POLITYKA ENERGETYCZNA – ENERGY POLICY JOURNAL

2025 ✦ Volume 28 ✦ Issue 3 ✦ 99–127

DOI: 10.33223/epj/205955

Gulnar Sydykova[1], Anvar Anarbaev[2], Kultan Islambek[3], Aknur Zhanserikkyzy[4], Asylbek Nurzhanovich Kazanbekov[5]

Investigation of RES on a sustainable energy system

Abstract: This research focuses on investigating and improving technical solutions for utilizing evacuated tube heat collectors and solar concentrators to enhance heat transfer efficiency and adapt solar installations to integrate with existing fuel oil heating systems. The research methodology included the development of a mathematical model to describe heat transfer in evacuated tube heat collectors, the creation of an algorithm to calculate the system's design parameters, and numerical modeling to assess temperature characteristics, efficiency, and the impact of key factors affecting the system. As a result of the study, the developed mathematical model made it possible to accurately describe the processes of heat transfer and the interaction of solar radiation with evacuated tube heat collectors and solar radiation concentrators, and to identify analytical dependencies linking the design parameters of the system (pipe diameter and module length) with heat engineering characteristics such as the temperature of the heat

✉ Corresponding Author: Gulnar Sydykova; e-mail: gulnarsydykova09@gmail.com

[1] Korkyt Ata Kyzylorda University, Kazakhstan; ORCID iD: 0000-0002-6841-028X; e-mail: gulnarsydykova09@gmail.com

[2] National Research University "Tashkent Institute of Irrigation and Agricultural Mechanization Engineers Institute", Uzbekistan; ORCID iD: 0000-0003-4643-3277; e-mail: a_anarbaev@outlook.com

[3] Korkyt Ata Kyzylorda University, Kazakhstan; ORCID iD: 0000-0001-9485-0425; e-mail: islambekkul1@hotmail.com

[4] Korkyt Ata Kyzylorda University, Kazakhstan; ORCID iD: 0000-0002-6164-6775; e-mail: aknurzhan@outlook.com

[5] Korkyt Ata Kyzylorda University, Kazakhstan; ORCID iD: 0009-0001-5029-2975; e-mail: ankazanbekov@hotmail.com

carrier and the efficiency of heat transfer. During the study, the relationship between the geometric parameters of the system, solar flux, reflection coefficient, and angular inaccuracy was investigated, which helped identify key factors affecting the efficiency of solar energy capture and the temperature distribution within the system. Numerical calculations have shown that increasing the system's length and adjusting the diameter of the pipes significantly improved the efficiency of solar radiation and affected the coolant's temperature. The paper also analysed the temperature characteristics, including the effect of the coolant flow rate and its distribution along the length of the tube heat collector. The calculation results showed that to optimize the system, it is necessary to consider the interaction of various parameters, including geometry and radiation characteristics, in order to maximise the efficiency of solar power plants. Additionally, the study confirmed the relationship between the receiver diameter and the concentration number, enabling a more accurate prediction of the system's efficiency under various operating conditions. Thus, the results obtained can be used to optimize the design of solar thermal systems, improve their efficiency, and accurately calculate design parameters.

Keywords: solar radiation concentrator, evacuated tube heat collector, steam consumption, design parameters, heating systems, high-temperature installations

Introduction

In winter, when the demand for thermal energy increases significantly, heating oil plays a key role in the operation of thermal power plants in Uzbekistan. It is used as the primary fuel source, providing a reliable energy supply even at low temperatures. Moreover, natural gas is gradually becoming the dominant type of fuel, but additional fuels are still needed to maintain the stability of energy systems. Thus, coal is primarily used to generate electricity, while fuel oil is more commonly used to operate heating supply systems. Its popularity is conditioned by its ability to maintain a high level of thermal energy and the stability of the equipment. However, the use of fuel oil requires special storage and operating conditions, which makes it an important but technically challenging fuel in winter and low temperature conditions.

The difficulties that arise when using fuel oil are related to its physical and chemical properties. The increased viscosity and significant surface tension prevent efficient fuel spraying in boiler installations (Grigorenko et al. 2019; Kravets et al. 2024). To optimize the combustion process, the fuel oil is heated to a temperature of 170–180°C, which significantly reduces its viscosity and accelerates thermal reactions, including decomposition and subsequent reaction of residual components. However, these measures significantly increase the energy costs associated with heating and maintaining the optimal temperature of the fuel oil, which makes its operation the most expensive compared to other fuels. The energy costs associated with the preparation and use of fuel oil can exceed 9% of the system's total energy consumption, underscoring the need to develop more efficient approaches for its application in this industry (Normuminov et al. 2023; Grigorenko et al. 2020).

Modern research in the field of improving fuel energy system efficiency aims to address several significant gaps in this area. Among the key challenges is the need to reduce energy consumption for the preparation and use of conventional hydrocarbon fuels, such as fuel oil, and improve the quality of their combustion (Gutarevych et al. 2020). Additionally, there is a significant need to develop technologies that will integrate conventional fuels with renewable energy sources (RES). Such integration approaches can reduce dependence on fossil resources and reduce the carbon footprint by creating more environmentally friendly energy systems. Research in this field aims to propose new methods and solutions that reduce energy losses, enhance the efficiency of thermal engineering processes, and adapt existing power systems to the transition to combined or alternative energy sources.

One of the key aspects of utilizing renewable energy sources in conventional energy processes is the development of technologies that ensure stable and efficient interaction between fossil fuel-based and renewable energy systems (Tropina et al. 2014; Rogovyi 2018). The study by Grigoriev et al. (2024) noted that the use of solar thermal installations in combination with hot water boilers can reduce energy consumption for fuel preparation. However, it was also emphasized that to ensure the system's protection in winter, it must use a non-freezing coolant or regulated heating. Lipiński et al. (2021) highlighted the efficiency of using various types of solar concentrators to increase heat transfer in boilers, but also emphasized that insufficiently accurate calculations of temperature characteristics under changing operating conditions can reduce system efficiency. Rebhi et al. (2022) emphasized the importance of heat transfer in solar installations, which allows for predicting temperature fields and heat transfer efficiency. However, it was found that failure to consider all factors affecting the system's efficiency in real-world operation may lead to insufficiently accurate results.

When implementing solar thermal installations with concentrators for heating fuel oil, it is important to consider the technical limitations and economic efficiency of such systems in the conditions of existing energy infrastructures. The study by Kumar et al. (2022) considered the methodology for optimizing the operation of solar thermal systems with concentrators, which allowed for increasing their efficiency. However, the study did not address the issues of scalability and the application of these solutions in large energy complexes. Bagherian and Mehranzamir (2020) considered the possibility of integrating solar systems into existing power plants to improve their efficiency; however, the problem of high implementation costs for older systems remained unresolved. Yousef et al. (2021) explored the potential of combining hybrid solar and conventional energy sources. However, no sufficiently effective solution was proposed for load balancing between solar and conventional sources under conditions of unstable solar radiation.

In addition, when using solar thermal installations, an important aspect is the search for optimal methods to increase thermal efficiency and minimise energy losses during operation. Research by Sareriya et al. (2022) focused on optimizing the design of solar concentrators to improve temperature characteristics, which increased the system's efficiency. However, it did not account for the impact of long-term material degradation under the influence of external factors. Patel (2023) examined the possibility of using new types of heat exchangers in solar thermal installations, which led to a reduction in energy losses and improved heat transfer; however, the study did not consider the cost and potential difficulties associated with production. The study by Malwad and Tungikar (2021) analyzed the effect of various materials on the efficiency of a solar energy concentrator, but did not address the problems associated with maintenance and the resistance of these materials to external influences.

The purpose of this study was to develop and analyse technical solutions for the use of high-temperature solar installations based on existing heat sources designed for heating fuel oil, which will optimize their preparation processes and reduce conventional fuel consumption. As part of the study, tasks were set that included calculating the thermal energy required at various stages of fuel oil preparation, considering the specifics of technological processes, and developing design parameters for an evacuated tube heat collector and a solar radiation concentrator based on the required thermal characteristics.

1. Materials and methods

The methodology of this study included an integrated approach that combined theoretical and numerical methods to develop a model and analyse heat transfer processes in a system of evacuated tube collectors (ETC) and concentrated solar power (CSP).

During the research, a detailed mathematical model was developed that encompasses all the primary aspects of heat transfer in heat collector pipes and their interaction with solar radiation. The model was based on heat transfer equations that consider both conductive and convective processes, as well as the effects of radiation reflected and absorbed within the system. One of the key elements of the model was the geometry of the heat sink, including the shape of the pipes and the solar radiation concentrator, which directly affects the distribution of solar flux and the efficiency of its utilization. Geometric parameters such as the length of the pipes, their diameter, shape, and angular location relative to the solar flux have become the basis for more accurate calculations. The model considered the characteristics of solar radiation, such as the intensity of direct radiation and the angle of incidence of sunlight, which have a significant impact on the efficiency of solar radiation concentration and how this radiation is converted into heat. An additional important aspect of the developed model was a detailed description of the heating process of the coolant, including its interaction with the pipe walls. For this purpose, the calculations utilized equations for heat transfer between the coolant and the pipe walls, which include parameters such as the heat capacity, thermal conductivity, and viscosity of the liquid, as well as the flow rate of the coolant, which affects the heat transfer coefficient. This allowed for considering all the important physical processes occurring inside the evacuated tube heat collector, and more accurately simulating the behavior of the coolant under various operating modes of the system.

Following the creation of a mathematical model, a sequential study of the system's geometric and thermal properties forms the basis of the suggested technique for determining the design parameters of the evacuated tube collector and concentrated solar power (ETC-CSP) system. The working fluid's temperature, flow rate, heat capacity, viscosity, intensity of direct sunlight, concentrator's specular reflection coefficient, and geometrical dimensions of the tubes and concentrator are among the first set of input parameters that are specified. These values are used to calculate the cross-sectional area of the collection tubes, taking into account the coolant velocity and density. Additionally, the diameters of the tubes and the receiver's exterior dimensions are calculated while taking wall thickness into account.

The algorithm then assesses the system's thermal efficiency by estimating the heat flux incident on the receiver and the concentrator's aperture area using analytical connections while accounting for the concentrator's and collector's efficiency coefficients. The coolant temperature distribution along the tube collector's length is then numerically modeled, taking into account changes in coolant velocity, heat transfer properties, and geometrical parameters, in addition to thermal losses and the approach of the coolant and collector housing temperatures to thermal equilibrium.

The algorithm optimizes the system's geometric characteristics, including the tubes' length and diameter, the factors governing the concentration of solar light, and the reflection coefficients, based on the temperature profile that has been determined. The goal of this optimization is to increase heat transfer efficiency within the given operating parameters. The coolant temperature distribution, thermal efficiency, ideal collector and concentrator element dimensions, and the system's overall energetic properties are among the parameters that make up the algorithm's output. By utilizing this algorithm as a computational module, ETC-CSP systems can be designed quickly and accurately, thereby enhancing the study's practical applicability and promoting the advancement of solar thermal technology.

The study also included numerical modeling, which served as the basis for calculating the temperature characteristics and efficiency of the ETC-CSP system in various operating modes. The simulation encompassed several key aspects, including calculating the temperature of the coolant in various sections of the tube collector and estimating the temperature of the pipe walls and other system components. An important element of the calculations was the influence of parameters such as the speed of the coolant, which can significantly alter the nature of heat exchange, and its distribution along the length of the evacuated tube collector, directly affecting the system's efficiency. Numerical modelling also included an analysis of the system's design parameters, such as the diameter of pipes and the length of modules, which can significantly change the thermal characteristics of the system. Various combinations of these parameters allowed evaluating their effect on the efficiency of heat transfer and stabilisation of the temperature field inside the system. During the numerical calculations, analytical dependencies were obtained that demonstrated how changes in key system parameters, such as the velocity of the coolant and the geometric dimensions of the pipes, affect the temperature characteristics of the system. These dependencies helped to identify the main factors that have the most significant impact on the efficiency of heat transfer and the temperature of the coolant, and to determine the optimal operating conditions of the system for various operating modes. The results also provided an opportunity for more accurate prediction of the system behaviour under real conditions and optimization of design solutions aimed at improving the efficiency of solar thermal installations.

2. Results

The Tashkent Heat and Power Plant operates four hot-water boilers, each with a thermal capacity of 100 GJ/h (corresponding to 116 MW). To organize the combustion of fuel in each boiler, six vortex-type injectors are used, designed to operate on both gas and fuel oil. These devices are equipped with steam-mechanical nozzles to improve fuel atomisation. The nozzles are placed on opposite sides of the boiler chamber, forming a triangular circuit with vertices directed upward, which contributes to uniform heat transfer and enhances the overall performance of the system.

When choosing heating technology, Uzbekistan's climate is a significant consideration. The region's typical minimum winter temperature is around –5°C, which places considerable strain on heating systems, especially during the winter. At the same time, there is a fair amount of solar radiation; in the winter, the average direct solar radiation is between 600 and 650 W/m^2. Nevertheless, low temperatures and weather variations restrict the effectiveness of solar thermal systems, particularly during the winter, despite the significant potential of solar energy. The need to integrate traditional fuel oil-based heating systems is justified by this circumstance. Considering the unique characteristics of the local climate, this method guarantees the consistent maintenance of the necessary temperature regimes. The technical specifications and modes of operation of the systems under study are determined by these environmental variables, highlighting the suitability and practical significance of the suggested solutions.

Hot water boilers are designed to burn both gaseous fuels and liquid fuel oil. Liquid fuel in the form of M-100 fuel oil is delivered to the facility in railway tanks. The fuel oil is drained into a special intake chute under the influence of gravity. Furthermore, as illustrated in the flow chart (Fig. 1), the fuel oil is heated to a temperature of 170–180°C using steam, with the output parameters of which are temperature T_{out} = 200–250°C and pressure p = 0.8–1.2 MPa. Heating is carried out through heat exchange devices (heaters 1 and 2), which are connected to a high-temperature solar installation with a concentrating element, which provides an additional increase in thermal energy.

The consumption of thermal energy to ensure the operation of the fuel oil storage and supply system includes a combination of heat losses and costs associated with various stages of fuel processing:

- heat losses during discharge of fuel oil into receiving tanks ($Q_{dr.fo}$),
- energy required to heat the fuel in the storage tanks ($Q_{st.fo}$),
- thermal energy spent on heating the main fuel oil pipelines ($Q_{pl.fo}$),

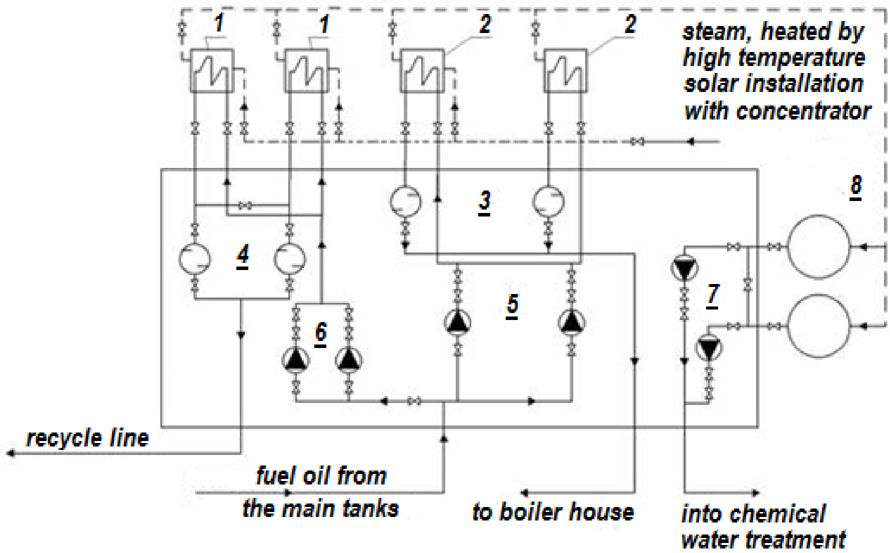

Fig. 1. Schematic diagram of a single-stage fuel oil pumping station
1 – fuel oil recirculation heaters; 2 – basic fuel oil heaters; 3 – fine filtration systems; 4 – pre-filtration systems; 5 – main pumps for supplying fuel oil; 6 – recirculation type units; 7 – pumps for pumping condensate; 8 – tanks for collecting and storing condensate
Source: compiled by the authors

Rys. 1. Schemat ideowy jednostopniowej stacji pompowania oleju opałowego

- heat consumed for heating fuel oil in heaters or fuel tanks ($Q_{t.fo}$), and the energy lost when steam is sprayed through nozzles ($Q_{sp.fo}$), Gcal.

The measurements showed that with steam operating parameters (pressure 0.8 MPa and temperature 200°C), steam costs are distributed as follows: for heating, draining, and cleaning processes of ten railway tanks, each of which holds 60 tonnes of fuel, steam consumption is 7.65 t/h, which is equivalent to 85–120 kg of steam per tonne of fuel oil. The cost of steam for maintaining the 10-metre-long drain chutes of the double-track overpass is 0.1 t/h, which, for a total length of 35 m, is equal to 3.5 t/h. Heating of fuel oil in intermediate tanks with a volume of 1,000 m^3 requires 2.0 tonnes of steam per hour.

The system calculation algorithm includes the main blocks:

1. Assessment of the economic characteristics of fuel oil.

2. Design of the master plan of the fuel oil supply system and pipeline routes, considering the optimal location of steam satellites to minimise heat losses.

3. Choice of the optimal technological configuration of the system.

4. Determination of the leading and additional equipment of the fuel oil supply system based on their technical parameters.

5. Analysis of the structure and interrelationships of the elements of the heat technology scheme.

6. Thermal analysis of the thermal technology scheme of the system.

7. Thermodynamic analysis of the fuel oil supply system.

8. Estimation of energy costs for thermal and electrical energy required for the operation of the entire system.

9. Analysis of the share of the cost of the fuel oil supply system in the overall structure of energy consumption of the enterprise to optimize costs.

10. Development of measures to improve the efficiency of energy consumption in the fuel oil supply system.

When the required fuel oil temperature of 160°C or higher is reached using standard heaters, difficulties often arise, even if the methods of heat exchange intensification provided for in standard designs are used. Reducing the fuel flow rate to raise the fuel oil temperature or reducing the pressure in the system after the first stage pumps (in case of significant fuel oil return volumes) may result in overloading and failure of the second stage pumps designed for further fuel oil lifting (Torepashovna et al. 2022; Panevnyk 2024). Such problems can be effectively addressed by utilizing high-temperature solar installations that help maintain a stable temperature throughout all stages. To achieve this, it is necessary to calculate the optimal number of solar collectors with the required concentration coefficient to provide the necessary energy to heat the fuel oil to the required temperatures (Anarbaev and Koroly 2021; Fialko et al. 1994).

The heater is a surface-type heat exchanger with a heat exchange surface area of 15 m^2, designed for heating fuel oil. It is designed for processing fuel oil in a volume of 12,800 kg/hour, with an increase in temperature from 110°C to 170°C. To ensure this process, the steam consumption is 1,536 t/h.

The consumption of thermal energy for steam spraying in fuel oil, expressed in Gcal, is determined when boilers are equipped with steam-mechanical sprayers as follows (1):

$$Q_{sp.fo} = q_{sp.fo} \cdot B_{fo} \cdot \left(I_{st} - I_{fw}\right) \cdot 10^{-3} \quad (1)$$

where:

$q_{sp.fo}$ – specific steam consumption for spraying, of fuel oil, depending on the viscosity of the fuel oil, 0.02–0.03 is assumed,

B_{fo} – amount of fuel oil sprayed, tonnes,

I_{st}, I_{fw} – enthalpy of steam corresponding to the temperatures of the fuel oil required for spraying 200°C and feed water T_{fw} = 10°C, respectively.

At $Q_{sp.fo}$ = 0.512 kcal/kg, the steam consumption is defined as (2):

$$G_{sp.fo} = Q_{sp.fo} / (c_{hc} \cdot (T_{out} - T_{in})) \quad (2)$$

where:

c_{hc} – heat capacity of the heat carrier-steam.

The steam consumption for steam-mechanical sprayers is (3):

$$G_{pm} = 0.984 \text{ t/h} \tag{3}$$

Total steam consumption in the process sections of the heat source is defined as (4):

$$G_{dr.fo} + G_{st.fo} + G_{pl.fo} + G_{t.fo} + G_{sp.fo} = 12.52 \text{ t/h} \tag{4}$$

Solar heat can be accumulated using various technologies (He et al. 2020; Ismanzhanov et al. 2012). Some systems utilize parabolic concentrators that focus sunlight on special channels within which the working fluid circulates (Masood et al. 2022; Zhangabay et al. 2023). It is heated to a temperature reaching ~240°C and pumped through a series of heat exchangers. Simultaneously, the fuel oil in the tanks is heated. To minimise heat losses, the receiver tube can be enclosed in a transparent protective glass shell located along the focal line of the parabolic concentrator. Such systems are often equipped with mechanisms with uniaxial or biaxial motion that determine the position of the sun to maintain an optimal level of energy concentration.

Within the framework of this study, a model based on the interaction between the ETC system and the CSP, as presented in Pitz-Paal et al. (2007), was applied. A special feature of the approach is the adaptation of the solar concentrator's parameters, considering the specific requirements for fuel oil supply systems in thermal sources. This approach allows for effective integration of solar energy into the fuel heating process, ensuring the necessary productivity and compliance with technological conditions.

To achieve these goals, it is necessary to determine the maximum efficiency of converting solar energy into SEC within the ETC-CSP system. These indicators are key for analysing the operational characteristics of existing solar installations and identifying prospects for their further optimization. Designing an efficient system involves accurately determining parameters such as the focal length (f), the opening angle (U_0), and considering geometric deviations, for example, the maximum (α_{ia}) or root mean square (α), which provide the required average concentration of solar radiation on the active surface of the heat collector (C'') or the entire working heat transfer area (C'') (Pitz-Paal et al. 2007). For a high-performance thermal system (HPTS), the primary task is to achieve the required temperature of the coolant with minimal heat losses, ensuring the system's high efficiency. An important step in solving this problem is assessing possible concentrations of solar radiation and developing a methodology for accurately calculating key parameters of the CSP. The first part of the task, namely, the analysis of possible levels of solar energy concentration and the corresponding technological characteristics for adequate heating of the coolant, will be discussed further.

Arasu and Sornakumar (2007) calculated the maximum average concentrations of solar fluxes (C) for the illuminated part of the ETC using the geometric method and the geometric inaccuracy parameter. Khanna et al. (2016) obtained an analytical formula for the maximum concentration of solar radiation in the focus of an accurate CSP. Ceylan and Ergun (2013) also derived a formula for the concentration (C) averaged over the entire surface of the ETC using a geometric approach.

In real conditions, the geometric inaccuracies of the CSP (Fig. 2) can vary, and incomplete capture of solar radiation by the receiver is often observed.

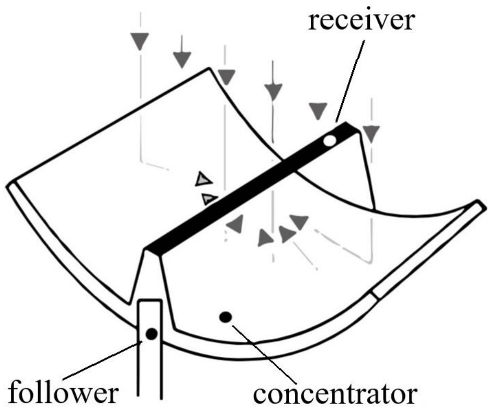

Fig. 2. Parabolic mirrors of a concentrated solar power (CSP)
Source: compiled by the authors

Rys. 2. Lustra paraboliczne skoncentrowanej energii słonecznej (CSP)

In such situations, the concentration C'', averaged over the surface of an evacuated tube heat collector per unit of collector length, is calculated considering these factors and is determined by the equation (5):

$$C'' = E_{av} / \left(E_0 \cdot R_z\right) = \psi_{TVHR} / \left(\pi d \cdot E_0 \cdot R_z\right) = \left(r \int_{-\pi}^{\pi} d\theta \int_{S_c} B(a)\left(a \cdot n_P\right)\left(a \cdot n_A\right) dS_M / M \cdot A^4 \right) / \pi d \quad (5)$$

where:

ψ_{TVHR} – flux of concentrated solar radiation per unit length of ETC and expressed relative to $E_0 \cdot R_z$,

S_c – surface of the CSP, oriented to point A.

Consdiering the definition, the coefficient of flux capture by the receiver in fractions of the flux incident on the CSP can be written as (6):

$$\eta_c = \psi_{TVHR}/D \quad (6)$$

In order to determine the possible values of C'' in practice and establish its relationship with the parameters of the CSP, it is necessary to know the limits of the change in the diameter of the ETC – D. Moreover (7):

$$\eta_c = \psi_{TVHR}/D = 1 \tag{7}$$

In general, this is a fairly arbitrary parameter, but there is a minimum value for it. It follows from this condition that (8):

$$C'' = C' = \sin U_0 / \left[\pi \cdot \left(\psi_0 + 2\alpha_{ia}\right)\right] \tag{8}$$

where:

C' – maximum possible average concentration on the surface of the ETC under the condition that the flux is completely captured by the receiver, or at $\eta_c = 1$,

α_{ia} – geometric parameter of the inaccuracy of the geometry of the CSP, determined by measuring the radius of the spot of the solar image in the focal plane and assigning it to the extreme point of the concentrator with the coordinate U_0, or in this case, for the CSP (9):

$$\alpha_{io} = 0.5\left[r_p \cdot \cos U_0 \cdot \left(1 + \cos U_0\right) / P - \psi_0\right] \tag{9}$$

where:

P – focal parameter of the CSP ($P = 2f$, f – focal length),

ψ_0 – angular radius of the Sun. For the illuminated part of the ETC, the concentration is equal to C.

Thus (10):

$$C = \sin U_0 / \left(\pi \cdot \left(\psi_0 + 2\alpha_{ia}\right)\right) \cdot \left[\left(90 + U_0 - \psi_0 - 2\alpha_{ia}\right) / 180\right] \tag{10}$$

From (8) and (10), for the limiting case $\eta_c = 1$, it follows that the relation between and between C and C' (11):

$$C = C' \cdot \left[\left(U_0 + 90 - \psi_0 - 2\alpha_{ia}\right)\right] U_0 > 90 + \psi_0 + 2\alpha_{ia} \tag{11}$$

As can be seen from (11), with full illumination of the ETC surface, $C = C'$, and their values should be determined from (8).

It can be noted that for the case of an accurate concentrator ($\alpha_{ia} = 0$), the maximum value, or $C_m \approx 72.36$, occurs at $U_0 \approx 70.30$, and the maximum C'', or $C''_m = C'_m = 68.5$, occurs at $U_0 \approx 90°$ (Shanmugan et al. 2016).

It follows from equations (8)–(11) that for a given U_0 condition of complete interception of the flow from the concentrator, or $\eta_c = 1$, the maximum value of one of the main generalised parameters of the ETC-CSP system *D/d* equals (12):

$$D / d_0 = \pi \cdot C' = \sin U_0 / \left(\psi_0 + 2\alpha_{ia}\right) \tag{12}$$

The minimum allowable diameter of the d_0 receiving element, calculated based on (12), is denoted as d_0. Thus, expression (8) determines the maximum possible average concentration of C for a given U_0, or the minimum possible diameter of the d_0 ETC at which the receiving element still completely intercepts the flow from the concentrator, or at $\eta_c = 1$. The values of C at $\eta_c = 1$ and the various values of the geometric parameter of the α_{ia} CSP, inaccuracy is shown in Figure 3.

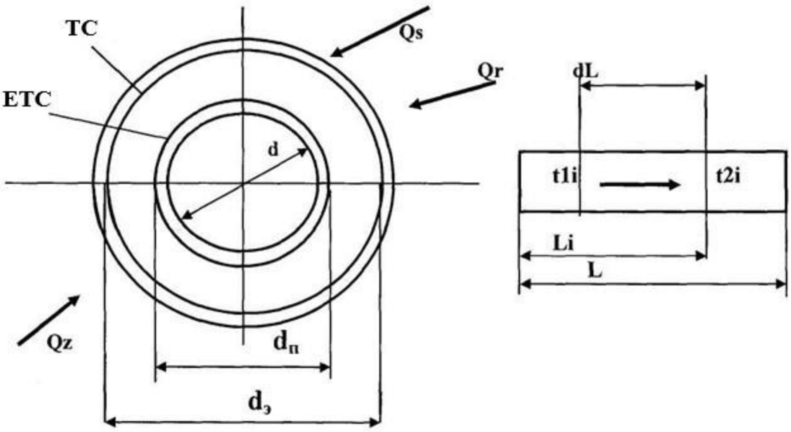

Fig. 3. Geometric parameters of an evacuated tube collector (ETC) with a single-layer translucent coating (TC)
Q_s – falling heat flows of the Sun, Qz – Earth, Qr – sky
Source: compiled by the authors

Rys. 3. Parametry geometryczne kolektora rurowego próżniowego (ETC)
z jednowarstwową przezroczystą powłoką (TC)

In turn, Figure 4 shows a graph that demonstrates that the dependence C' on the parameter α_{ia} has a similar shape to the dependence C described in the study (Stančin et al. 2020). Considering that in practice the current values α_{ia} are on the order of 10 arc minutes, the maximum achievable value of C' at a coefficient of $\eta_{yc} = 1$ is limited to the range 30–35. The results based on an optical-geometric analysis (in particular, for the case of an ideal energy utilisation coefficient $\eta_c = 1$) allow establishing preliminary boundaries for the parameters C, C'' and the minimum permissible diameter d_0. These indicators can be considered as an initial approximation to the accurate determination of the characteristics of a solar energy concentrator and an evacuated tube collector.

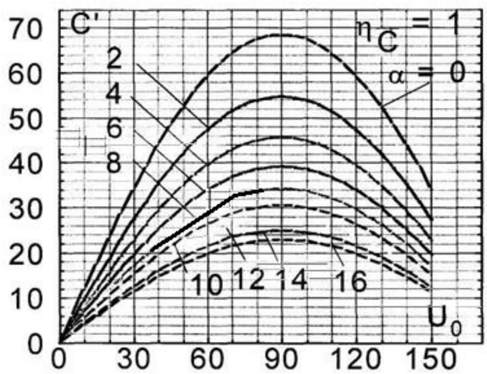

Fig. 4. The maximum possible values of the average concentration of ETC for various errors α_{ia} depending on the opening angle of the CSP U_0
Source: compiled by the authors

Rys. 4. Maksymalne możliwe wartości średniego stężenia ETC dla różnych błędów α_{ia} w zależności od kąta otwarcia CSP U_0

A graph showing the ratio of the surface area of the CSP to the area of the coolant pipe, depending on the opening angle U_0, is shown in Figure 5.

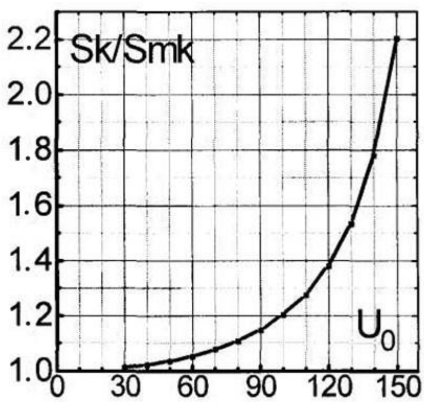

Fig. 5. The ratio of the surface area of the CSP to the area of the coolant pipe, depending on the opening angle U_0
Source: compiled by the authors

Rys. 5. Stosunek powierzchni CSP do powierzchni rury chłodziwa w zależności od kąta otwarcia U_0

Figure 6 presents graphs showing the relationship between the parameters C'' and η_{ia}, and the ratio d/d_0. The study was conducted for the CSP with an opening U_0 angle of 90°. The calculations consider various values of the geometric error parameter α_{ia}, and the standard deviations of the shape of the concentrator, distributed according to a uniform law.

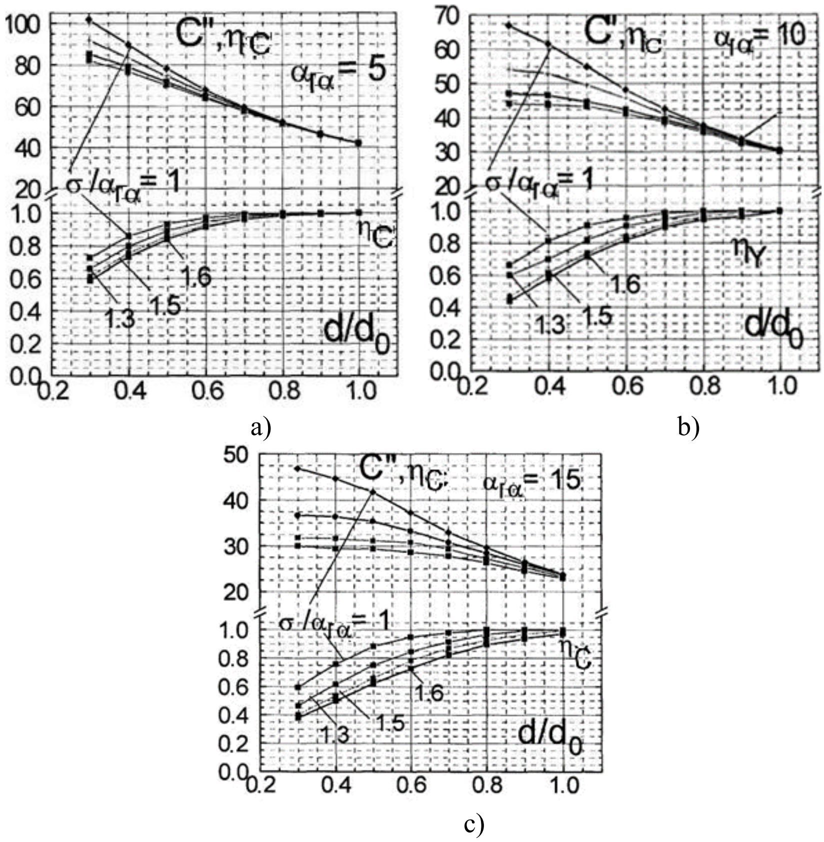

Fig. 6. The average concentration of C'' and the flux captured by the receiving element η_c depending on the ratio of and σ/α_{ia} for =90° at different temperatures when a) $\alpha_{ia} = 5$; b) $\alpha_{ia} = 10$; c) $\alpha_{ia} = 15$
Source: compiled by the authors

Rys. 6. Średnie stężenie C'' oraz strumień wychwycony przez element odbiorczy η_c w zależności od stosunku d/d_0 oraz σ/α_{ia} dla $U_0 = 90°$ przy różnych temperaturach α_{ia}

Based on computational studies performed using the detailed mathematical model of CSP presented in Figure 6, the results show that the average radiation concentration C'' can increase significantly when the geometric error parameter α_{ia} is varied. This is possible even with a moderate reduction in the radiation capture coefficient η_c, which makes the approach to optimizing the concentrator parameters very promising. For example, with a value of $\alpha_{ia} = 10'$ (arcminutes), a standard deviation ratio of $\sigma/\alpha_{ia} = 1$, and a value of $\eta_c = 0.95$, calculations show that the ratio of the receiver diameter to the minimum permissible value is $d/d_0 = 0.6$, and the average concentration of C'' reaches 48.2. In the case of an ideal capture coefficient $\eta_c = 1$, the concentration would be $C'' = 30.3$. This indicates a 1.59-fold increase in the average concentration at the selected parameters.

It should be emphasised that under the condition $\sigma/\alpha_{ia} = 1$ and the capture coefficient $\eta_c = 0.95$, there is an almost identical ratio between the diameter of the receiver d and its limit value d_0, or (13):

$$d/d_0 = 0.6 \tag{13}$$

For the case where $\alpha_{ia} = 5'$, the average concentration of $C'' = 67.9$ is reached, while the concentration at the focus of C is 41.9. Under conditions $\alpha_{ia} = 15'$, the values of C'' and C are 37.3 and 23.8, respectively. This indicates an increase in the average concentration of C'' by 1.62 times for $\alpha_{ia} = 5'$ and 1.57 times for $\alpha_{ia} = 15'$ relative to the values of C. Thus, under conditions $\sigma/\alpha_{ia} = 1$ and $\eta_c = 0.95$, another universal relation (14) was revealed:

$$C'' = 1.6 \cdot C \tag{14}$$

It is worth noting that with the ratio $d/d_0 = 1$, it remains possible to almost completely capture the radiation fluxes even with an increase in the relative geometric error σ/α_{ia} to a value of about 1.6. Under such conditions, the capture coefficient remains equal to $\eta_c = 1$, indicating the system's high efficiency. This confirms that with optimal design parameters of the concentrator, even with significant deviations in geometry, the full use of available solar radiation remains.

The detailed numerical model of the CSP, along with computational experiments performed on its basis, enabled the derivation of new approximate analytical dependencies that describe the relationship between the key parameters of the CSP system. These results can be applied to develop a unified methodology for the preliminary design of CSP parameters and to determine the characteristics of integrated systems, including CSP, ETC. At the next stage of the analysis, it is advisable to examine the main parameters and thermal characteristics of the ETC in detail. Particular attention should be paid to the methodology for calculating these characteristics, which plays a key role in ensuring high system efficiency and reducing heat losses.

For steady-state analysis, a practical approach is to use integral heat transfer equations. In this approach, the characteristics of the solar concentrator are considered as a parameter of the average solar radiation concentration C'', which is integrated into the system of heat transfer equations. This enables a more accurate simulation of the thermal processes within the system. A special algorithm has been developed to calculate the design parameters of an evacuated tube heat collector (ETC) system in combination with a concentrated solar power (CSP) in stationary mode.

For calculations, the main initial data are the following parameters: the flow rate of the working fluid-steam G, which is determined at the outlet of the ETC-CSP system, and the temperature of the working fluid upon entry into the system T_{in} and upon exit T_{out}. In addition, important parameters include the characteristics of the working fluid itself, such as its heat capacity and viscosity, as well as the intensity of direct sunlight E_0 and the specular reflection coefficient R_z, which describes the ability of the concentrator mirrors to reflect sunlight. These data are the basis for further calculations and optimization of the system.

Considering that the speed range of the working fluid (coolant) w is usually known, it is possible to determine the area of the inner cross-section of the tube collector S_r as follows (15):

$$S_r = G/(w \cdot p_0) \cdot 0.5 \tag{15}$$

where:

p_0 – density of the working fluid at the inlet to the receiver.

In the case of round tube collectors, which is common practice in such systems, it is also necessary to consider an important parameter – the inner diameter of the pipe d_{in} (16):

$$d_{in} = 4G/(\pi \cdot w \cdot p_0) \cdot 0.5 \tag{16}$$

Based on the wall thickness h_T, the outer diameter of the intake pipe (17) is determined:

$$d = d_{in} + 2h_T \tag{17}$$

Further, considering the thermal efficiency of the receiver $-\eta_r$, which depends on T_{out} the average concentration of C', and the capture coefficient of the flow reflected from the concentrator by the receiver – ψ_k, the flow reflected from the concentrator (18) is determined:

$$\psi_k = Q/(\eta_r \cdot \eta_c) \tag{18}$$

Based on the conducted research, it is recommended to use an efficiency factor $\eta_c = 0.95$ for the solar concentrator system. This indicator reflects the high degree of concentration of sunlight and its conversion into heat. For evacuated tube heat collectors, the efficiency coefficient η_r is approximately 0.8, indicating a satisfactory but somewhat limited heat conversion in these devices.

For further calculations, knowing the magnitude of the flux reflected from the solar concentrator, it is possible to determine the area of the concentrator aperture. The area of the aperture is S_{mk} calculated using the Equation (19):

$$S_{mk} = L_k \cdot D \tag{19}$$

where:

L_k – length of the concentrator,

D – its width.

Thus (20):

$$S_{mk} = \psi_k/E_0 \cdot R_z \tag{20}$$

The values of the length L_k and width D of the concentrator were selected based on design constraints, considering several factors, including the possible diameters of the receiver d and the diameter of its transparent body d_e. The range of D values for the concentrator varies from 2 to 6 m, due to both technological capabilities and system efficiency requirements. In addition, a deeper study of the relationship between the diameter of the receiver d and the concentration number C'' of the solar radiation concentrator was carried out. These studies have identified key parameters that affect the efficiency of the system and heat transfer in a tube collector. The obtained results were integrated into an algorithm and a numerical calculation programme that simulates the process of heating a coolant along the length of a tube collector using concentrated solar radiation.

The first value of the hub diameter D is determined considering (13), and is expressed as (21):

$$D = \pi \cdot d_0 \cdot C' = \pi \cdot \left(d / 0.6\right) \cdot C' \tag{21}$$

Next, (22) is defined:

$$L_k = S_{mk}/D \tag{22}$$

The Equation for determining the temperature of the coolant at the outlet of a high-T_{out} temperature solar installation, depending on the length of the intake pipe L and temperature, T_{in} is expressed as (23):

$$\frac{T_{out} - T_0 - \alpha_0 \cdot E_0 \cdot C''}{T_{in} - T_0 - \alpha_0 \cdot E_0 \cdot C''} = \exp \cdot \left(- \frac{d \cdot L}{w \cdot \rho_0 \cdot c_{hc}} \right) \tag{23}$$

where:

α_0 – bandwidth of the transparent ETC housing.

The following initial data were used in the calculations: direct solar radiation density E_0 = 650 W/m^2, specular reflection coefficient R_z = 1, concentration number C'' = 15, initial temperature T_0 = 200°C, ambient temperature T_a = 100°C, receiver diameter d = 15 mm, tube diameter d_r = 17 mm, the diameter of the transparent case $d_e = 1.2 \cdot d_r$, the outer diameter of the case $d_{2e} = d_e$ + 2 mm, the coefficient α_0 = 0.9.

The reflection coefficient is a measure that defines the fraction of solar radiation reflected by the surface of concentrators or mirrors (Kudabayev et al. 2022; Kravtsova et al. 2024). It ranges from 0 to 1, where 1 represents total reflection and 0 corresponds to complete absorption. This coefficient is measured using specialized instruments that assess the intensity of reflected light within the solar spectrum range. A high reflection coefficient increases the efficiency of solar collectors by enabling greater concentration of solar energy onto the receiver, which raises the temperature of the heat carrier and enhances the overall system performance. In this study, the recommended reflection coefficient value for concentrators is approximately 0.95, indicating high-quality reflective surfaces and contributing to improved system efficiency.

As shown in Figure 7, at the initial section of the tube collector, at low linear velocities (m/s), the model accurately reflects the change in coolant temperature along the length of the receiver within the operating temperature range. However, as the speed of the coolant increases, the heating process slows down: the temperature and heat exchange efficiency change slowly. These data confirm that about 50 m of ETC-CSP modules are necessary to reach the required temperature of the heated steam at the outlet of the system.

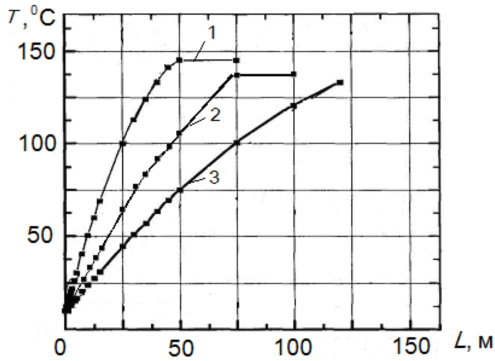

Fig. 7. Change in the temperature of the coolant along the length of the ETC-CSP pipe depending on the velocity of the coolant at the inlet to the pipe (w)
1 – 0.01 m/s; 2 – 0.02 m/s; 3 – 0.03 m/s
Source: compiled by the authors

Rys. 7. Zmiana temperatury chłodziwa wzdłuż długości rury ETC-CSP w zależności od prędkości chłodziwa na wlocie do rury (w)

Figure 8 shows data on the heating temperature of the water and the transparent housing of the ETC for the case discussed earlier.

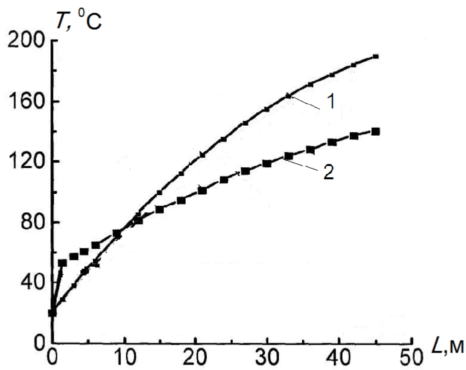

Fig. 7. Heating dynamics in ETC-CSP at $w = 0.01$ m/s
1 – temperature of the coolant ; 2 – temperature of the walls of the transparent housing
Source: compiled by the authors

Rys. 7. Dynamika nagrzewania w ETC-CSP przy $w = 0,01$ m/s

From the graphs presented, it can be seen that as the receiver length increases, the water temperature first increases with acceleration; however, after reaching a certain value, this process slows down. This is conditioned by the fact that the equilibrium temperatures of the water and the transparent body become similar, and subsequently the water temperature increases more slowly. In addition, it is worth paying attention to the heating temperatures of the walls of the transparent housing (t_{ei}), which also reach quite high values. This underlines the importance of considering the temperature of the housing, as it can affect the efficiency of the system and the durability of the materials from which the ETC housing is made.

In addition, based on the analysis of the graph, it can be observed that the temperature of the coolant reaches an almost equilibrium value at a distance of approximately one-third of the total length of the ETC-CSP. This indicates that in the first part of the receiver length, intensive heating of the coolant occurs, after which the heating process slows down and approaches thermal equilibrium. The results of the conducted research, based on the developed mathematical model, can be effectively used in practice when calculating parabolic trough-shaped solar radiation concentrators used in high-temperature installations where the heating temperature of the coolant exceeds 200°C. Such calculations allow for more accurate prediction of the thermal characteristics of the system and optimization of its design parameters to increase operational efficiency.

3. Discussion

As part of this study, a detailed mathematical model has been developed, providing a tool for analyzing the operation of evacuated tube heat collectors and solar concentrators in power systems. This model enables a deeper understanding of the heat transfer and heating processes of the coolant, providing an accurate assessment of the fundamental parameters governing the operation of such systems. The developed methodology considers a wide range of factors affecting system performance, thereby opening up opportunities for optimizing design solutions and enhancing the efficiency of solar power plants, which is particularly important in the context of transitioning to sustainable energy systems. However, it is worth noting that the introduction of high-temperature solar installations with concentrators requires a customized approach for each facility. The specifics of upgrading a heat technology scheme depend directly on the characteristics of a particular power plant or boiler house, as well as the equipment used. This approach allows for considering the unique operating conditions and ensures the optimal integration of the solar installation into the existing system, which significantly increases its efficiency and reduces operating costs.

The study by Stančin et al. (2020) explored the potential of utilizing alternative energy sources to enhance the efficiency of existing heat exchange systems, highlighting that the incorporation of renewable sources can result in a substantial reduction in fossil fuel consumption. However, the study did not provide a clear answer to the questions of the durability of such systems at high temperatures and loads. Stokowiec et al. (2023) considered options for upgrading thermal power plants to increase their efficiency through the introduction of new technological processes and improved heat transfer, which confirmed the high efficiency of the proposed methods, but the disadvantage of the study was the lack of large-scale tests, which limits the application of the findings in extensive industrial facilities. Muñoz et al. (2022) focused on investigating thermal cycles in systems where attention was paid to the combined use of solar energy as a fuel; however, the study did not adequately consider the economic aspects of integrating such technologies into existing energy systems. Thus, this study, unlike the mentioned papers, focuses on an accurate mathematical model for optimizing solar installations with concentrators, which allows considering the individual characteristics of objects and effectively integrating technologies into existing systems.

The results of this study showed that for the efficient operation of fuel oil facilities, it is necessary to accurately determine the parameters of the coolant, including steam consumption, which in this case amounted to 12.52 t/h. This indicator is crucial for optimizing heat technology processes, as it determines the amount of energy required to heat and maintain the necessary temperature conditions in boilers, which directly impacts the overall process efficiency. Accurate calculation of steam consumption also helps avoid excessive energy costs and resource consumption, thereby optimizing fuel use and minimizing losses. The data obtained is also important in the development and implementation of systems using renewable energy sources to compensate for heat losses and reduce the load on conventional systems. Understanding the required steam consumption enables the effective integration of solar thermal installations or other alternative sources that can reduce dependence on fossil resources and increase the sustainability of the energy system (Ismanzhanov and Tashiev 2016; Miroshnichenko et al. 2025).

Awais et al. (2021) considered the effect of steam consumption on the efficiency of heat exchange processes. However, they did not address the possible impact of fluctuations in coolant temperature on steam consumption, which can lead to errors in calculations under real operating conditions. Filkoski et al. (2020) analyzed the possibilities of optimizing energy and steam consumption in installations using new technological solutions; however, the study did not provide data on the long-term economic feasibility of such solutions, which limits the possibility of their implementation on an industrial scale. Okonkwo et al. (2021) investigated the efficiency of heat transfer in thermal engineering systems. However, they did not adequately consider the influence of external factors, such as the unpredictability of the load on the system, which makes it difficult to accurately assess the effectiveness of the considered solutions in real-world conditions. Unlike the mentioned papers, this study focuses on the accurate calculation of steam consumption required to optimize thermal processes in fuel oil facilities, which significantly improves energy efficiency and provides a more comprehensive view of the possibilities for improving energy systems.

In the course of this study, the optical and energy characteristics of solar radiation concentrating elements were calculated, which enabled a more accurate assessment of their effectiveness under various conditions. This step was critically important for optimizing the operation of solar installations, as the solar radiation concentrator determines the efficiency of converting solar energy into heat. Additionally, the concentrating element of an evacuated tube heat collector was calculated in stationary mode, which enabled the acquisition of accurate data on its temperature characteristics under various operating conditions. These data served as the basis for optimizing the design features of heat sinks and systems in general, thereby increasing their reliability and stability in the long term. In the future, the results obtained can be used to develop more efficient and economical solar thermal systems, which will contribute to improving energy efficiency and reducing carbon emissions in various energy sectors.

Alfwzan et al. (2024) analyzed heat transfer in solar thermal systems, which improved the accuracy of forecasting temperature conditions. However, the study did not address the impact of seasonal changes on system efficiency, which limits the possibility of applying the data obtained in the long term. Moosavian et al. (2021) investigated the efficiency of parabolic solar collectors under variable climatic conditions, yielding beneficial results for enhancing their efficiency in specific regions. However, the study's limitation was its focus on only one type of collector. The study by Panduro et al. (2022) analyzed the use of alternative materials for solar collectors, identifying the potential advantages of such solutions. However, no tests were carried out in real-world operating conditions, which limits the possibility of their widespread use. Thus, unlike the above-mentioned papers, this study calculated not only the optical and energy characteristics of elements that concentrate solar radiation but also provided detailed modeling of an evacuated tube heat collector in stationary mode, which yielded more accurate data on its characteristics. In contrast, the mentioned papers did not consider the geometric features of heat collectors.

As a result of calculations carried out during this study, which utilized initial data on solar radiation, temperature conditions, and the geometry of the elements, the heat transfer in an evacuated tube heat collector was estimated. The results showed that at low coolant speeds, the temperature increases faster, while with increasing speed, heating slows down, indicating an approach to thermal equilibrium. This effect is especially noticeable in the fact that the heating process slows down as the receiver length increases, which is associated with the approach of the water temperature to the temperature of the housing. This result is important for the design of solar heat collector systems, as it confirms the need to optimize the receiver length to achieve the required temperature. Specifically, approximately 50 m of ETC-CSP modules are required to achieve the desired temperature of the heated steam. It is also important to increase the temperature of the walls within the transparent housing, which requires careful consideration of the materials used to ensure durability and efficiency.

The study by Bretado-de los Rios et al. (2021) investigated the effect of various liquids on the efficiency of heat exchange in solar installations, noting the effectiveness of using innovative solutions. However, it did not consider dynamic temperature changes in real-world operating conditions, which limits the applicability of the data obtained. The study by Salamah et al. (2022) analyzed the durability of solar systems, noting their overall resistance to various external conditions, but without addressing the effect of changes in the geometry of solar collectors on the system's overall stability. The study by Sharma et al. (2022) analyzed ways to optimize heat transfer in renewable energy systems using new technical solutions, noting the effectiveness of using artificial intelligence and machine learning methods. However, the lack of testing on the scale of real installations limits the practical application of the results obtained. Unlike the mentioned papers, this study offers a more in-depth analysis of the temperature characteristics of the coolant in evacuated tube solar collectors. Additionally, it takes into account the impact of coolant velocity and temperature conditions on system efficiency, making the results more applicable to practical tasks in solar thermal installations (Bandura et al. 2023).

Thus, the results of this study, along with those mentioned in the papers, emphasize the importance of an integrated approach to optimizing solar thermal systems and heat sinks. The data obtained allows for more accurate prediction of the thermal characteristics, which contributes to improving the efficiency and reliability of such systems. However, unlike other studies, this research considers the features of temperature conditions and the influence of various structural elements on the system's operation, which expands the possibilities for practical application in high-temperature solar installations. It is essential to recognize that such research holds strategic importance for the advancement of solar energy, as it enables the development of more efficient, sustainable, and cost-effective technologies that will contribute to enhancing energy security and reducing carbon emissions on a global scale.

Conclusions

As a result of this study, a mathematical model of the ETC-CSP was developed, which effectively describes the processes of heating the coolant and enables an accurate assessment of the basic parameters of such systems' operation. The model considers the influence of various factors, which provides highly accurate results suitable for further practical applications in the field of solar energy.

During the study, key parameters influencing the thermal characteristics of the ETC-CSP system were examined, including the system's geometry, the properties of the solar flux, and the energy capture efficiency. Geometric parameters such as the length and diameter of the pipes and the shape of the concentrator had a significant impact on the temperature distribution inside the system. Special attention was paid to the development of a methodology for calculating the design parameters of the ETC-CSP system, which enables the accurate prediction of the coolant and temperature fields inside the system and optimizes the design of such installations.

Additionally, as part of the study, new analytical dependencies were obtained that relate the characteristics of the concentrator to its design and thermal parameters. The relationship between the receiver diameter and the CSP concentration number was revealed, allowing for more accurate prediction of the system's efficiency under various conditions. This opens up opportunities for improving the design of solar power plants, increasing their efficiency and operational characteristics.

A key finding of the study was the confirmation of the relationship between the angular error and the reflection coefficient on the system's efficiency. It was noted that these factors, along with the parameters of the solar flux and geometry, affect the temperature characteristics of heating the coolant. The study also analysed the effect of the coolant flow rate and its distribution along the length of the tube collector. Data has been obtained that shows how different operating modes of the system affect temperature and heat transfer efficiency. Additionally, numerical calculations were employed to assess the impact of design parameters, including pipe diameter and system module length, on the efficiency of the ETC and CSP. The results showed that increasing the system's length or adjusting the pipe diameter can significantly improve the efficiency of trapping solar radiation and increasing the coolant temperature.

The practical application of the developed mathematical model and numerical algorithms was demonstrated by optimizing the fuel oil heating system at the Tashkent Heat and Power Plant. Specifically, the algorithm was used to determine the optimal module lengths and pipe diameters for the ETC-CSP system, enabling the coolant temperature to reach the required range of 170–180°C while significantly reducing steam consumption to approximately 12.52 t/h. Numerical simulations confirmed that a collector length of approximately 50 meters, combined with these optimized parameters, is sufficient to achieve the target thermal regime. This practical example validates the feasibility of integrating high-temperature solar installations into existing fuel heating processes, thereby reducing energy costs and contributing to lower greenhouse gas emissions. Such results highlight the direct engineering applicability of the theoretical findings for modernizing thermal installations and enhancing energy efficiency in industrial settings.

It should be noted that this study has some limitations, including the use of the model only for specific geometries of the ETC-CSP system and a limited range of parameter values, such as angular inaccuracy and coolant flow rate. For further research in this area, it is advisable to study the influence of a broader range of parameters, including a variety of concentrator geometries and operating modes under real operating conditions, and to conduct experiments to derivate the obtained theoretical data, which will provide more accurate prediction of the efficiency of solar thermal systems under various operating conditions, and to improve the methods of design and optimization of such installations to increase their energy efficiency and reliability in duty cycle.

The Authors have no conflicts of interest to declare.

References

Alfwzan et al. 2024 – Alfwzan, W.F., Alomani, G.A., Alessa, L.A. and Selim, M.M. 2024. Sensitivity analysis and design optimization of nanofluid heat transfer in a shell-and-tube heat exchanger for solar thermal energy systems: A statistical approach. *Arabian Journal for Science and Engineering* 49, pp. 9831–9847, DOI: 10.1007/s13369-023-08568-0.

Anarbaev, A. and Koroly, M. 2021. Autonomous hybrid solar-heat pump for system heat-cooling in buildings. [In:] *VII International Scientific Conference "Integration, Partnership and Innovation in Construction Science and Education"*. Tashkent: IOP Publishing, DOI: 10.1088/1757-899X/1030/1/012178.

Arasu, A.V. and Sornakumar, T. 2007. Design, manufacture and testing of fiberglass reinforced parabola trough for parabolic trough solar collectors. *Solar Energy* 81(10), pp. 1273–1279, DOI: 10.1016/j.solener.2007.01.005.

Awais et al. 2021 – Awais, M., Ullah, N., Ahmad, J., Sikandar, F., Ehsan, M.M., Salehin, S., Bhuiyan, A.A. 2021. Heat transfer and pressure drop performance of nanofluid: A state-of-the-art review. *International Journal of Thermofluids* 9, DOI: 10.1016/j.ijft.2021.100065.

Bagherian et al. 2020 – Bagherian, M.A. and Mehranzamir, K. 2020. A comprehensive review on renewable energy integration for combined heat and power production. *Energy Conversion and Management* 224, DOI: 10.1016/j.enconman.2020.113454.

Bandura et al. 2023 – Bandura, I., Romaniuk, M., Komenda, N., Hadai, A. and Volynets, V. 2023. Optimisation of energy solutions: Alternative energy, reactive power compensation, and energy efficiency management. *Machinery & Energetics* 14(4), pp. 121–130, DOI: 10.31548/machinery/4.2023.121.

Bretado-de los Rios et al. 2021 – Bretado-de los Rios, M.S., Rivera-Solorio, C.I. and Nigam, K.D.P. 2021. An overview of sustainability of heat exchangers and solar thermal applications with nanofluids: A review. *Renewable and Sustainable Energy Reviews* 142, DOI: 10.1016/j.rser.2021.110855.

Ceylan, İ. and Ergun, A. 2013. Thermodynamic analysis of a new design of temperature controlled parabolic trough collector. *Energy Conversion and Management* 74, pp. 505–510, DOI: 10.1016/j.enconman.2013.07.020.

Fialko et al. 1994 – Fialko, N.M., Prokopov, V.G., Meranova, N.O., Borisov, Yu.S., Korzhik, V.N. and Sherenkovskaya, G.P. 1994. Single particle-substrate thermal interaction during gas-thermal coatings fabrication. *Fizika i Khimiya Obrabotki Materialov* (1), pp. 70–78.

Filkoski et al. 2020 – Filkoski, R.V., Lazarevska, A.M., Mladenovska, D. and Kitanovski, D. 2020. Steam system optimization of an industrial heat and power plant. *Thermal Science* 24(6), pp. 3649–3662, DOI: 10.2298/TSCI200403284F.

Grigorenko et al. 2019 – Grigorenko, G.M., Adeeva, L.I., Tunik, A.Y., Korzhik, V.N., Doroshenko, L.K., Titkov, Y.P. and Chaika, A.A. 2019. Structurization of coatings in the plasma arc spraying process using B4C + (Cr, Fe)(7)C-3-cored wires. *Powder Metallurgy and Metal Ceramics* 58(5–6), pp. 312–322, DOI: 10.1007/s11106-019-00080-1.

Grigorenko et al. 2020 – Grigorenko, G.M., Adeeva, L.I., Tunik, A.Y., Korzhik, V.N. and Karpets, M.V. 2020. Plasma arc coatings produced from powder-cored wires with steel sheaths. *Powder Metallurgy and Metal Ceramics* 59(5–6), pp. 318–329, DOI: 10.1007/s11106-020-00165-2.

Grigoriev et al. 2024 – Grigoriev, D., Bekbolatova, J., Bulbul, O., Nygymanova, A. and Shopaeva, A. 2024. Experimental study of operation of a solar water heating system in winter. *Bulletin of KazATK* 131(2), pp. 523–529, DOI: 10.52167/1609-1817-2024-131-2-523-529.

Gutarevych et al. 2020 – Gutarevych, Y., Mateichyk, V., Matijošius, J., Rimkus, A., Gritsuk, I., Syrota, O. and Shuba, Y. 2020. Improving fuel economy of spark ignition engines applying the combined method of power regulation. *Energies* 13(5), DOI: 10.3390/en13051076.

He et al. 2020 – He, Y.-L., Qiu, Y., Wang, K., Yuan, F., Wang, W.-Q., Li, M.-J. and Guo, J.-Q. 2020. Perspective of concentrating solar power. *Energy* 198, DOI: 10.1016/j.energy.2020.117373.

Ismanzhanov et al. 2012 – Ismanzhanov, A.I., Murzakulov, N.A. and Azimzhanov, O.A. 2012. Investigation on heat exchange in interlayer space of multilayer greenhouses. *Applied Solar Energy* (*English translation of Geliotekhnika*) 48(2), pp. 118–120, DOI: 10.3103/S0003701X12020107.

Ismanzhanov, A.I. and Tashiev, N.M. 2016. Development and research of the technology for powdering agricultural products using solar energy. *Applied Solar Energy* (*English translation of Geliotekhnika*) 52(4), pp. 256–258, DOI: 10.3103/S0003701X16040101.

Khanna et al. 2016 – Khanna, S., Sharma, V., Kedare, S.B. and Singh, S. 2016. Experimental investigation of the bending of absorber tube of solar parabolic trough concentrator and comparison with analytical results. *Solar Energy* 125, pp. 1–11, DOI: 10.1016/j.solener.2015.11.046.

Kravets et al. 2024 – Kravets, T., Semerak, M., Galyanchuk, I., Yurasova, O. and Kharchuk, A. 2024. Analytical study on improving the efficiency and environmental friendliness of solid organic fuels. *Machinery & Energetics* 15(3), pp. 84–93, DOI: 10.31548/machinery/3.2024.84.

Kravtsova et al. 2024 – Kravtsova, D., Ziuhan, U. and Fraimovych, A. 2024. Solar panels' energy efficiency optimization using mathematical methods with computerisation of calculations. *Journal of Kryvyi Rih National University* 22(2), pp. 68–72, DOI: 10.31721/2306-5451-2024-2-22-68-72.

Kudabayev et al. 2022 – Kudabayev, R., Mizamov, N., Zhangabay, N., Suleimenov, U., Kostikov, A., Vorontsova, A., Buganova, S., Umbitaliyev, A., Kalshabekova, E. and Aldiyarov, Z. 2022. Construction of a model for an enclosing structure with a heat-accumulating material with phase transition taking into account the process of solar energy accumulation. *Eastern-European Journal of Enterprise Technologies* 6(8–120), pp. 26–37, DOI: 10.15587/1729-4061.2022.268618.

Kumar et al. 2022 – Kumar, K.H., Daabo, A.M., Karmakar, M.K. and Hirani, H. 2022. Solar parabolic dish collector for concentrated solar thermal systems: A review and recommendations. *Environmental Science and Pollution Research* 29, pp. 32335–32367, DOI: 10.1007/s11356-022-18586-4.

Lipiński et al. 2021 – Lipiński, W., Abbasi-Shavazi, E., Chen, J., Coventry, J., Hangi, M., Iyer, S., Kumar, A., Li, L., Li, S., Pye, J., Torres, J.F., Wang, B., Wang, Y. and Wheeler, V.M. 2021. Progress in heat transfer research for high-temperature solar thermal applications. *Applied Thermal Engineering* 184, DOI: 10.1016/j.applthermaleng.2020.116137.

Malwad, D. and Tungikar, V. 2021. Development and performance testing of reflector materials for concentrated solar power: A review. *Materials Today: Proceedings* 46, pp. 539–544, DOI: 10.1016/j.matpr.2020.10.744.

Masood et al. 2022 – Masood, F., Nor, N.B.M., Elamvazuthi, I., Saidur, R., Alam, M.A., Akhter, J., Yusuf, M., Ali, S.M., Sattar, M. and Baba, M. 2022. The compound parabolic concentrators for solar photovoltaic applications: opportunities and challenges. *Energy Reports* 8, pp. 13558–13584, DOI: 10.1016/j.egyr.2022.10.018.

Miroshnichenko et al. 2025 – Miroshnichenko, D., Lebedev, V., Shved, M., Fedevych, O. and Pyshyev, S. 2025. Valorization of Lignite Use in "Green" Technologies: A Review. *Chemistry and Chemical Technology* 19(1), pp. 157–173, DOI: 10.23939/chcht19.01.157.

Moosavian et al. 2021 – Moosavian, S.F., Borzuei, D. and Ahmadi, A. 2021. Energy, exergy, environmental and economic analysis of the parabolic solar collector with life cycle assessment for different climate conditions. *Renewable Energy* 165, pp. 301–320, DOI: 10.1016/j.renene.2020.11.036.

Muñoz et al. 2022 – Muñoz, M., Rovira, A. and Montes, M.J. 2022. Thermodynamic cycles for solar thermal power plants: A review. *Wiley Interdisciplinary Reviews: Energy and Environment* 11(2), DOI: 10.1002/wene.420.

Normuminov et al. 2023 – Normuminov, J., Anarbaev, A. and Xurramov, B. 2023. Modeling of thermal processes during the motion of combustion products in the gas chimneys of boilers. *AIP Conference Proceedings* 2552(1), 030028, DOI: 10.1063/5.0112376.

Okonkwo et al. 2021 – Okonkwo, E.C., Wole-Osho, I., Almanassra, I.W., Abdullatif, Y.M. and Al-Ansari, T. 2021. An updated review of nanofluids in various heat transfer devices. *Journal of Thermal Analysis and Calorimetry* 145, pp. 2817–2872, DOI: 10.1007/s10973-020-09760-2.

Panduro et al. 2022 – Panduro, E.A.C., Finotti, F., Largiller, G. and Lervåg, K.Y. 2022. A review of the use of nanofluids as heat-transfer fluids in parabolic-trough collectors. *Applied Thermal Engineering* 211, DOI: 10.1016/j.applthermaleng.2022.118346.

Panevnyk, O. 2024. Study of the kinematic field of mixed flows. *Prospecting and Development of Oil and Gas Fields* 24(1), pp. 23–31, DOI: 10.69628/pdogf/1.2024.23.

Patel, A. 2023. Enhancing heat transfer efficiency in solar thermal systems using advanced heat exchangers. *Multidisciplinary International Journal of Research and Development* (*MIJRD*) 2(6), pp. 31–51. [Online:] https://www.mijrd.com/papers/v2/i6/MIJRDV2I60003.pdf [Accessed: 2025-05-10].

Pitz-Paal et al. 2007 – Pitz-Paal, R., Dersch, J., Milow, B., Tellez, F., Ferriere, A., Langnickel, U., Steinfeld, A., Karni, J., Zarza, E. and Popel, O. 2007. Development steps for parabolic trough solar power technologies with maximum impact on cost reduction. *Journal of Solar Energy Engineering* 129(4), pp. 371–377, DOI: 10.1115/1.2769697.

Rebhi et al. 2022 – Rebhi, R., Menni, Y., Lorenzini, G. and Ahmad, H. 2022. Forced-convection heat transfer in solar collectors and heat exchangers: A review. *Journal of Advanced Research in Applied Sciences and Engineering Technology* 26(3), pp. 1–15. [Online:] https://www.researchgate.net/profile/Hijaz-Ahmad/publication/360996739_Forced-Convection_Heat_Transfer_in_Solar_Collectors_and_Heat_Exchangers_A_Review/links/62972bd0431d5a71e771cdea/Forced-Convection-Heat-Transfer-in-Solar-Collectors-and-Heat-Exchangers-A-Review.pdf [Accessed: 2025-05-10].

Rogovyi, A. 2018. Energy performances of the vortex chamber supercharger. *Energy* 163, pp. 52–60, DOI: 10.1016/j.energy.2018.08.075.

Salamah et al. 2022 – Salamah, T., Ramahi, A., Alamara, K., Juaidi, A., Abdallah, R., Abdelkareem, M.A., Amer, E. and Olabi, A.G. 2022. Effect of dust and methods of cleaning on the performance of solar pv module for different climate regions: Comprehensive review. *Science of The Total Environment* 827, DOI: 10.1016/j.scitotenv.2022.154050.

Sareriya et al. 2022 – Sareriya, K.J., Andharia, J.K., Vanzara, P.B. and Maiti, S. 2022. A comprehensive review of design parameters, thermal performance assessment, and medium temperature solar thermal applications of Scheffler concentrator. *Cleaner Engineering and Technology* 6, DOI: 10.1016/j.clet.2021.100366.

Shanmugan et al. 2016 – Shanmugan, S., Vijayan, M., Suganya, V., Monisha, C., Sangavi, R., Geetanjali, P. and Sandhya, B. 2016. Honeycomb encapsulated atmospheric solar collector along with single basin solar still in highly energy absorbing weather condition. *Indian Journal of Science and Technology* 9(5), DOI: 10.17485/ijst/2016/v9i5/87153.

Sharma et al. 2022 – Sharma, P., Said, Z., Kumar, A., Nizetic, S., Pandey, A., Hoang, A.T., Huang, Z., Afzal, A., Li, C., Le, A.T., Nguyen, X.P. and Tran, V.D. 2022. Recent advances in machine learning research for nanofluid-based heat transfer in renewable energy system. *Energy & Fuels* 36(13), pp. 6626–6658, DOI: 10.1021/acs.energyfuels.2c01006.

Stančin et al. 2020 – Stančin, H., Mikulčić, H., Wang, X. and Duić, N. 2020. A review on alternative fuels in future energy system. *Renewable and Sustainable Energy Reviews* 128, DOI: 10.1016/j.rser.2020.109927.

Stokowiec et al. 2023 – Stokowiec, K., Wciślik, S. and Kotrys-Działak, D. 2023. Innovative modernization of building heating systems: The economy and ecology of a hybrid district-heating substation. *Inventions* 8(1), DOI: 10.3390/inventions8010043.

Torepashovna et al. 2022 – Torepashovna, B.B., Kairbergenovna, M.A., Sergeyevich, K.M., Uyezbekovna, T.G. and Kairbekovna, Z.A. 2022. AP13068541 Development of an Experimental Energy Complex Based on an Upgraded Boiler Plant Using Biofuels. [In:] *2022 International Conference on Communications, Information, Electronic and Energy Systems, CIEES 2022.* Institute of Electrical and Electronics Engineers, DOI: 10.1109/CIEES55704.2022.9990656.

Tropina et al. 2014 – Tropina, A.A., Kuzmenko, A.P., Marasov, S.V. and Vilchinsky, D.V. 2014. Ignition system based on the nanosecond pulsed discharge. *IEEE Transactions on Plasma Science* 42(12), pp. 3881–3885.

Yousef et al. 2021 – Yousef, B.A.A., Hachicha, A.A., Rodriguez, I., Abdelkareem, M.A. and Inyaat, A. 2021. Perspective on integration of concentrated solar power plants. *International Journal of Low-Carbon Technologies* 16(3), pp. 1098–1125, DOI: 10.1093/ijlct/ctab034.

Zhangabay et al. 2023 – Zhangabay, N., Kudabayev, R., Mizamov, N., Imanaliyev, K., Kolesnikov, A., Moldagaliyev, A., Umbitaliyev, A., Kopzhassarov, B., Fediuk, R. and Merekeyeva, A. 2023. Study of the model of the phase transition envelope taking into account the process of thermal storage under natural draft and by air injection. *Case Studies in Construction Materials* 18, DOI: 10.1016/j.cscm.2023.e02050.

Gulnar Sydykova, Anvar Anarbaev, Kultan Islambek, Aknur Zhanserikkyzy, Asylbek Nurzhanovich Kazanbekov

Badanie odnawialnych źródeł energii w kontekście zrównoważonego systemu energetycznego

Streszczenie

W niniejszym artykule skoncentrowano się na analizie i doskonaleniu rozwiązań technicznych dotyczących wykorzystania kolektorów rurowych próżniowych oraz koncentratorów słonecznych w celu zwiększenia efektywności transferu ciepła oraz adaptacji instalacji słonecznych do pracy w istniejących systemach ogrzewania olejem opałowym. Metodologia badawcza obejmowała opracowanie modelu matematycznego opisującego transfer ciepła w kolektorach rurowych próżniowych, stworzenie algorytmu do obliczania parametrów projektowych systemu oraz modelowanie numeryczne służące ocenie charakterystyk temperaturowych, efektywności oraz wpływu kluczowych czynników oddziałujących na system. W wyniku badań przygotowany model matematyczny umożliwił precyzyjne opisanie procesów transferu ciepła oraz interakcji promieniowania słonecznego z kolektorami rurowymi próżniowymi i koncentratorami promieniowania słonecznego oraz identyfikację zależności analitycznych łączących parametry konstrukcyjne systemu (średnicę rur i długość modułu) z właściwościami cieplnymi, takimi jak temperatura nośnika ciepła oraz efektywność transferu ciepła. W trakcie badań zbadano zależności pomiędzy parametrami geometrycznymi systemu, strumieniem słonecznym, współczynnikiem odbicia oraz błędem kątowym, co pozwoliło zidentyfikować kluczowe czynniki wpływające na efektywność pozyskiwania energii słonecznej oraz rozkład temperatur wewnątrz systemu. Obliczenia numeryczne wykazały, że zwiększenie długości systemu oraz dostosowanie średnicy rur znacząco poprawiły efektywność absorpcji promieniowania słonecznego, a także wpłynęły na temperaturę czynnika chłodzącego. W pracy przeanalizowano także charakterystyki temperaturowe, w tym wpływ przepływu czynnika chłodzącego oraz jego rozkładu wzdłuż długości kolektora rurowego. Wyniki obliczeń wskazały, że do optymalizacji systemu konieczne jest uwzględnienie współdziałania różnych parametrów, w tym geometrii oraz właściwości promieniowania, w celu maksymalizacji efektywności instalacji solarnych. Dodatkowo w wyniku badań potwierdzono zależność pomiędzy średnicą odbiornika a liczbą koncentracji, co pozwoliło na dokładniejsze przewidywanie efektywności systemu w różnych warunkach eksploatacyjnych. Tym samym uzyskane wyniki mogą być wykorzystane do optymalizacji konstrukcji systemów solarno-termicznych, poprawy ich efektywności oraz precyzyjnego obliczania parametrów projektowych.

SŁOWA KLUCZOWE: koncentrator promieniowania słonecznego, kolektor rurowy próżniowy, zużycie pary, parametry projektowe, systemy grzewcze, instalacje wysokotemperaturowe