

ЕНЕРГЕТИКА ТА ЕНЕРГОЗБЕРЕЖЕННЯ

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The toolkit for rising the efficiency of the multi-module solar collector system using as attachments to boilers*Alla Denysova*^{1✉}, *Sergey Gayduk*², *Oksana Zhaivoron*³¹⁻³National University "Odesa Polytechnic", 1 Shevchenko Ave., Odesa, 65044, Ukraine✉ e-mail: alladenysova@gmail.comORCID: ¹<http://orcid.org/0000-0002-3906-3960>; ²<https://orcid.org/0000-0003-1627-2986>;³<https://orcid.org/0000-0001-6750-2388>

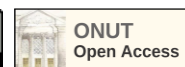
This article is devoted to the methods for increasing the efficiency of the multi-module solar collector system using as attachment to the boiler. To achieve the major aim of the study the mathematical model was proposed and comparative analysis of efficiency of the alternative heating system using of the multi-module solar collector system using as attachments to boilers, which correspond to the requirements of the energy saving technologies. A mathematical model of the heat exchange process in the system's elements was developed, taking into account the solar capabilities of the operating region. A methodology for calculating the efficiency of the multi-module solar collector system using as attachments to boilers was presented. The algorithm of numerical modelling of the heat exchange process in the system's elements taking into account the climate conditions was developed. The numerical modelling of thermal processes in the elements of the alternative heating system using of the multi-module solar collector system as attachments to boilers was carried out. The estimation methods for the energy efficiency of the proposed alternative heat supply schemes were offered. Factors influencing the thermal and economic efficiency of a combined alternative heat supply system using of the multi-module solar collector system as attachments to boilers were identified. Design schemes for interaction between the solar collectors' attachments to the boilers were developed. The analysis of the results of numerical modelling of thermal processes in the alternative heating system was presented. The rational ways of increasing the efficiency of the alternative heating system with the account of climatic conditions were grounded. Results of simulation, conclusions and decisions for the practical application of the alternative heating system using of the multi-module solar collector system as attachments to boilers were developed. This methodology for rising the efficiency enables the calculation of the thermal efficiency coefficient, heat removal coefficient, and heat transfer coefficient, taking into account the design and operating conditions of the multi-module solar collector system as attachments to boilers. The developed toolkit enables the determination of optimal values for the mass flow rate of the coolant, taking into account the circuit designs and design features of the solar collectors. The significance of the obtained results consists in justification of conditions, which make it possible to use the multi-module solar collector system as attachments to boilers at the energy saving principles

Keywords: Solar collector; Efficiency; Forced circulation; Modelling; Energy saving; Heating system; Operating modes; Climatic conditions

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The global requirement for sustainable energy provision and a political imperative for energy indepen-

dence of Ukraine have combined to increase interest in the use of renewable energy sources to meet growing energy demands. Current power systems are still dominated by fossil fuel-based electricity generation

and operated on supply following the changing demand. At present, the problem of energy saving can be solved both by the energy losses reduction and assimilation of the innovation technologies of generating and consumption of energy.

One most efficient technology of the energy saving is the implementation of the renewable energy sources (RES) for heating [1]. However, the works presented in literature, which describe the peculiarities of the use of the heating tools for the low temperature heating, ventilation and heat water supply are insufficient [2].

The energy sector offers the possibility to efficiently use renewable energies and therewith provide carbon free energy from non-exhaustible resources. Already today, the majority of renewable energy deployment takes place in the energy sector and the observed learning and growth rates suggest that the share of renewable energies in energy supply will continue to rise steeply [3]. Especially in Ukraine, where ambitious greenhouse gas emission reduction targets have been legislated, renewable energies play a key role. The solar energy is bound to be the most important source, due to its large potential in Ukraine [4], the observed growth rates, but also the existing support schemes [5].

2. Analysis of the latest research on the use of the alternative heating system using the solar collectors

The foreign researches [3-6], lack the methods, which can describe the alternative systems and conditions of their practical application for heating with different heating units for the environmental conditions of the Ukraine and South-Eastern Europe. The features of influence the heat-circuit design solutions and operating modes with the account on the replacement factor of an alternative heating systems haven't been clarified till now [6-11]. Today, there is a need to move to greater use of renewable energy sources, which are inexhaustible and can guarantee energy and environmental security.

When assessing the efficiency of a solar collector (SC), parameters dependent on climatic conditions and design characteristics are typically considered. The nature and extent of the influence of these factors on the SC's efficiency is typically determined under conditions of natural work fluid circulation within the SC [6]. When solar collectors are used as attachments to hot water boilers, additional data on the SC's effici-

ency is required, as coolant circulation is forced.

The issue of increasing the efficiency of heat for the use of various heat generators [12], operating in the alternative heat supply system is given great attention [13-16].

But there is no theoretical information on the operation of the system with the multi-module solar collector system using as attachments to boilers, according to the schedule of the working process, depends on the duration of the period of heat generation during the day that is the function of the outside air temperature, taking into account the operating conditions of the customer [16].

Using solar collectors in conjunction with traditional heating systems with water boilers requires additional research of the efficiency of the multi-module solar collectors as attachments to boilers, because in this case, the coolant circulation in the circuit is forced.

Thus, it is necessary to analyze the efficiency of solar collectors, firstly, by optimizing their design to reduce the cost of the combined system, and secondly, by assessing the impact of the heated water flow rate per square meter of solar collector area, as well as the water circulation rate in the collector tubes. In this case, optimal values for these parameters can ensure high efficiency of the combined system and the coordinated operation of the solar collector and boiler unit. At present, the problem of energy saving can be solved both by the thermal losses' reduction and assimilation of the innovation technologies of generating, distribution, regulation and consumption of the heat.

3. The aim and tasks of the study

The main aim of the study is to determinate the efficiency of the effect of use the multi-module solar collector system as attachments to boilers.

The objective of this study is to develop the toolkit in order to optimizing the influencing parameters during the combined operation of multi-module solar collectors using as attachments to boilers, as part of the alternative heating system of given configuration (Figure 1).

Our work differs from those foreign papers presented earlier in that this article analyses the efficiencies of the multi-module solar collector system using as attachments to boilers, which ensure the maximum replacement of the thermal load, which correspond to the requirements of the energy saving technologies.

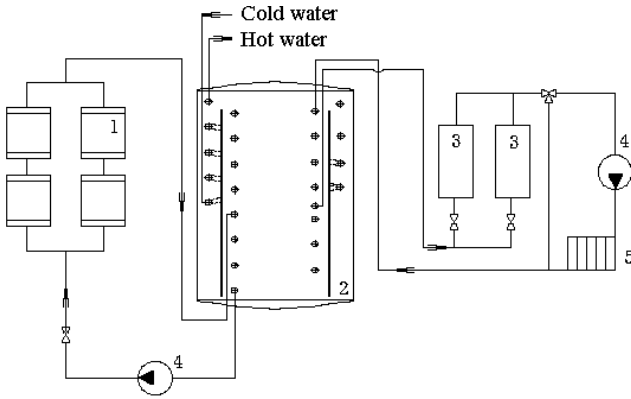


Figure 1 – Multi-module solar collector system using as attachments to boilers: 1 – solar collector module; 2 – storage tank; 3 – boiler; 4 – pump; 5 – consumer

This reduces the consumption of the hydrocarbon fuel in the structure of the heat balance of the regions and ensures the substantial energy saving effect.

To achieve the goal, it is necessary to solve the following tasks:

- to develop the mathematical model of forced turbulent fluid flow in the pipes of the multi-module solar collectors using as attachments to boilers;
- to justify the possibility of use the multi-module solar collector system as attachments to boilers, taking into account the climatic factors;
- determine the energy saving effect of use the multi-module solar collector system as attachments to boilers.

4. Research methodology and data processing

We propose a calculation method for a multi-module heating system acting as an attachment to hot water boilers.

The energy balance of the heating system:

$$H_{SC} \cdot A_{SC} (\alpha \cdot \tau) = Q_U + Q_W, \quad (1)$$

where H_{SC} – solar radiation flux density incident on the absorber, W/m^2 ; A_{SC} – absorber plate area, m^2 ; α – glass coating transmittance; τ – absorber plate absorptivity; Q_U – heat flux transferred from the absorber to the liquid, W ; Q_W – heat flux from the absorber plate to the environment, W .

The heat flux transferred from the absorber plate to the fluid Q_U determines the heat transfer capacity of the absorber:

$$Q_U = m \cdot c_p (T_1 - T_2), \quad (2)$$

where m – mass flow rate of the absorber coolant, kg/s ; c_p – the specific heat capacity of the environment, $kJ/(kg \cdot K)$; T_1 , T_2 – the fluid temperatures at the absorber inlet and outlet, respectively, K .

The heat flux Q_W determines the heat loss of the absorber:

$$Q_W = k \cdot A_{SC} (T_{SC} - T_a), \quad (3)$$

where k – the total heat loss coefficient of the absorber, $W/(m^2 \cdot K)$; T_{SC} – the average temperature of the absorber plate, K ; T_a – the ambient air temperature, K .

Heat flux transferred along the plate, the source of which is the solar radiation per unit length of the absorber tube [6],

$$q_U = \left[d + \left(\frac{W}{2} \right) \cdot F \right] \cdot (\alpha \cdot \tau) \cdot H_{SC} - k \cdot (T_F - T_a), \quad (4)$$

where $F = th[p \cdot (W - d)/2] / [p \cdot (W - d) \cdot 2]$ – finning efficiency; W – distance between tubes, m ; d – inner diameter of tubes, m ; T_F – temperature of working fluid, K ; p – parameter of finning efficiency of the absorber plate of the solar collector, which can be determined by the equation:

$$p = \left(\frac{2 \cdot a_F}{\lambda \cdot \delta} \right)^{0,5}, \quad (5)$$

where: a_F – heat transfer coefficient from the absorber to the liquid in the tubes, $W/(m^2 \cdot K)$; λ – thermal conductivity of the plate material, $W/(m \cdot K)$; δ – thickness of the absorber plate, m .

The heat flux q_U is removed by water circulating in the tube at temperature T_f :

$$Q_U = \pi \cdot d \cdot a_F \cdot (T_F - T_f), \quad (6)$$

As for the entire surface of the absorber, taking into account formulas (1-5), it follows that the total useful heat flow [3] is equal to:

$$Q_U = F_R \cdot A_{SC} \cdot [(\alpha \cdot \tau) - k \cdot (T_F - T_a)], \quad (7)$$

where F_R – coefficient of the heat transfer from the solar collector, which can be determined by the equation:

$$F_R = \frac{\frac{m \cdot c_p}{k \cdot A_{SC}}}{1 - \exp(-k \cdot A_{SC} \cdot F')}. \quad (8)$$

Coefficient of heat transfer of the solar collector F_R is equal: [7]

$$F_R = \frac{G \cdot c_p (T_2 - T_1)}{[H_{SC} (\alpha \cdot \tau) - k (T_1 - T_a)]}, \quad (9)$$

where $G = m / A_{SC}$ – consumption of water per unit area of the solar collector, $\text{kg}/(\text{s} \cdot \text{m}^2)$.

Coefficient of efficiency of the solar collector is equal:

$$F' = \frac{\frac{1}{k}}{W \left[\left(\frac{1}{k [d + (W - d) F]} + \frac{1}{\pi \cdot d \cdot a_F} \right) \right]}, \quad (10)$$

Equation (10) takes into account the ratio of the thermal resistance between the heat transfer system and the environment to the thermal resistance during the process of heat exchange between the working fluid and the environment.

It should be noted that the heat transfer coefficient a_F from inner surface of the tube to the liquid can varies within the range of 100 to 5000 $\text{W}/(\text{m}^2 \cdot \text{K})$, which is determined by the flow rate mode and geometry of cross-section of the tube.

When calculating the heat transfer coefficient for hot water supply systems with natural circulation, the water heating temperature is typically specified, and the efficiency is determined graphically [7,8] taking into account the average temperature of the absorber plate T_{SC} and the ambient temperature T_a , taking into account the number of transparent collector coatings.

In this case, the flow rate and velocity of the coolant are determined based on empirical data, taking into account the temperature difference $\Delta T = (T_2 - T_1)$, the relative position of the heat transfer coefficient and the storage tank. Therefore, it is impossible to accurately estimate the working fluid circulation velocity through the heat transfer coefficient tubes.

If a multi-module solar collector system operating in conjunction with a hot water boiler is used to replace part of the heat load, the heat transfer fluid temperature required by the consumer is guaranteed by the boiler, while the solar collectors act as a forced-circulation water economizer, providing preheating of the boiler water.

The existing methodology for calculating solar collectors with natural circulation does not provide an answer to this question.

To study the change in the solar collector efficiency factor F' as a function of the heat transfer coefficient a_F , it is necessary to first establish the dependence of the heat transfer coefficient on the fluid flow regime in the pipes.

For forced turbulent fluid flow in the pipes, the heat transfer intensity can be determined using the formula [9]

$$Nu_F = 0,021 \cdot Re_F^{0,8} Pr_F^{0,43} \left(\frac{Pr_F}{Pr_m} \right)^{0,25}, \quad (11)$$

where $Re_F = (V \cdot d)/\nu$ – Reynolds number; V – water velocity in the pipes, m/s ; ν – kinematic viscosity coefficient, m^2/s ; Pr – Prandtl number.

Equation (11) determines the average heat transfer in straight smooth pipes for $(l/d) > 50$. The determining temperature is the average liquid temperature $T_m = 0,5 \cdot (T_1 + T_2)$, and the determining dimension is the internal diameter of the pipe d . The Pr_m is selected based on the average value surface temperature of the pipe wall.

For forced laminar fluid flow in pipes, the dependence of heat transfer intensity on the flow mode can be determined using equations [10],

– in viscous mode for Rayleigh number: $Ra = Gr \cdot Pr \leq 8 \cdot 10^5$

$$Nu_F = 1,55 \cdot \left(Re_F \cdot Pr_F \cdot \frac{d}{l} \right)^{1/3} \left(\frac{\mu_F}{\mu_m} \right)^{1/7}, \quad (12)$$

– in viscous-gravitational mode for Rayleigh number: $Ra = Gr \cdot Pr > 8 \cdot 10^5$;

$$Nu_F = 0,15 \cdot \left(Re_F^{0,33} Pr_F^{0,43} Gr_F^{0,33} \right) \left(\frac{Pr_F}{Pr_m} \right)^{0,25} \quad (13)$$

that allows to determine the heat transfer coefficient from the absorber to the liquid in the tubes.

Figure 2 shows the calculated fluid circulation schemes for the three most typical connection options of the solar collectors' modules at the same total flow rate of the work fluid ΣG (m^3/s), but with different specific flow rates $G = \Sigma G / A_{SC}$, $\text{m}^3/(\text{s} \cdot \text{m}^2)$.

The number of tubes in one solar collector module is assumed to be 6, the tube length $l = 1$ m, the internal diameter $d = 0.01$ m, the distance between tubes is $W = 0.15$ m; coefficient of finning efficiency $F = 0.94$; working fluid is water.

5. Results of simulation, conclusions and decisions

The results of simulation of the thermal efficiency of the multi-module solar collector system according to our toolkit for rising the efficiency were obtained for different options of connection the solar collector modules (Figure 2) and for different specific flow range modes: $\Sigma G/A_{SC} = 0.01 \cdot 10^{-3}$; $0.04 \cdot 10^{-3}$; $0.16 \cdot 10^{-3}$; $0.64 \cdot 10^{-3} \text{ m}^3/(\text{s} \cdot \text{m}^2)$ allow us to analyse the efficiency of the solar collectors in a wide range of circulation rates in its pipes.

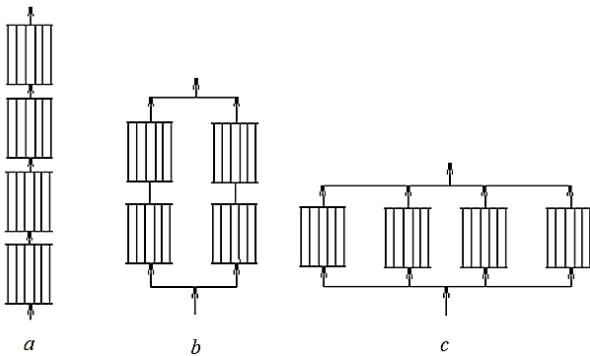


Figure 2 – Calculation schemes for different connection options of the solar collectors: *a* – series; *b* – parallel-series; *c* – parallel

The Figure 3 shows results of numerical modelling the coefficient of the thermal efficiency F' and coefficient of the heat transfer F_R for varying flow conditions determined by the specific fluid flow rate G and the design parameters of the solar collectors for three configurations of its connection. The velocity of flow is assumed to be $V = 4 \cdot G / (\pi \cdot d \cdot n) = 0.01 \text{ m/s}$, which corresponds to a specific fluid flow rate of $G = 18 \cdot 10^{-3} \text{ m}^3/(\text{s} \cdot \text{m}^2)$. The number of pipes in one module is 6.

For similar conditions the Figure 4 shows results of numerical modelling the change in the heat transfer coefficient α_F of inner surface of the absorber tube to the coolant and the change in the corresponding temperature difference ΔT .

Forced circulation of water in the collector increases the efficiency factor to $F' = 0.95$, while the heat removal coefficient also increases to $F_R = 0.95$, and the temperature of the heated water approaches the absorber surface temperature at temperature difference of $\Delta T = 1 \text{ }^\circ\text{C}$, that significantly rise the thermal efficiency of the collector [11-12].

The proposed toolkit allows to calculate the heat transfer coefficient from the pipe surface to the coolant circulating within them and determine the efficiency of a multi-module collector system acting as an attachment to a boiler [13-17].

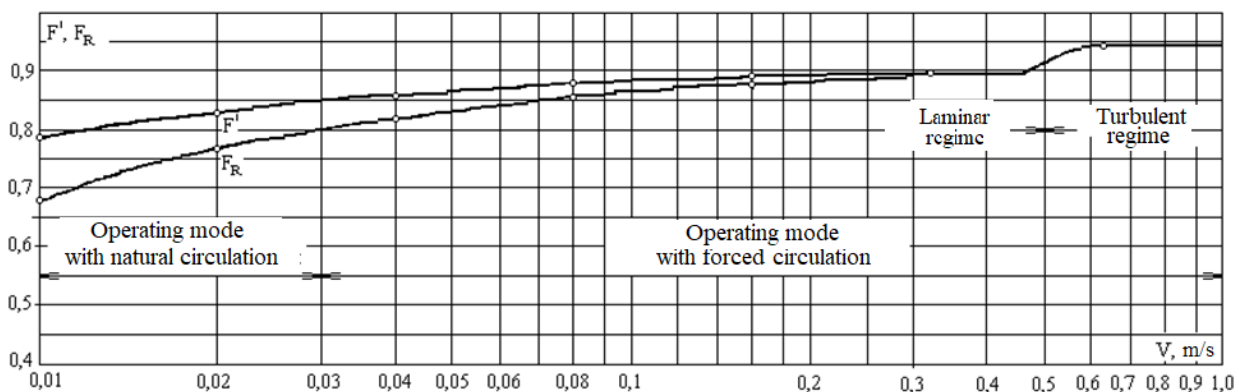


Figure 3 – Dependence of the efficiency coefficient F' and heat removal coefficient F_R on water circulation rate in pipes of the solar collector for $d = 0.01 \text{ m}$ and $T_m = 40 \text{ }^\circ\text{C}$

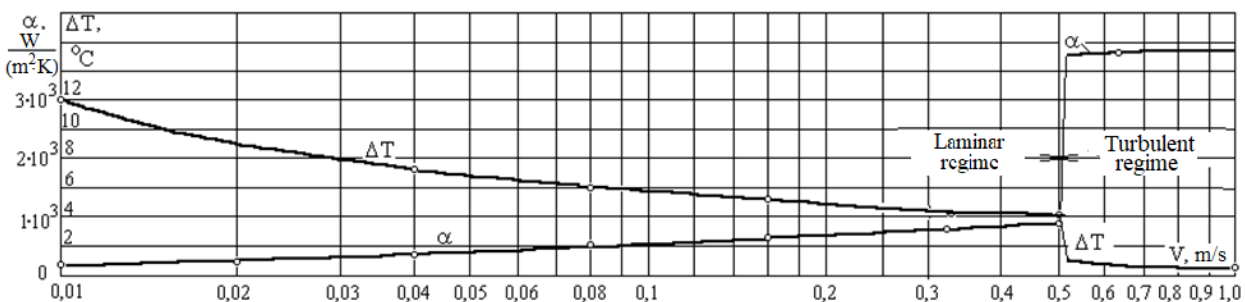


Figure 4 – Dependence of the heat transfer coefficient α_F and temperature difference ΔT on water circulation velocity in pipes of the solar collector for $d = 0.01 \text{ m}$ and $T_{cp} = 40 \text{ }^\circ\text{C}$

The proposed toolkit for perfection of the thermal efficiency of solar collectors allows to determine the heat transfer coefficient between the inner wall of the solar collector's absorber plate and the water circulating in the pipes at natural and forced circulation mode of work, as well as the absorber plate temperature, which has a significant impact on the total heat loss coefficient of the solar collector.

Analysis of the calculation results shows that the efficiency coefficient for solar collectors with natural circulation of the work fluid corresponds to the range $F = 0.8-0.85$, and the heat removal coefficient lies in the range $F_R = 0.68-0.8$. Moreover, the water temperature at the outlet of the solar collector is 10°C lower than the absorber plate temperature, resulting in low thermal efficiency of solar boiler attachments.

The use of forced circulation of the coolant in solar boiler attachments allows increasing the efficiency factor to $F = 0.95$, while the heat removal coefficient increases to $F_R = 0.95$, and the temperature of the heated water approaches the surface temperature of the absorber plate, which has a positive effect on the thermal efficiency of the alternative heat supply system.

CRedit author statement

Alla Denysova: development of the mathematical model, supervision. **Sergey Gayduk:** numerical modelling. **Oksana Zhaivoron:** analysis of results of simulation

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Інструментарій підвищення ефективності багатомодульної сонячної колекторної системи з використанням її як додатку до котлів

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Стаття присвячена методам підвищення ефективності використання багатомодульної системи сонячних колекторів як додатків до котлів. Для досягнення основної мети дослідження було запропоновано математичну модель та виконано порівняльний аналіз ефективності альтернативної системи опалення на базі багатомодульної системи сонячних колекторів як додатків до котлів, що відповідають вимогам енергозберігаючих технологій. Було розроблено математичну модель процесу теплообміну в елементах системи з урахуванням геліотехнічних можливостей регіону експлуатації. Представлено методологію розрахунку ефективності багатомодульної системи сонячних колекторів з використанням їх як додатку до котлів. Розроблено алгоритм числового моделювання процесів теплообміну в елементах системи з урахуванням кліматичних умов. Виконано чисельне моделювання теплових процесів в елементах альтернативної системи опалення з використанням багатомодульної системи сонячних колекторів як додатку до котлів. Запропоновано методи оцінки енергоефективності запропонованої альтернативної схеми теплозабезпечення. Визначено фактори, що впливають на теплову та економічну ефективність багатомодульної системи сонячних колекторів як додатку до котлів. Розроблено схемно-конструктивні принципи взаємодії сонячних колекторів, які працюють як додатки до котлів. Представлено аналіз результатів чисельного моделювання теплових процесів в альтернативній системі опалення. Обґрунтовано раціональні шляхи підвищення ефективності запропонованої системи альтернативного теплозабезпечення з урахуванням кліматичних умов. Розроблена методика підвищення ефективності дозволяє розрахувати коефіцієнт теплового ККД, коефіцієнт тепловіддачі та коефіцієнт теплопередачі багатомодульної системи сонячних колекторів як додатку до котла, з урахуванням конструктивних та експлуатаційних чинників. Запропонований інструментарій дозволяє визначати оптимальні значення масової витрати теплоносія з урахуванням схемних рішень та конструктивних особливостей сонячних колекторів. Значення отриманих результатів полягає в обґрунтуванні умов, що дозволяють використовувати багатомодульну систему сонячних колекторів як додатку до котлів на засадах енергозбереження.

Ключові слова: Сонячний колектор; Ефективність; Вимушена циркуляція; Моделювання; Енергозбереження; Система теплозабезпечення; Режим роботи; Кліматичні умови

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