagram of double circuit solar installation with thermosyphon circulation

The assumed installation's operation is fulfilled as follows.

Solar energy E with temperature t_0 is absorbed by the solar collector 1, with the temperature t_1 , which, heating the solar energy flow, passes through translucent insulating double glass unit 2. The heat, obtained from the solar stream, heats the liquid in the coils 3, which is removed from the collector, and replaced with cold water from the water pipe with a tap for cold water 8, and in the dosing unit syphon 7 there takes place constant thermosyphon circulation by means of circulation tube 10. Further the liquid flows into a heat pump 11, which consists of 12 - condenser with a temperature t_2 , in which a heat exchanger is made in the coil form, absorbing the thermal medium heat, reduces its temperature lower than the atmospheric air temperature (Q_2) by means of a speed control valve 14, thereby helping on the additional heat absorption from the atmospheric air. The scheme also shows the solar irradiation, reflected from semi-transparent coating (Q_0) and absorbing panel surface (Q_1). In the heat pump there is fulfilled a heat carrier power transfer with a relatively low temperature, to a condenser's heat exchanger transfer medium 15 in the coil form with higher temperature t_2 , which increases the square, as well as the heat exchange intensity. To execute such a cycle there is used a compressor 13 with temperature t_3 , electric drive 17. Further, by means of the condenser heat exchanger 15 with temperature t_4 , the heat from the heat pump (Q_5) is transferred to the heat exchanger tank-accumulator Q_6 with temperature t_6 of the heating system 18. As the installation has two circuits, it is provided with automatic circulation pumps 19 and 20 for liquid circulation between the solar collector and evaporator, condenser and tank-accumulator. Water temperature is conditioned to the demanded technological level and provided the consumers for hot water and heating supply.

1.2. Energy and exergy model

Instant useful energy, accumulated by the solar collector is computed according to the following equations [5, 6, 10]

$$Q_u = A_c F_R [I_T(\tau\alpha) - U_l(T_{in} - T_a)] = m \dot{C}_{p,wa} (T_0 - T_i) \quad (1)$$

Alternatively, the instant useful energy, accumulated with the solar collector might be computed as

$$\dot{Q}_u = \dot{m} C_{p,wa} (T_{out} - T_{in}) \quad (2)$$

Collector's instant performance is computed as

$$\eta_{en} = \frac{Q_u}{I_T A_c} \quad (3)$$

Temperature distribution between the tubes and collector's efficiency factor is discussed in detail [10].

Let's write down the equations for the flow energy and exergy in the heat pump system and its components, as they are considered to be established with the system's flow volume, energy and exergy equations have been derived for the system and its components.

The heat, extracted from the heat pump heat exchanger Q_u is computed according to the following equation:

$$Q_u = \dot{m} C_p (T_{out} - T_{in}) \quad (4)$$

Heat transfer factor in the condenser is computed as follows

$$\dot{Q} = \dot{m} (h_2 - h_1) \quad (5)$$

Heat exchange speed in the evaporator amounts to

$$\dot{Q} = \dot{m} (h_1 - h_4) \quad (6)$$

Compressor implementation speed [33]

$$W_{com} = \frac{\dot{m}_{ref}(h_2 - h_1)}{\eta} \quad (7)$$

where η – energy efficiency

The total system efficiency factor «COP_{sys}», which represents the ratio of the condenser load to the total expenditures on the compressor operation and circulation pumps is computed according to the following equation

$$COP_{sys} = \frac{Q_u}{(W_{com} + W_{pumps})} \quad (8)$$

Working inlet into the circulation pump [36]

$$W_{pump} = \frac{\Delta PV}{\eta} \quad (9)$$

where ΔP – pressure loss, V – volume flow rate of water - glycolic mixture, η – the pump mechanical performance.

ΔP – pressure loss is recorded as:

$$\Delta P = 0.5f \frac{L}{D} \rho U^2 + \sum \zeta \quad (10)$$

where U – speed, f – fraction losses, ζ – resistance specific loss, L – tube length.

Exergy speed is calculated according to the following equation

$$\dot{E}_x = \dot{m}_{ref} [(h - h_0) - T_0(s - s_0)] \quad (11)$$

Exergy destructions in the heat exchanger (condenser and evaporator), in the expansion valve and solar collector are computed as follows:

Heat exchanger:

$$\dot{E}_{xdest,HE} = \sum \dot{E}_{x,in} - \sum \dot{E}_{x,out} - \sum \dot{E}_{xdest} \quad (12)$$

$$\dot{E}_{xdest,HE} = \dot{m}_{wa} (\psi_{in} - \psi_{out}) + \dot{Q}_r \left(1 - \frac{T_0}{T_{ground}}\right) \quad (13)$$

Thermal pump

$$\dot{E}_{xdest,pump} = \dot{W}_{pump} - (\dot{E}_{x,out} - \dot{E}_{x,in}) \quad (14)$$

Expansion valve:

$$\dot{E}_{xdest,valve} = \dot{m}_{ref} (\psi_{in} - \psi_{out}) \quad (15)$$

Entry mode, which is used as a solar collector:

$$\dot{E}_{xdest,col} = \dot{m}_{wa} (\psi_{in} - \psi_{out}) + \dot{Q}_u \left(1 - \frac{T_0}{T_s}\right) \quad (16)$$

$$\dot{E}_{xdest,col} = \dot{m}_{wa} (\psi_{in} - \psi_{out}) + A_c I_T \left(1 - \frac{T_0}{T_s}\right) \quad (17)$$

Heat exchangers (condenser and evaporator) exergy efficiency is defined through increasing the cold flow exergy, divided by decrease of hot flow exergy on the basis of speed as follows:

$$\varepsilon_{HE} = \frac{\dot{m}_{cold}(\psi_{cold,out} - \psi_{cold,in})}{\dot{m}_{hot}(\psi_{hot,in} - \psi_{hot,out})} \quad (18)$$

Circulation pumps exergy performance is determined with an equation:

$$\varepsilon_{pump} = \frac{\dot{E}_{x,out} - \dot{E}_{x,in}}{\dot{W}_{pump}} \quad (19)$$

GSHPS exergy efficiency is computed:

$$\varepsilon_{sys} = \frac{\dot{E}_{x,out}}{\dot{E}_{x,in}} = 1 - \frac{\sum \dot{E}_{xdest}}{\sum \dot{E}_{x,in}} \quad (20)$$

2. Research outcomes

In the research herein we have conducted the energy and exergy studying the analysis of dual circuit flat solar collector with thermosyphon circulation. Figure 4 shows the hourly change of solar radiation intensity and atmospheric temperature as regard to Almaty city, Kazakhstan (longitude /latitude: 77 degrees of East longitude and 43 degrees of North latitude).

The authors of the article herein have considered the solar-energetic resources of the Republic of Kazakhstan. To assess the potential of the solar energy, falling onto the territory in one or another district, it is necessary to have the data on the solar power potential. Having generalized the actual observations and theoretical calculations there has been obtained data on: annual and latitudinal movement of possible monthly and annual amounts of direct solar radiation falling onto the perpendicular surface at clear sky conditions, information on sunshine period, solar radiation daily movement for typical days of the year, maps of distributing the average monthly radiation sums along the territory within June and December, as well, the distribution maps of «technically applicable and economically profitable solar power», developed criteria for defining the conception. In the root of all solar systems designed indices upon assessing the solar-energetic resources on Kazakhstan territory there are laid. The qualitative characteristics of direct solar radiation, falling on the horizontal surface, which can be used for recomputation of any orientation from horizontal to inclined plane. Proceeding from statistical processing the direct total radiation average values and sunshine period there have been differentiated five zones and drawn up a histogram, characterizing the opportunities of implementing the solar installations on the territory of Kazakhstan [1].

To calculate the exergy analysis we have applied the computer simulation program (subprogram MATLAB ode45), based on Runge-Kutta quartic method for solving the above-mentioned non-linear ordinary differential equations. To secure the elaborated numerical model's accuracy, the water capacity numerical results have been confirmed with corresponding experimental temperatures [12].

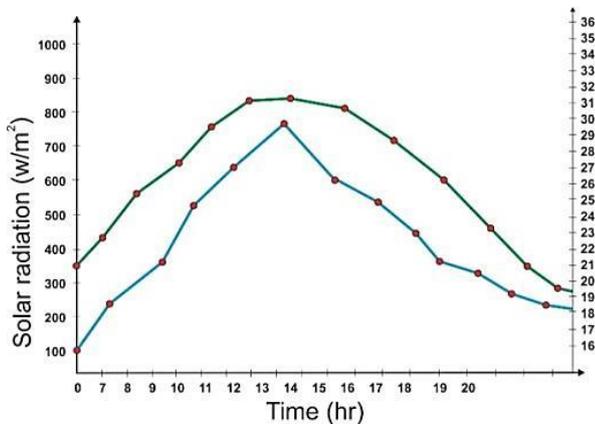


Fig. 4. Dependence of the solar radiation on hourly change of meteorological conditions in Almaty city (Kazakhstan)

Figure 4 show offered system's hourly energy and exergy efficiency change and all components exergy destruction speed. According to the dependence thereof it can be said, that the solar radiation intensity for Almaty city in summer period is of the most value at midday, as the total solar radiation reaches its peak height.

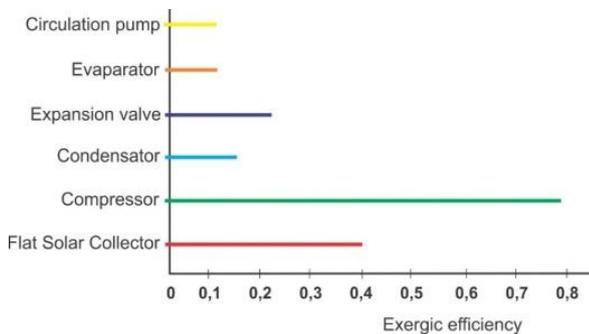


Fig. 5. Exergy performance indices of double circuit flat solar collector with thermosyphon circulation

Figure 5 presents the exergy performance indices of double circuit flat solar collector with thermosyphon circulation. As it is seen from the figure, the most process irreversibility judging from the thermodynamic indices is conditioned by the heat pump compressor. It is due to the overheat great extent, achieved in the end of compression and evaporation processes, which brings to big temperature gradient, linked with the heat exchange initial phase based on the heat pump cycle. Exergy performance value for overall system equals to 70. Reasons for exergy destruction in the system include a compressor, heat exchanger (condenser and evaporator), and circulation pumps. Water and coolant thermodynamic properties (working liquid, R218 have been obtained from the database NIST.

3. Conclusion

Exergy analysis of the flat solar collector with thermosyphon circulation is based on the heat losses factor calculation, collector's heat release coefficient and the plate impact factor. But, accuracy computation will lead to the perfection. In the work

herein it has been proved, that maximum exergy level can be reached with the temperature range, but the heat pump efficiency factor lowers, at that, the atmospheric temperature makes a positive influence at thermal effectiveness, while it negatively affects the exergy performance. As well, it has been proved, that at circulating solar water supply system the exergy efficiency can be about 4%.

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Prof. Waldemar Wojcik

e-mail: waldemar.wojcik@pollub.pl

Director of Institute of Electronics and Information Technologies, Faculty Electrical Engineering and Computer Science, Lublin University of Technology. Doctor of Technical Sciences, Professor.

Scientific interests: mathematical modelling, optical fibre in telecommunication systems and networks, electronic devices, Bragg fibre gratings, fibre optic sensors.

ORCID ID: 0000-0002-0843-8053

**Prof. Maksat Kalimoldayev**

e-mail: mnk@ipic.kz

Academician of NAS RK, doctor of physical and mathematical sciences, professor, Vice President, Chief Scientific Secretary of the National Academy of Sciences of the Republic of Kazakhstan the General director of the Institute of Information and Computational Technologies of the Ministry of Education and Science CS of the Republic of Kazakhstan. Research areas: modelling, control and optimization of complex systems, information security, artificial intelligence technology, robotic systems, speech technology, etc.

ORCID ID: 0000-0003-0025-8880

**Prof. Yedilkhan Amirgaliyev**

e-mail: amir_ed@mail.ru

Doctor of technical sciences, professor, head of the laboratory of mathematical and computer modelling of the Institute of Information and Computing Technologies of the Science Committee of RK MES. The Institute is the leading organization in the field of information technology in the country. The main directions of the research laboratory is an intelligent decision-making systems, robotics, wireless sensor technology, computer modelling of technological processes, etc.

ORCID ID: 0000-0002-6528-0619

**M.Sc. Murat Kunelbayev**

Master of physics, a senior fellow at the Institute of Information and Computational Technologies of the Ministry of Education and Science CS of the Republic of Kazakhstan. Research interests: Simulation model of microhydroelectric power plant, solar collector, energy, technology design of complex systems.

ORCID ID: 0000-0002-5648-4476

**Ph.D. Aliya Kalizhanova**

e-mail: kalizhanova_aliya@mail.ru

Candidate of physical and mathematical sciences, associate professor, the deputy general director of the Institute of Information and Computational Technologies of the Ministry of Education and Science CS of the Republic of Kazakhstan. Scientific interests of the leader: mathematical modelling of systems, models of transport systems network analysis, optimization methods, technologies for developing sensor systems for signals receive-transmit, mathematical modelling of Bragg fibre gratings.

ORCID ID: 0000-0002-0843-8053

**Ph.D. Ainur Kozbakova**

e-mail: ainur79@mail.ru

Ph.D. on a specialty "Information Systems", a senior fellow at the Institute of Information and Computational Technologies of the Ministry of Education and Science CS of the Republic of Kazakhstan. Research interests: mathematical modelling of discrete systems, evacuation tasks, operations research, technology design of complex systems.

ORCID ID: 0000-0002-5213-4882

**M.Sc. Timur Merembayev**

e-mail: merembaevt@gmail.com

Ph.D. Student specialising in "Information Systems", a programmer at the Institute of Information and Computational Technologies of the Ministry of Education and Science CS of the Republic of Kazakhstan. Research interests: mathematical modelling of discrete systems, evacuation tasks, operations research, technology design of complex systems.

ORCID ID: 0000-0001-8185-235X



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