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Thermodynamic Analysis of an Experimental Model of a Solar-Heat Supply System

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Abstract: In this study, the problem of the operability of the solar-heat supply system in the cold region of Kazakhstan receiving minimal solar radiation was studied. The importance of this study lies in the question of how a dual-circuit solar installation can work for productivity in the northern regions of Kazakhstan. In the course of the study, an efficiency reduced from the energy efficiency increased by using a transparent glazed window reduced the supply of coolant into the pipe. Cold liquid heat enters the resulting stream, heat transfer increases, and the intermediate walls heat up. In this study, a method was used to determine the thermal characteristics of a glazed flat collector, which contains a brief and accurate description. From the results obtained, it can be concluded that the effectiveness of 2.40 and 2.53 was recognized in this study. It was also investigated that the thermal capacity of the solar collector depends on the thickness of the absorbing layer. Having conducted this experimental study, we were convinced that it is reliable for the northern regions of Kazakhstan.

Keywords: flat solar collector; heat pump; solar radiation; solar-heat supply system

MSC: 80A19; 74H80

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1. Introduction

1.1. The Main Idea

In the works [1,2], attention is mainly paid to various systems with low energy consumption and low refrigerant consumption, which can effectively provide comfortable indoor air-conditioning parameters in India. Researchers have developed two mathematical models, energy consumption and refrigerant consumption, which reduce the need for refrigerant. We also studied the possibility of using 65% of the parameters for indoor use, for use as the main tool in buildings with a low-energy consumption and the area of indoor air conditioning and water heating compared to traditional systems. In [3], the development of a mathematical model of the material of enclosing structures in the energy consumption of the room is proposed. In the article [4], four heating systems using solar-powered heat pumps were designed, and photovoltaic systems of gas stations and photovoltaic cells connected to a water heat pump were modeled. Photovoltaic systems in combination with an air pump have the possibility of connecting systems with a water heat pump and energy in the grid, which makes this technology the most environmentally friendly. The article [5] investigates two of the most popular methods of modernization, covering the buildings of cities with a predominance of cooling. In [6], a complex energy system under study for heating the main room with power from a heat pump was developed; when powered via an electric current, the supply of hot water to the heat pump increases efficiency (efficiency), since the temperature with an air source increases. Each system is carefully designed to maintain thermal comfort conditions at a high level. In [7], a mathematical analysis of solar water heating was developed, which accounts for the majority of all applications on the market. An article [8] was developed that could potentially eliminate these problems.

In [9], systems were developed and investigated in which water is used as a working fluid, and this water is used in the systems. The problems of the solar-heat supply system are traditionally associated with the occurrence of corrosion. In the study [10], an approach to the mathematical analysis of efficiency is proposed for calculating the properties of a passing object and the characteristics of its corresponding environment. In the document, after the description, an explanatory application of this method is presented, taking into account the emphasis on the installation. The results obtained are consistent with the results of the generally accepted, standard thermo-dynamic analysis of the stationary state with the same user needs, and the average primary power is approximately equal to a standard gas burner. This result practically does not depend on (with glazing) the operation of the collector.

1.2. Related Ideas

In the article [11], the equations of thermo-hydraulic characteristics of various roughness of a conical protrusion were developed and the characteristic conditions were considered. The method of flow and temperature increase was used in the study. The roughness of the edges of the ledge was assessed. The article [12] describes the evaluation using working radiation. The results of experimental analysis in transient modes under conditions of zero solar radiation are shown and discussed, and a characteristic efficiency of 3.23 was obtained. The article [13] considers the feed from the point of view of the hydraulic layout and climatic conditions. For comparison with the electric water heating system, three common hot water systems were selected: a conventional solar hot water system, a solar combined system with one tank, and a solar combined system with two tanks, and their technical and economic aspects were evaluated. There were additional capital costs for solar combined systems. The article [14] investigates the characteristics of the efficiency of a heat pump, which consisted in evaluating their operation, where the efficiency of the system ranged from 2.5 to 5.0. In the study [15], a solar heat pump system was proposed that could operate in serial or parallel mode. In the article [16], a water heater is investigated. System efficiency (COP) achieves greater ice-heating and provides excellent evaporator icing delay. In the article [17], the evaporator and condenser are based on the continuity and conservation equations. The pressure and density of the refrigerant are given in the corresponding tables. The results of comparing the simulation data with what is necessary during modeling to reduce the required time and some mechanical modifications for the presented prototype are also presented. In the article [18], the work is aimed at ensuring that a new mathematical model of SAP performance is currently being carried out, and has been developed in good faith, yet the presence of differences can lead to serious inconsistencies when comparing the analysis of different configurations. In the article [19], a solar-heat supply system was developed, in which it was determined that the COP level changes significantly in line with changes in solar radiation based on the mathematical theory of convection, which allows heat to be absorbed due to a higher ambient temperature and a lower evaporation temperature. In the study [20], a mathematical model of thermal characteristics was developed, and an analysis was carried out for the refrigerant R134a using a solar collector with one lid. In the article [21], a capacious water tank was investigated under vacuum conditions. The equations of nonstationary state defining the mass, momentum, concentration, and conservation of energy are developed and investigated. Numerical data show an increase in the gutter edge by at least 19.78%. In the article [22], a mathematical model was developed, and a simulation modeling of transfer phenomena was carried out. Numerical results have also been obtained that are absorbed faster than zeolite. In addition, a static study of the adsorption–ejection system is carried out to obtain an important solar efficiency.

When the intense solar radiation ambient temperature changes, the COP values for the system change depending on different structural schemes. This study is a new design that includes various optimization strategies. In the course of the study, an experimental setup

was developed and investigated, optimizing design parameters that can help in reducing the complexity of the classification system.

2. Methodology

In this study, the main task was to improve and influence various environmental emissions on the effectiveness of the use of thermosiphon circulation. Figure 1 shows a two-circuit solar installation with thermosiphon circulation, proposed in [23]. The study examines the dynamics of the total consumption of electric and thermal energy in agriculture and in the whole country. Experimental results of studies of the effectiveness of the proposed system are presented [24].

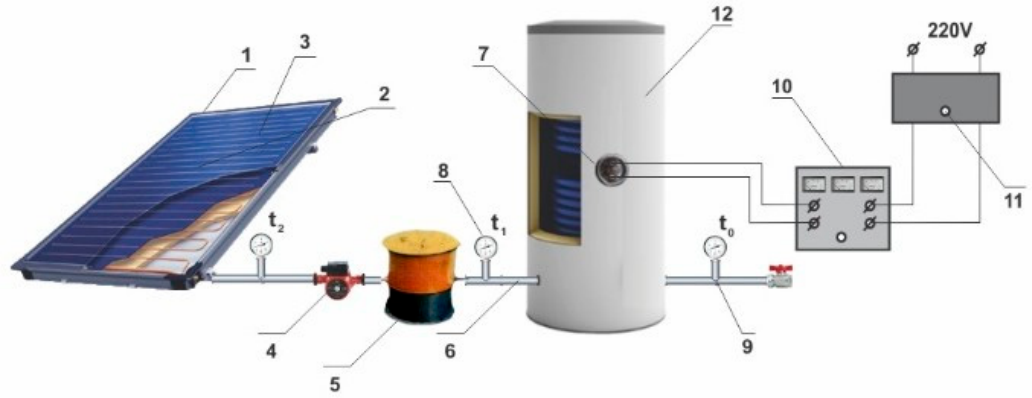


Figure 1. Principal diagram of solar-heat supply system [24] (Wojcik, W., Amirgaliyev, Y., Kunelbayev, M., ... Sundetov, T., Yedilkhan, D. Developing the system of collecting, storing, and processing information from solar collectors. International Journal of Electronics and Telecommunications. 2021, 67(1), 65–70. 1—heat insulated body; 2—translucent cover; 3—tank absorber; 4-circulating pump; 5—thermal pump; 6—pipeline; 7—THE; 8, 9—thermometers for temperature measuring at inlet and outlet from the tank-absorber and environment; 10—kit of electric measuring devices K 501; 11—autotransformer; 12—tank-accumulator; 13-controller.

In this research methodology, it is shown how the main parameters of the installation were optimized and justified based on the energy performance indicators, which directly depend on the corresponding parameters of the solar installation. Therefore, the bulk of inventions and patents registered in the world are concentrated mainly in the field of creating new designs and technologies for solar collectors.

3. Thermal Characteristics of a Glazed Flat-Plate Collector

The amount of heat given by a flat solar collector is calculated from [25]:

$$Q_u = F' A_c [S(\tau\alpha) - U_L(T_e - T_a)], \quad (1)$$

where F'= the collector efficiency factor; A_c = collector area; S = solar radiation in the collector plane; $\tau\alpha$ = transmittance-absorptance product; U_L = the total heat loss coefficient and (T_a) = the effective transmission-absorption coefficient of the coating system; U_L can be estimated as follows [21]:

$$U_L = U_B + U_t + U_c. \quad (2)$$

The upper-loss coefficient can be calculated using an empirical equation derived using Klein [22]:

$$U_t = \left[\frac{M}{\left(\frac{C}{T_P}\right)\left\{\frac{T_P - T_a}{M+F}\right\}^e} + \frac{1}{h_w} \right]^{-1} + \left[\frac{\sigma\left(T_p{}^2 + T_a{}^2\right)\left(T_p + T_a\right)}{\left(\varepsilon_p + 0.059 M h_w\right)^{-1} + \left\{\frac{2M + \mathrm{f} - 1 + 0.133\varepsilon_p}{\varepsilon_g}\right\} - M} \right], \quad (3)$$

where:

$$f = \left(1 + 0.089h_w - 0.116h_w\varepsilon_p\right)\left(1 + 0.07866M\right) \quad (4)$$

$$e = 0.43\left(1 - \frac{100}{T_p}\right) \quad (5)$$

$$C = 520\left(1 - 0.000051{\cdot}\beta^2\right) \text{ for } 0 < \beta < 70^\circ;\ \text{use } \beta = 70^\circ \text{ when } 70^\circ\ < \beta < 90^\circ \quad (6)$$

The coefficient of convective heat transfer h_w for an external glass coating is determined using [26]:

$$h_w = 5.7 + 3.8\mathrm{V} \quad (7)$$

To solve the thermal characteristics of a solar collector, the Hottel–Willier–Bliss equation is used [27]:

$$F' = \frac{1}{\left\{\frac{WU_L}{\pi D_0 h_{fi}} + \frac{1}{\left(\frac{D_0}{W} + \frac{1}{\left(\frac{WU_L}{C_{\text{bond}}} + \frac{W}{(W-D_0)F}\right)}\right)}\right\}} \quad (8)$$

$$F = \frac{\tanh\left[\frac{m(W-D_0)}{2}\right]}{\left[\frac{m(W-D_0)}{2}\right]} \quad (9)$$

In addition, the equations [28,29]:

$$F' = \left[\frac{\frac{1}{U_L}}{W\left[\frac{1}{U_L[D_0+(W-D_0)F]}\frac{1}{C_b} + \frac{1}{\pi D_i h_{fi}}\right]}\right] \quad (10)$$

Using Equation [30], it is possible to calculate the mass of the refrigerant in the heat pump.

$$\mathrm{m}_r = \frac{\eta_v * \mathrm{V_D}}{V} \quad (11)$$

$$\eta_v = -0.163 * \left(\frac{P_2}{P_1}\right) + 0.6563 \quad (12)$$

Efficiency of the solar-heat supply system [30]:

$$\eta = \frac{Q_u}{A_c \mathrm{I}_T} \quad (13)$$

The COP of a heat pump can be estimated as [30]:

$$\mathrm{COP} = \frac{Q_c}{W_{comp}} \quad (14)$$

4. Experimental Setup and Instruments

Figure 2 shows an experimental installation of a heat pump. Fundamentally changing the situation allows for heat pumps, which are widespread in the field of energy and industry. Heat pumps are of particular importance in agriculture, and they can be used for both heating and cooling. When a heat pump is used for heating, it is used for the hot water supply, absorbing heat from a colder, cooled medium, such as cooled milk or renewable energy sources. An important operational parameter of a heat pump is the temperature regime of the compressor, which affects the conversion coefficient and its service life. In this article, the authors propose self-regulating the cooling of the compressor. The directions of improvement and the principal advantages of the heat pump proposed for development are substantiated. It is proposed to change the layout principle of the

main elements of the heat pump, replace the traditionally expensive, dimensional, and metal-intensive plate heat exchangers of the evaporator and condenser with the tubular flexible heat exchangers, and place the compressor inside the flexible heat exchangers of the evaporator laid in a circle around it. This will ensure the self-regulation of the cooling of the compressor, maintenance of its thermal balance, softening of the temperature regime of the windings of its electric motor, and absorption of the heat released from the surface of the compressor during operation.

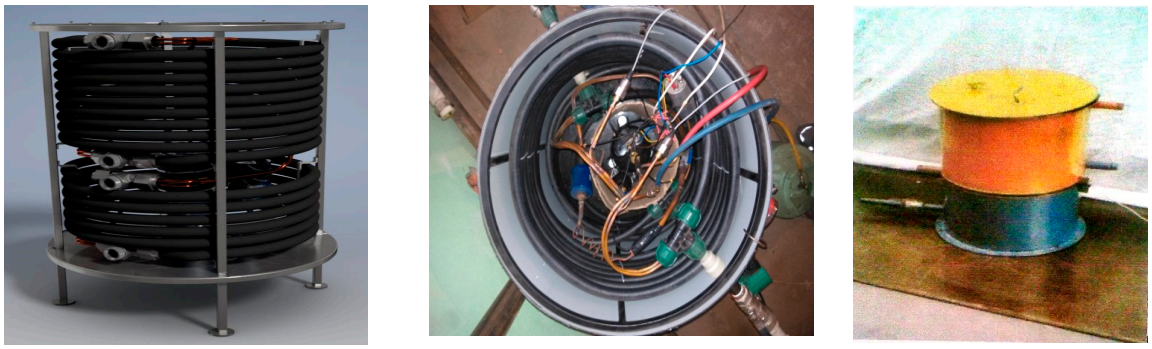


Figure 2. Schematic diagram of the heat pump.

Figure 3 shows the test bench on which the experimental work was carried out.



Figure 3. Test bench.

Figure 3 shows the test bench where the experimental work was carried out. The test bench was made and investigated on a farm in the Republic of Kazakhstan. The stand consists of four flat solar collectors and heat-insulating translucent glass with double glazing with reduced pressure. The coolant is made of thin-walled corrugated stainless pipe. The heat from the solar flow heats the liquid removed from the collector, and cold water from the siphon enters its place. There is a constant circulation of heat, which increases the efficiency of heat transfer by eliminating additional partitions between the panel and thermal insulation.

The Figure 4 shows an industrial design and a general view of a two-circuit solar installation, which consists of a heat pump, an accumulator tank, a circulation pump, and an expansion tank.

Research studies together with HP SPP are carried out on a laboratory stand (Figure 5). It is of an industrial design and has two-circuit solar installation, as can be seen from this figure. The translucent glazing of the solar installation is reduced, and there is also a cooling pipe. Water from the flat solar collector of the siphon takes its place, removing heat and eliminating the partitions of the thermal energy panel. Water from a flat solar collector enters a circulation pump—a household appliance for pumping liquid. An electric motor and a working shaft are installed in the housing. Then the rotor turns on, which

begins to rotate the impeller, which generates reduced pressure at the inlet and increased pressure at the outlet. The circulating water enters the spiral-to-spiral heat exchanger in the intensity range, after which the water is pumped into the storage tank. There is also an expansion tank—an element of the heating system designed to receive excess water from its thermal expansion due to heating. The air temperature around the compressor inside the evaporator heat exchanger is maintained at a stable level and is about 200 °C. The surface temperature of the evaporator heat exchanger is about 120 °C; moreover, with an increase in the temperature of the compressor, the surface temperature of the evaporator and the air temperature around the compressor decrease. This mode confirms the cooling effect of the compressor by the evaporator and the partial absorption by the evaporator of the heat generated by the compressor. The method is favorable for the operation of the compressor. However, when the compressor is displaced from the center, the air temperature around the compressor is lower by between 4–50 °C. This can be explained by the fact that when the compressor is located in a zone close to the evaporator, it cools better, the surface temperature is lower and, accordingly, it heats the air surrounding it less.

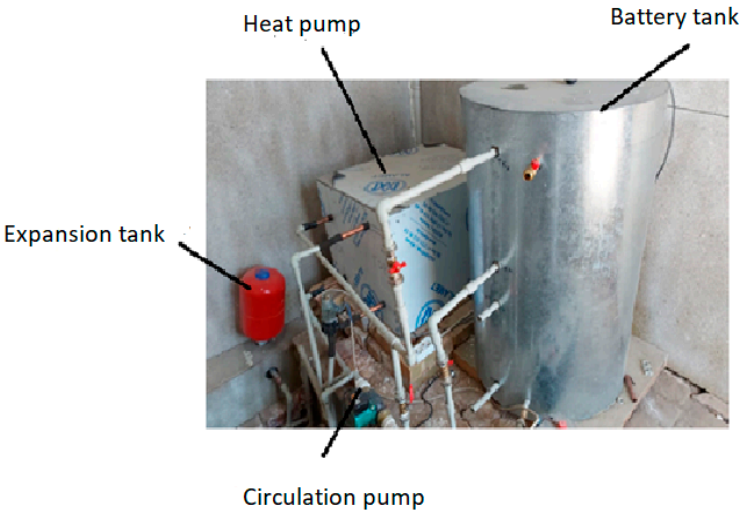


Figure 4. Industrial design and general view of a two-circuit solar installation.

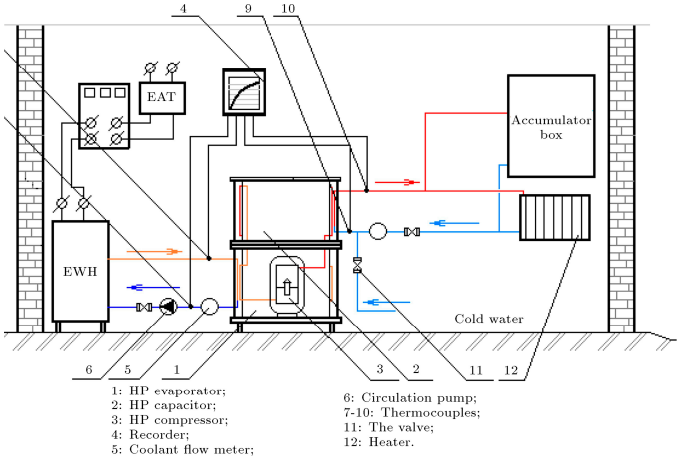


Figure 5. Industrial design and general view of a two-circuit solar installation.

5. Results and Discussion

The experiment was conducted in a cold climate as shown after the establishment of stationary conditions with different intensities of solar radiation on different days and with a change in ambient temperature.

Figure 6 shows how F′ increases with the increasing thickness of the absorbing plate and decreases accordingly with the increasing value of W/m^2.

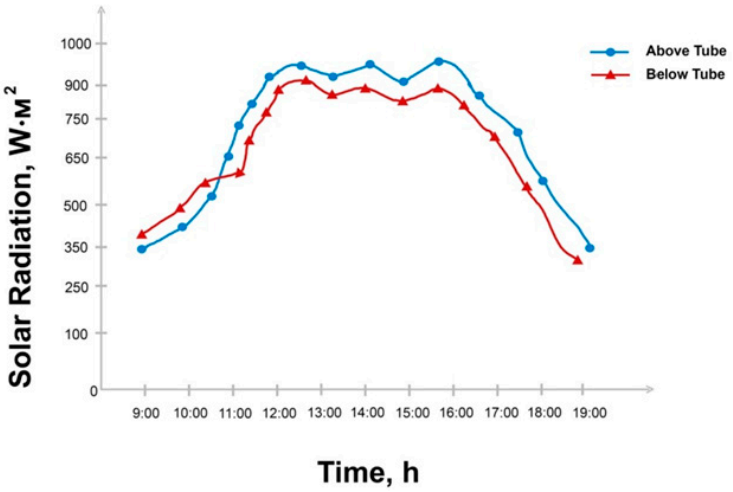
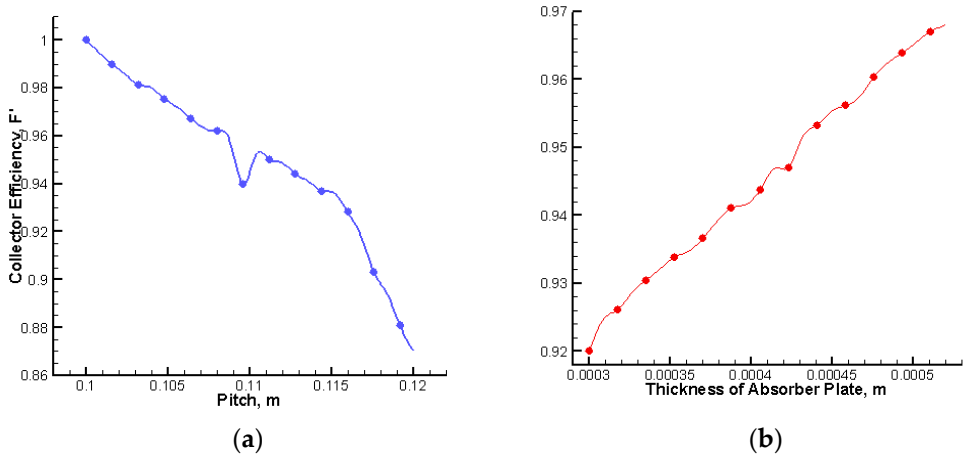


Figure 6. Changes in the intensity of solar radiation over time.

Figure 7a,b shows the changes in collector efficiency for the (a) tube pitch; and (b) the thickness of the absorbing plate. The thickness under the absorbing plate ranged from 50% to 65%, and the thickness above the absorbing plate ranged from 63% to 77%.

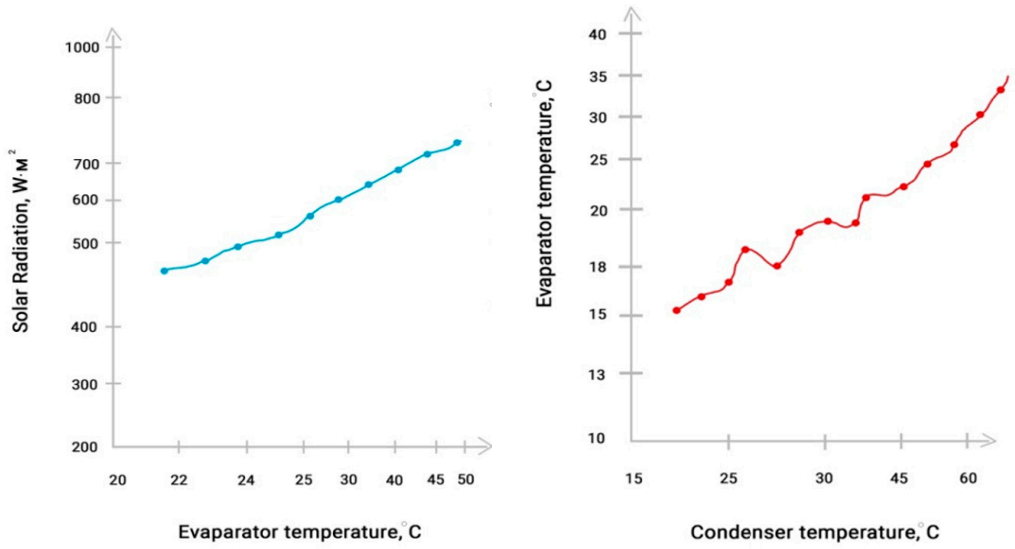


(**a**) (**b**)

Figure 7. Changes in the efficiency of the collector: (**a**) the pitch of the tubes; (**b**) the thickness of the absorbing plate.

Figure 8a,b shows the effect where with a rise in the evaporator temperature, the condensation temperature of the working fluid also increases. The location of the compressor in the evaporator area affects the performance of the TN. The evaporator absorbs part of the heat released from the compressor surface, which is then added to the main flow. Since the temperature difference between the compressor wall (about 80 °C) and the evaporator wall is about 60 °C, it can be assumed that the main flow is heat exchange via radiation between the surfaces.

Figure 9 shows the lower location of the pipes, where the evaporation temperature could be equal to the ambient temperature; therefore, a better performance achieved compared to the upper location of the pipes is shown.



(**a**) (**b**)

Figure 8. The evaporator temperature on the condenser temperature.

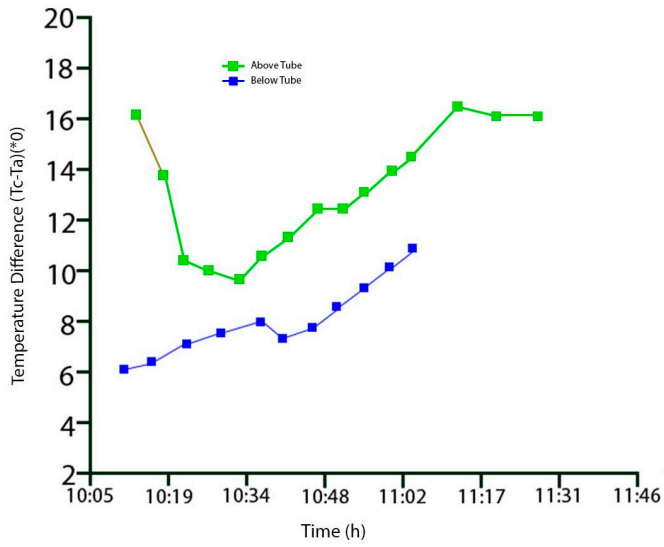


Figure 9. Changes in the temperature difference (Te–Ta) over time.

Figure 10 shows COP systems with variable evaporator temperatures. The results showed that the COP increases with an increase in the temperature of the heat pump evaporator within the range considered in this paper. Thus, flat solar collectors are better suited for operation in winter. The condenser in the thermal pump functions for heat transfer from the working body to the water, since it is heated. As a result, the working body transforms from a steamy state into a liquid, i.e., it condenses. To the thermal pump condenser, a jacket-tube construction is most frequently applied. The water being heated then passes inside the tubes, and a working body condenses at the pipes outer side in annular space. This confirms that a major part of steam (above 99%) condenses in the zone of mass condensation, where it permeates a comparably small amount of air. The temperature of the saturated steam does not usually exceed 50–60 °C. In the cooling zone, the partial steam pressure is less, and the steam-air mixture temperature is lower. In that zone, it is possible the condensate is subject to overcooling, which is not favorable for the installation's efficiency on the whole. Proceeding from graph experimental data, it is seen that the higher the cycle's cooling capacity in the cycle, the bigger the amount of the process

cycle's internal energy in the thermal pump that is released, which is confirmed with the first law of thermodynamics.

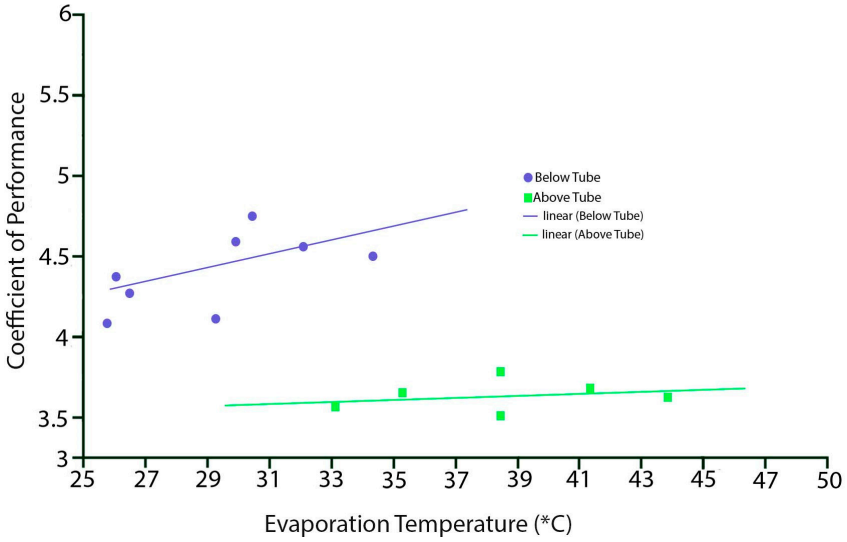


Figure 10. COP systems with variable evaporator temperature.

6. Conclusions

This study was conducted for flat plate collectors in the colder climate of Kazakhstan, with the experiment being conducted during the winter months. In this study, the method of the thermal characteristics of a glazed flat collector was used, which contains a brief and accurate interpretation. As a result of experimental work using 50 L, water can be heated from 200 °C to 450 °C in 60 min, and the efficiency of a flat plate collector varied from between 40% to 50% when the tubes were located under the absorbing plate. The results of experiments on seasonality in winter conditions with dense clouds and sunny weather are presented. It has been experimentally established that the power generated by a flat solar collector ranges from between 1.6 to 2.2 and from between 2.3 to 3 kW/m^2. The increase in power is explained by the absence of optical losses during the passage of solar energy through the glazing as well as the significant decrease in resistance to heat flow. This study confirmed that the solar-heat supply system in the future will produce new neural networks and predictive machine learning as well as learning.

Author Contributions: Conceptualization, M.K., Z.B.; methodology, Y.T.; software, S.I., D.K. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

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