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Article

Thermal Loss Analysis of a Flat Plate Solar Collector Using Numerical Simulation

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Abstract: In this paper, we studied theoretically and numerically heated losses of a flat solar collector to model the solar water heating system for the Kazakhstan climate condition. For different climatic zones with a growing cost for energy or lack of central heating systems, promising is to find ways to improve the energy efficiency of the solar system. The mathematical model (based on ordinary differential equation) simulated the solar system work process under different conditions. To bridge the modeling and real values results, we studied the important physical parameters such as loss coefficient, Nu, Ra, and Pr values. They impacted the efficiency of flat solar collectors and heat losses of the system. The developed mathematical models, the design and composition of the software and hardware complex, and automated control and monitoring systems allow solar hot water heating systems to increase the energy efficiency of life support systems and heat supply of buildings by reducing energy consumption for heat supply. The simulation result showed that during the daytime, the temperature of water in the collector is 70°C; the storage of heated water since heated water is cooled at night. We defined that a work period of the system can be extended with high efficiency (April–October) for Almaty region.

Keywords: Solar heating system; heat loss coefficient; dynamic simulation; flat plate collector

Nomenclature:

A	Area (m^2);
T_1	Temperature of output fluid from a heat exchanger (°C);
V_{col}	Volume of fluid in a collector cycle (m^3);
c_{col}	Specific heat capacity in a collector cycle (J/kg K);
T_{col}	Temperature of outlet fluid from collector (°C);
T_{inc}	Temperature of inlet fluid into collector (°C);

v_{col}	Volumetric flow rate in collector cycle (m^3/s);
I	Solar irradiance (W/m^2);
T_{out}	Temperature of collector ambient (°C);
U	Heat loss coefficient of collector (W/m^2°C);
$h_{c,p-c}$	Thermal conductivity coefficient (W/m^2°C);
$h_{r,p-c}$	Radiation coefficient from the glass coating to the absorber (W/m^2°C);
h_w	Wind heat transfer coefficient (10 W/m^2°C);
$h_{r,c-a}$	Radiation coefficient between the glass surface and the air (W/m^2°C);
h	Heat transfer coefficient (W/m^2 K);
L	Distance between the absorbent and the glass;
k	Heat conductivity of the insulating material (W/mK);
g	Gravitational constant ($g = 9.81$ m/s^2);
ΔT	Temperature difference between the boards;
v	Kinematic viscosity (m^2/s);
T_p	Absorbent temperature;
T_c	Glass surface temperature;
Nu	Nusselt number
Pr	Prandtl number

Greek symbols:

η	Efficiency (precentage)
ρ_{col}	Density of fluid in colletor (kg/m^3)
β'	Volume expansion coefficient;
α	Thermal diffusivity (m^2/s);
ε_c	Absorbent emission (0.88);
ε_p	Glass emission (0.95);
σ	Stefan-Boltzmann constant (5.670367×10^{-5} W m^2 K^{-4})

1 Introduction

Each year renewable energy becomes an important role in our daily lives. Using renewable energy can reduce energy consumption and decrease our dependence on fossil energy. The most straightforward way to use renewable energy is solar energy which allows getting clean energy without pollution. Researchers study mathematical models and designs of solar heating systems for domestic buildings.

One of the researches is devoted to estimating solar hot water heating and analyzing data in South Korea for three years [1]. A solar water heating system was installed for multi-family housing with 1179 families in 14 units. Results of the research showed that comparison of conventional boiler for heating water (efficiency = 85%) with solar hot water heating system showed a positive environmental effect and was estimated to reduce 71.9 L/year of oil and reduction of 186.3 tons CO2. The authors of the paper [2] provided the numerical experiment of a centralized solar hot water heating system developed for a high-rise residential building in Hong Kong.

The author of the research [3] considered a solar hot water heating system and simulated the solar system with the flat collector, storage tank, and circulation. It analyzed two designs of hot circulation: water–water and water–air. The result of the research showed that the design of water–air does not become effective. In the paper [4], there was a review of research on solar energy absorption by a solar system with different fluid types. The main focus of the research was a solar-based absorption cooling systems, diffusion absorption systems, ejector–based absorption systems, compression absorption systems and cogeneration/trigeneration absorption systems. The thermodynamic properties of the most common working fluids were reviewed and analyzed for a ternary mixture in solar absorption systems. The author of the paper [5] calculated optical, thermal, and thermodynamic analysis of solar collectors and described methods of an estimatied efficiency.

In the research [6], the author investigated the construction and efficiency of solar hot water heating systems. The geometry and dimension of a solar system were defined based on the material's thermal properties. In research [7], the authors proposed to use the algorithms for calibration of small solar hot water heating systems and the application in Matlab.

Thermal performance is calculated based on the first law of thermodynamics (energy), but that does not allow estimating a flat solar collector [8]. The second law of thermodynamics (exergy) estimates the various losses in the flat solar collector and allows for estimating a solar hot water heating system [9–11]. The authors [12] used the numerical inverse Laplace homotopy technique for solving some interesting 1-D time fractional heat equations. The authors of [13] have provided the numerical arrangement of ordinary differential equations (ODE) that appeared from different problems; in the simulation of a solar hot water heating system, it can be considered to decrease the simulation time. In [14], the author provided analytical and numerical techniques for physical fields in the physical time-domain; the problems that appeared in a solar hot water heating system due to the mechanical deformation during the thermal gradient temperature are applied on the outer surface. In the paper [15], the authors presented numerically and graphically in isotherms, streamlines, local Nusselt number, global Nusselt number, and global fluid temperature.

In Kazakhstan, it is extensive attention to developing a solar hot water heating system. The system's price is high; therefore, it is unavailable for all customers. The new hybrid energy system with mathematical methods and computer simulation, software, and hardware help optimize the price of flat solar water heating systems. One way to efficiently use energy is to use a new source of energy (renewable and environmentally friendly) in Kazakhstan's fuel and energy system. So the development of an energy system based on the double-circuit solar system with a heat pump is an actual and urgent problem for autonomous power supply.

Kazakhstan has a high potential for the generation of solar energy potential. In the paper [16], the authors used the actual observations and theoretical calculations to generalize the most favorable period and localization of to use the solar energy in the Almaty region. The authors considered the solar collector with a storage tank, heat exchanger, and pump stations for hot water. The simulation was performed for different temperature conditions and solar irradiance for the Almaty region. The simulation process is done in Matlab and Simulink, and the tool is often used for other simulation processes and, in particular, for the simulation of solar hot water heating systems [17,18]. Using simulation, we evaluate the technical possibility of a solar water heating system and indicate system nodes to be modified and improved for Kazakhstan weather conditions.

In this paper, we investigate a solar hot water heating system in different Kazakhstan weather conditions. Previously, no studies have been devoted to simulating other Kazakhstan weather conditions. We focus on providing calculation parameters of a solar hot water heating system and the result of a simulation based on collected weather conditions. We consider a result of simulation to get knowledge about the effective heating system with parameters that will be effective in different regions.

The rest of the paper is organized as follows. In the next section, we describe the wavelet transformation, data analysis, and machine learning algorithms. The theoretical model is presented in Section 2. Energy analysis of a solar hot water heating system is presented in Section 3. The result of the simulation is presented in Section 4. Section 5 concludes the paper.

2 Theoretical Model

The solar system consists of several parts. To simplify the process of description and simulation, we describe each part of the system separately. Fig. 1 shows a solar hot water heating system with a heat exchanger coil in a storage tank below. The heat exchanger coil is installed inside the storage tank, and it allows heat water for consumption: heating and domestic hot water.

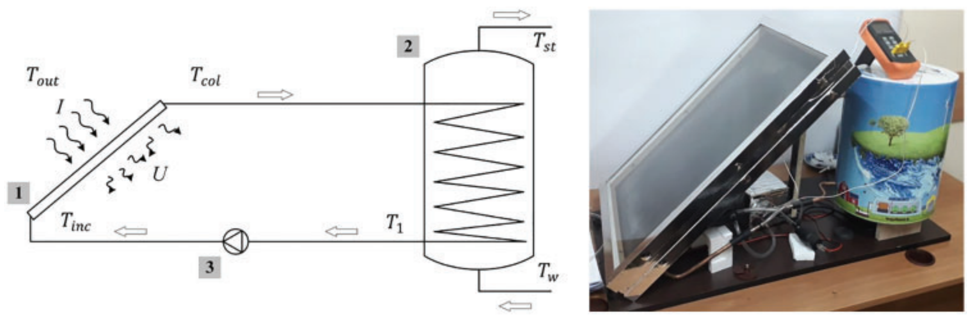

Figure 1: Schema of solar hot water heating system. Constructed solar hot water heating system. The solar hot water heating system. 1–flat solar collector; 2–storage tank with a heat exchanger; 3–pump

The central object of research is a flat solar collector, and we described a mathematical model of a flat solar collector separately Fig. 2 and energy analysis. The mathematical model of the collector is defined as a function: $T_{col} = f\left(T_{inc}, v_p, I, T_{out}, U\right)$, where T_{col}–temperature of outlet fluid from a collector, T_{inc}–temperature of inlet fluid into a collector, v_{col}–volumetric flow rate in collector cycle, I–solar irradiance, T_{out}–temperature of collector ambient, U–heat loss coefficient of a collector.

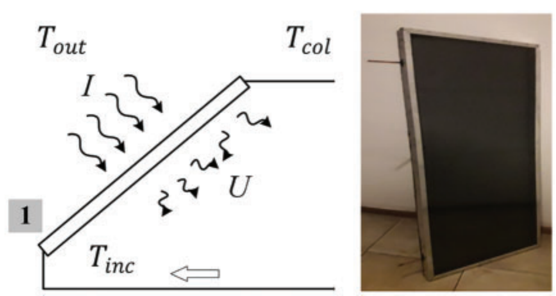

Figure 2: Schematic diagram of flat solar collector. Constructed flat solar collector. The solar hot water heating system

3 Energy Analysis

Based on solar energy absorbed by the plate of the collector, the heat loss coefficient of a collector, and heat absorbed by the fluid, the energy balance equation can be given by authors in the paper [19]:

$$\frac{dT_{col}(t)}{dt} = \frac{A\eta}{C} I(t) - \frac{UA}{C}\left(T_{avg}(t) - T_{out}(t)\right) + \frac{v_{col}}{V_{col}}\left(T_1(t) - T_{col}(t)\right), \tag{1}$$

where $C = \rho_{col} c_{col} V_{col}$–equation for calculation of overall heat capacity of the fluid, $T_{avg}(t) = \frac{T_1(t) + T_{col}(t)}{2}$–the average temperature of a fluid in a collector.

Input values of the flat solar collector are presented in Tab. 1. We used these parameters of the collector to analyze the heat loss coefficient.

Table 1: Input values of flat solar collector

Parameter	Value	Unit
Plate-to-cover spacing	30	mm
Plate emittance	0.95	
Wind heat transfer coefficient	10	W/m^2 C
Collector tilt	45	degree
Glass emittance	0.885	
Area	2	m^2

We used common loss factors for the solar collector; similar results were performed in [20]. We consider the flat solar collector for a system with a single glass coating. The analysis of the loss coefficient for the upper surface is carried out using the formula:

$$U_t = \left(\frac{1}{h_{c,p-c} + h_{r,p-c}} + \frac{1}{h_w + h_{r,c-a}} \right)^{-1}, \tag{2}$$

The convection coefficient between absorbed and glass coating $h_{c,p-c}$ was calculated using the parameters Nusselt, Rayleigh, and Prandtl. The heat transfer rate between two plates inclined at a certain angle to the horizon has an obvious significance in the operation of flat collectors. Convective heat transfer data are correlated in two or three dimensionless parameters: the Nusselt number Nu, the Rayleigh number Ra, and the Prandtl number Pr.

$$Nu = \frac{hL}{k}, \tag{3}$$

The dependence of the parameters Nu and Ra was calculated in [21].

$$Nu = 1 + 1.44 \left[1 - \frac{1708 (sin 1.8\beta)^{1.6}}{Racos\beta} \right] \left[1 - \frac{1708}{Racos\beta} \right]^{positive} + \left[\left(\frac{Racos\beta}{5830} \right)^{1/3} - 1 \right]^{positive}, \tag{4}$$

where positive exponent means that only positive values are used if the term is negative, then use zero.

$$Ra = \frac{g\beta' \Delta T L^3}{\nu\alpha}, \tag{5}$$

To calculate the thermal conductivity coefficient $h_{c,p-c}$ we use the Eq. (3):

$$h = Nu \frac{k}{L}, \tag{6}$$

The dependence of the temperature difference between the receiving surface and Ra, calculated by the Eq. (5). This formula can build a relationship between the number Ra and the temperature difference between the receiving surface and the absorbed Fig. 3. This graph noted that the *Ra* number is minimal with a significant difference between the surface, affecting the *Nu* numerical calculation.

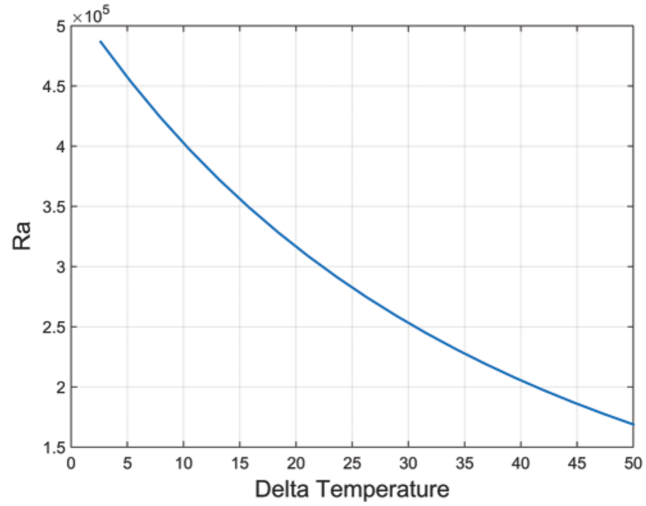

Figure 3: The dependence of the temperature difference and *Ra*

The correlation between *Ra* and *Nu* is calculated through the Eq. (4). Figs. 4 and 5 are plotted in a logarithmic format. The values of *Ra* were generated in the range of $5.96e + 03$–$2.44e + 05$ and for 5 different angles of inclination of the collector.

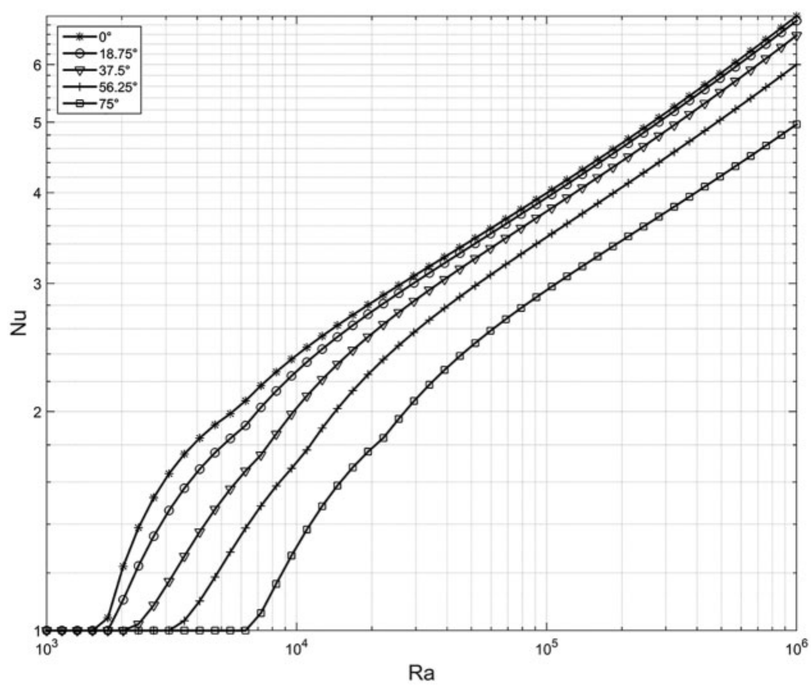

Figure 4: Dependence between *Ra* and *Nu*

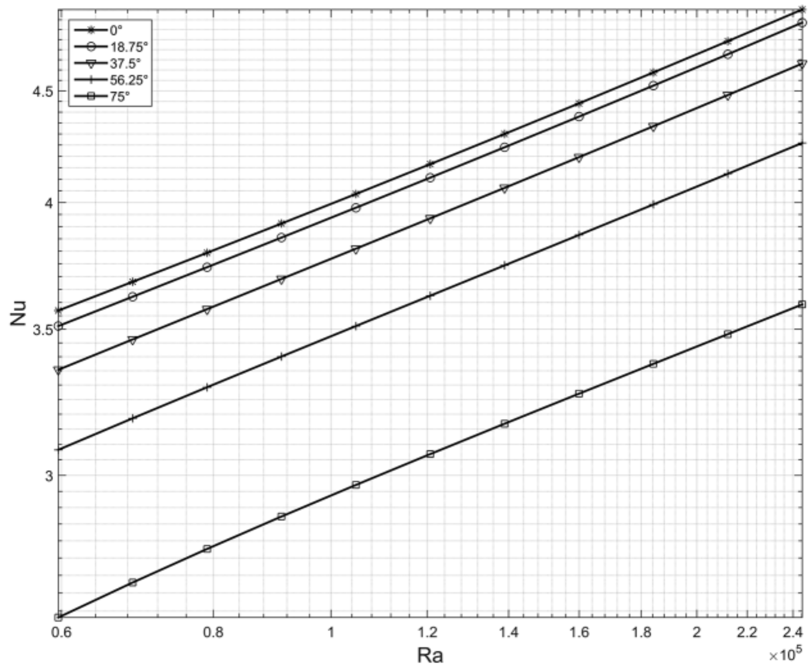

Figure 5: Dependence between *Ra* and *Nu* on a small scale

Fig. 6 shows the thermal conductivity *Nu* and heat transfer coefficient between absorbed and glass coating. The maximum *Nu* and thermal conductivity values gave a maximum value of a heat transfer coefficient; it needs to keep in mind during the design of a flat solar collector. Our main target is to gather maximum solar irradiance and heat water as quickly as possible.

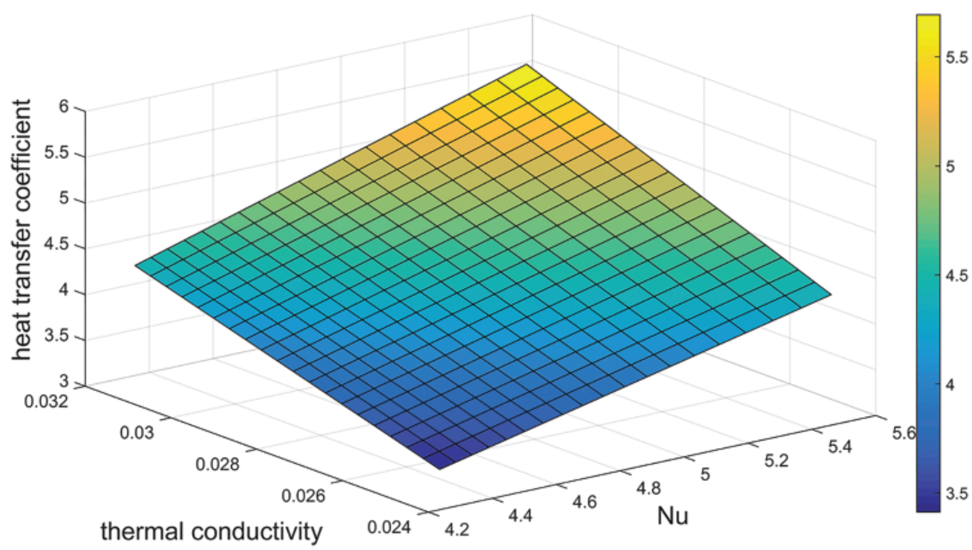

Figure 6: Dependence between the thermal conductivity, *Nu* and heat transfer coefficient

After the thermal conductivity coefficient has been calculated, it is necessary to calculate the radiation coefficient from the glass coating to the absorber.

$$h_{r,p-c} = \frac{\sigma\left(T_p^2 + T_c^2\right)\left(T_p - T_c\right)}{\frac{1}{\varepsilon_p} + \frac{1}{\varepsilon_c} - 1}, \tag{7}$$

The calculation of the radiation coefficient between the glass surface and the air is calculated by the equation:

$$h_{r,c-a} = \varepsilon_c \sigma\left(T_c^2 + T_a^2\right)\left(T_c + T_a\right), \tag{8}$$

The calculation of the temperature of the glass surface is calculated through the equation:

$$T_c = T_p - \frac{U_t\left(T_p - T_a\right)}{h_{r,p-c} + h_{r,c-a}}, \tag{9}$$

The process of calculating the loss coefficient for the top surface is iterative and depends on the temperature of the glass surface, Fig. 7 shows the flow-chart of this calculation.

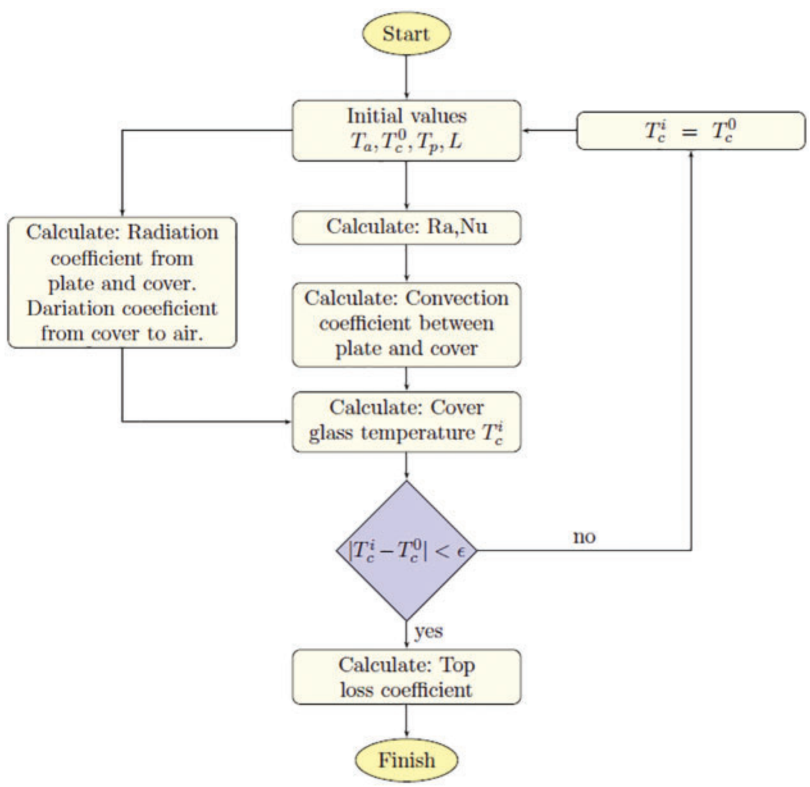

Figure 7: The flow-chart of calculation a maximum loss coefficient

During calculation, we get the following result for the maximum loss coefficient in Tab. 2.

The calculation results are the maximum loss coefficient from the collector plate to the ambient W/m^2C and equal to 7.528. On the basis of Eq. (2) we have got the range of loss coefficient for the

Table 2: Result of calculation of the maximum loss coefficient

Initial	Value	Calculated	Value
Ambient temperature, °C	40	Ra	5.28e + 05
Cover temperature, °C	50	Nu	5.4279
Plate temperature, °C	100	Convection coefficient between the plate and the cover, W/m^2C	4.8829
Space between cover and plate, m	0.03	Radiation coefficient from the plate to the cover, W/m^2C.	8.6584
		Radiation coefficient for the cover to the air, W/m^2C.	6.9555
		Cover glass temperature, °C	66.6

upper surface (one surface of the glass), it was calculated for different ambient temperature indicators [40; 20; −10], plate temperature has the range from 0°C to 200°C with h_ω wind heat transfer coefficient of 10 W/m^2C. In Fig. 8, we got a dependence between the average temperature of the plate and the maximum loss coefficient. The temperature and loss coefficient increased almost linearly except from 0°C to 60°C. Our calculated coefficient is 7.528; on the figure, this value is equivalent to the average temperature of the plate, about 120°C. This fact can be possible in the summertime.

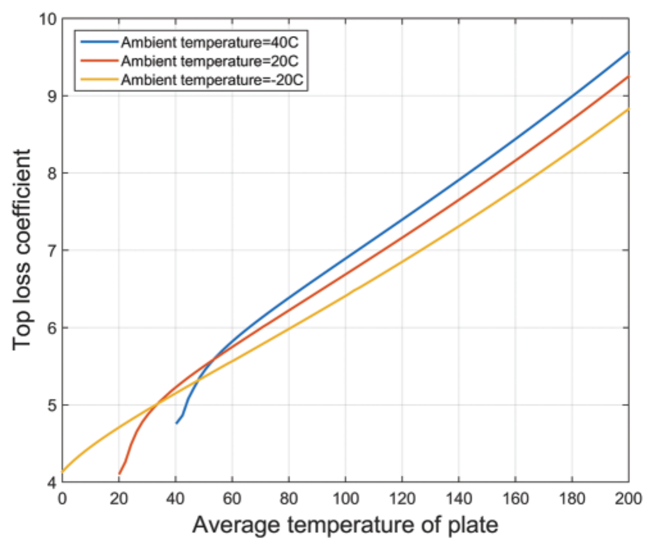

Figure 8: Dependence between the average temperature of plate and top loss coefficient

The calculation of the loss coefficient for the lower surface of the collector is calculated using the formula:

$$U_b = \frac{k}{L}, \tag{10}$$

where k is the heat conductivity of the insulating material (material–0.04 W/ (mK). L is the thickness of the insulating material. The heat loss coefficient for the lateral boundaries generally has small values and often is not calculated for the total heat loss coefficient. If it is necessary to calculate the exact heat loss values, the calculation will be performed using the formula [22].

$$U_b = \frac{(UA)_{edge}}{A}, \tag{11}$$

where U is calculated using Eq. (11), but for lateral isolation. Collector thickness: 0.1 m; insulation thickness: 0.01 m. The total loss coefficient will be calculated by summing all the coefficients.

$$U = U_t + U_b + U_e, \tag{12}$$

4 Result of Simulation and Discussion

In the simulation performed by Matlab/Simulink, the model was taken from research [23]. The Matlab codes for of simulation a solar hot heating water system can be found at https://github.com/TimurMZh/Simulation-of-solar-flat-collector. The created model has been simulated a full solar hot heating water system: flat collector, storage tank, and pumps. Based on the mathematical model of the flat solar collector Eq. (1), a block schema has been developed by Simulink; the block schema of the collector model is shown in Fig. 9. The simulation result is the temperature of outlet fluid from the collector.

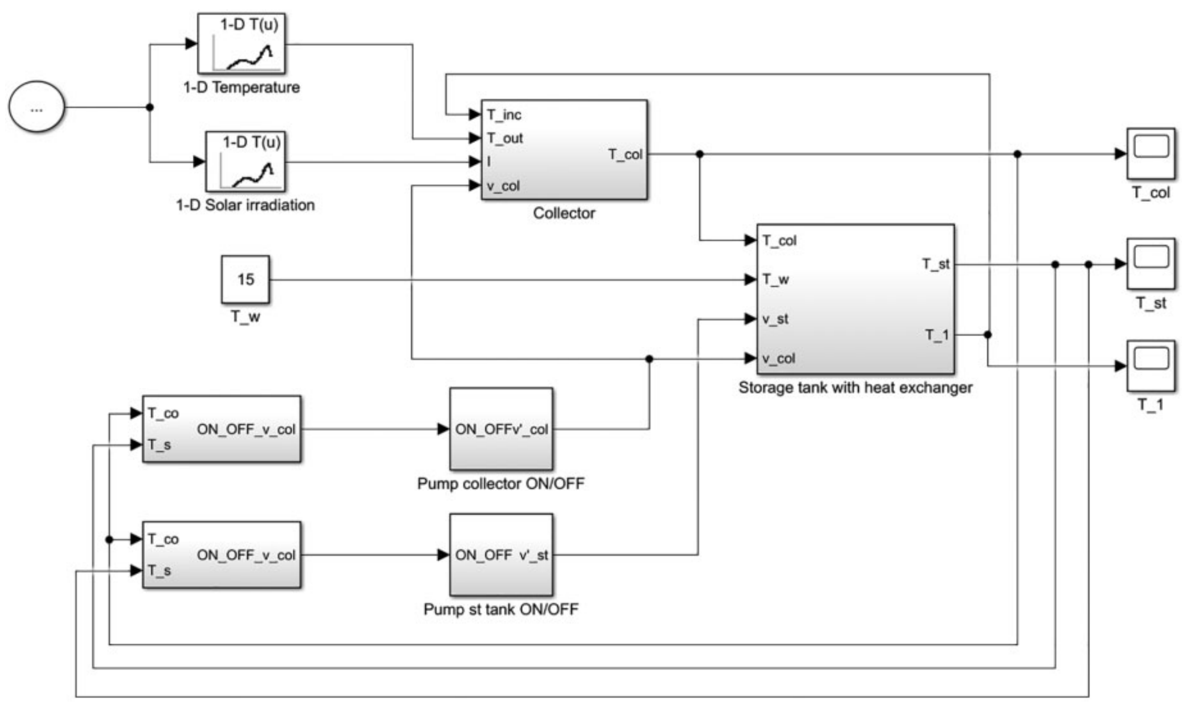

Figure 9: General block schema of the solar hot water heating system

We collected data for one year. The solar hot water heating system was installed in the Almaty city, in the foothills of Alatau; the height above the mean sea level 1088 meters. Input data: solar irradiance and ambient temperature. The result of the simulation is displayed in Fig. 10. Based on the figure, we can note that the solar hot water heating system will not provide an acceptable temperature in the flat collector and storage tank from December to March. The best result (high temperature) of the system will be provided from June to the middle of October. Fig. 10 shows a high correlation between solar irradiance and the collector and storage tank temperatures. Suppose the density of solar radiation is higher. In that case, the temperature is more monotonous, and the standard deviation of the temperature in the storage is close to the average value, for example, from July to August. The working process of the pump in the collector cycle depends on the reached temperature in the collector cycle, and we used the same limit values for activation of the pump as in research [18]. Fig. 10 showed that the pump turned to operate regularly in the summertime to transfer reached temperature from the collector into a storage tank. In wintertime, the pump does not work.

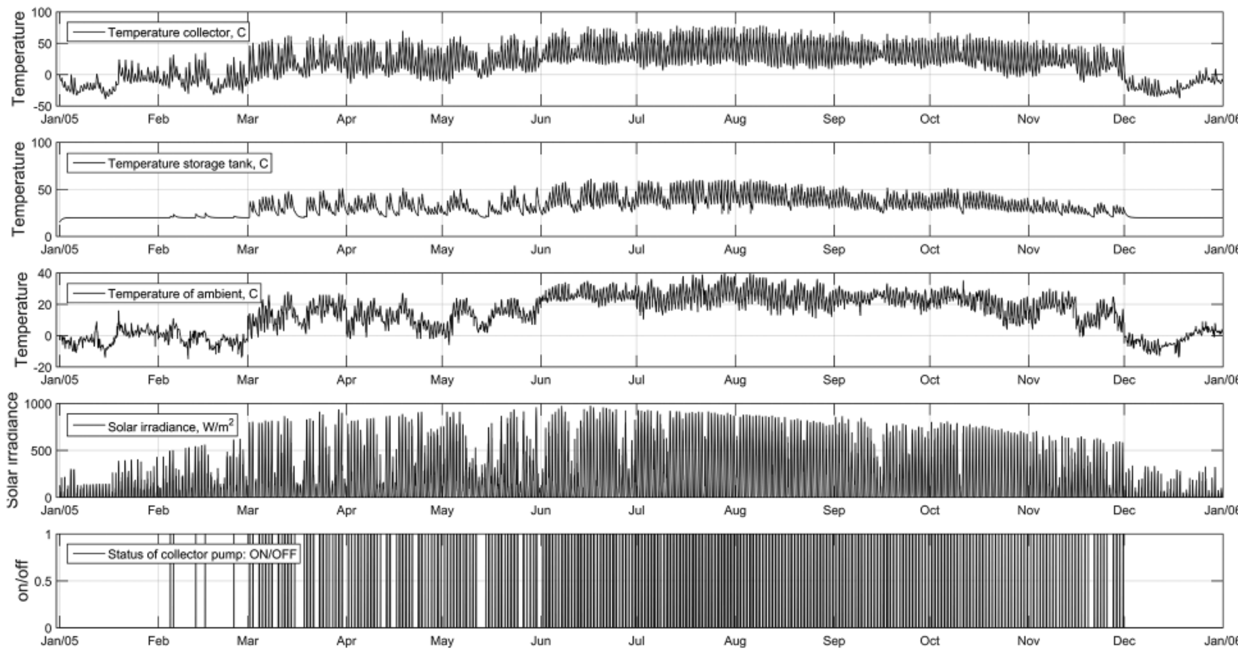

Figure 10: The result of simulation for one year

We scaled simulated data to 3 days (1st July–3rd July) to analyze simulated results in detail. The simulation result showed the maximum temperature of water in the storage tank 56.9°C in the Almaty region and in the collector is 60.5°C, the result presented in Figs. 11 and 12. As previously mentioned, a pump worked when the temperature in the collected reached a high temperature; it was reached in the daytime, and in the evening and night, a pump did not work. Also, we noted that the temperature in storage at night decreased monotonously without solar irradiation. Therefore, in Kazakhstan's north region, we recommended insulating the storage tank or locating it in a building. The problem of saving heating in a storage tank is still open for the north of Kazakhstan, and we would like to consider it in another paper.

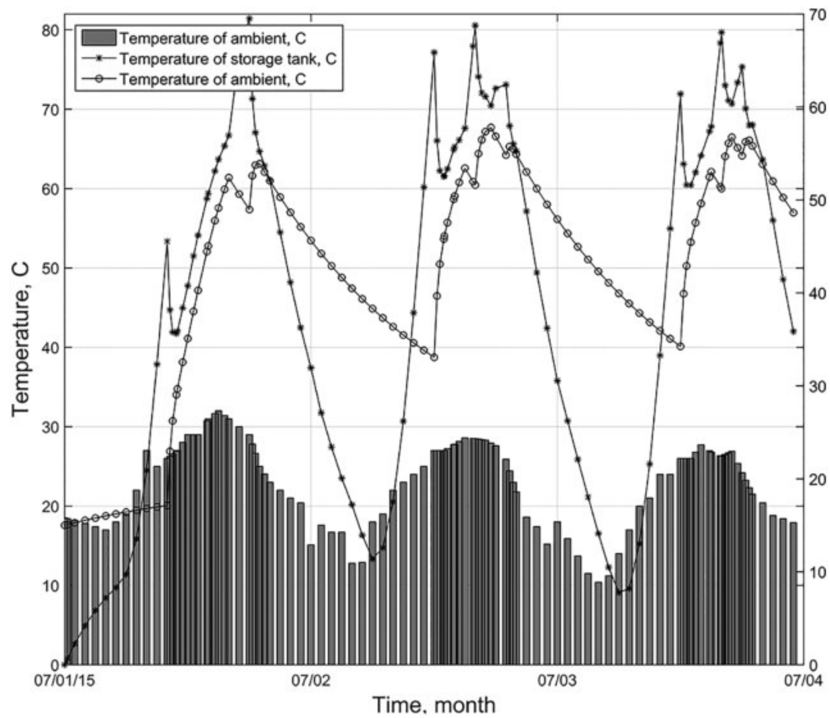

Figure 11: Ambient temperature, the temperature in collector and storage tank

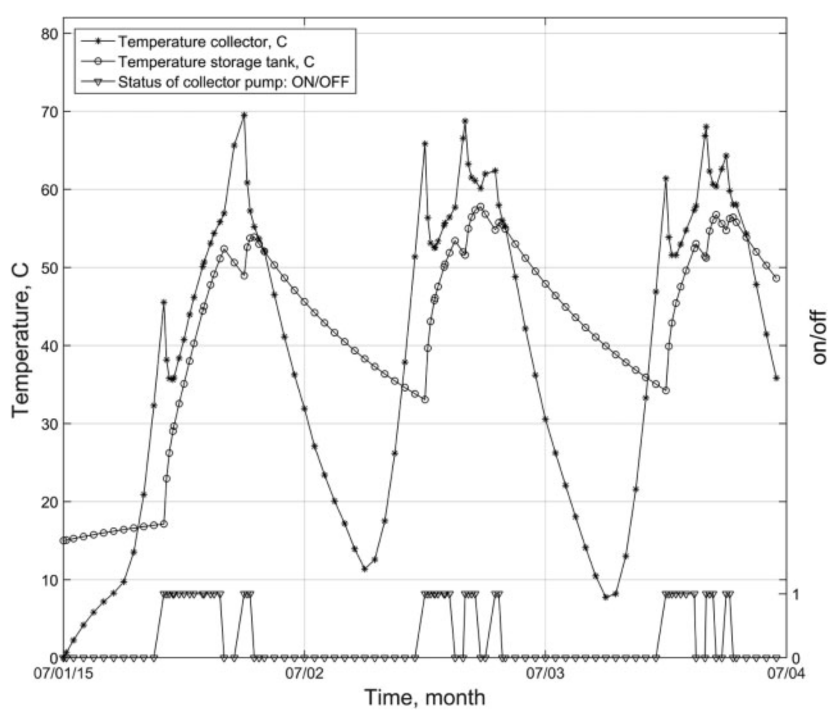

Figure 12: Temperature in collector and storage tank with pump operational mode

5 Conclusion

Before performing a water heating simulation, it is necessary to analyze the technical characteristics of the flat solar collector, such as the heat loss of the collector. This analysis takes more time but allows simulating more accurate results. After the calculated values, we can proceed to energy analysis. The main purpose of the simulation model is to determine the installation limit values and identify weak installation points for improvement. The developed simulation model makes it possible to simulate the operation of a solar hot water heating system in various climatic conditions (temperature and solar radiation) and different individual system parameters to increase the system efficiency in various climatic conditions of Kazakhstan.

The simulation result showed that during the daytime, the temperature of water in the collector is 70°C, and during that period, it can be used at home. The main problem is heated water storage since the heated water is cooled at night. Another task we can define from the simulation analysis is to find a way to extend the work period of the system with high efficiency (April–October); it will be engineering, technical, or programming of controller solutions. This point needs to investigate and improved.

The next stage of the research will be the numerical simulation of the reservoir design. It is necessary to determine the design with high and low efficiency. We will determine the optimal system parameters for different climatic conditions using machine learning algorithms to adjust the parameters. We will conduct an experiment and a comparative analysis of simulated and experimental data.

The figure displays the collector, storage tank, and pump operation mode temperatures. We can see a correlation between ambient temperature and heating water temperature when the temperature in the collector reaches 40°C. The pump switches and starts to transfer a heated fluid to the exchanger coil inside the storage tank and receives the cooled fluid in the collector cycle for heating. The second reason for cooling fluid in the cycle is weather conditions (decrease in ambient temperature, sunset).

In our future research, we intend to concentrate on machine learning and deep learning algorithm to forecast the efficiency of a solar hot water system. Another research perspective is to apply Neural ODE (normalizing flow) for computational fluid dynamics (CFD) analysis of solar hot water heaters.

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Conflicts of Interest: The authors declare that they have no conflicts of interest to report regarding the present study.

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