

Thermal loss analysis of a solar flat collector using numerical simulation

Ye. Amirgaliyev^{a,b}, T. Merembayev^{a,c}, M. Kunelbayev^a and A. Berdyshev^a

^aLaboratory of artificial intelligence and robotics, Institute of Information and Computational Technologies CS MES RK, Almaty, Kazakhstan; ^bDepartment of Computer Science, Al-Farabi Kazakh National University, Almaty, Kazakhstan; ^cDepartment of Computer Engineering and Telecommunication, International Information Technology University, Almaty, Kazakhstan

ARTICLE HISTORY

Compiled April 21, 2020

ABSTRACT

In this paper, we studied theoretically and numerically heat losses of a flat solar collector for the subsequent modelling of 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 solar system is simulated by the mathematical model (ODE model) of energy. To bridge the results of modelling and real values, our research investigated the important physical parameters such as loss coefficient, Nu, Ra, Pr values, which are impacting on the efficiency of solar flat collector and for heat losses of system. The developed mathematical models, the design and composition of the software and hardware complex, automated control and monitoring systems allow solar hot water heating system to increase the energy efficiency of a life support systems and heat supply of buildings, by reducing energy consumption for heat supply.

KEYWORDS

Solar heating system; Heat loss coefficient; Dynamic simulation; Solar flat collector; ODE

1. Introduction

Each year renewable energy become an important role in our daily lives. Using renewable energy can reduce the consumption of energy and decrease our dependence on fossil energy. The most explicit way to using renewable energy is solar energy that allows getting clean energy without pollution. In the world, there are researches concerning models, designs, and comparison of solar heating systems for domestic buildings.

One of the researches is devoted to estimating solar hot water heating and analysis data in South Korea for 3 years (Yoo, 2015). There was a work for installing a solar water heating system for multi-family housing with 1179 families in 14 units. Results of the research showed that comparing with conventional boiler for heating water (efficiency=85%) solar hot water heating system showed a positive environmental effect and estimated like reducing 71.9 L/year of oil and reduction of 186.3 ton CO₂.

Identical research was done in the article (Chow et al., 2006), The numerical research of a centralized solar hot water heating system was developed for a high-rise residential building in Hong Kong.

Another type of research concerning a solar hot water heating system was described in the article (Badescu, 2005). There was a simulation of the solar system with the flat collector, storage tank and circulation. It was analyzed two design of hot circulation: water – water and water – air. The result of research showed that the design water – air does not effective. In research (Siddiqui & Said, 2015) there is a review of articles in the area of solar energy absorption by a solar system with different types of fluid. The main focus of the research is 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 most common working fluids had been reviewed and using a ternary mixture in solar absorption systems. Author Soteris A. Kalogirou (Kalogirou, 2004) made a calculation of optical, thermal and thermodynamic analysis of solar collector, describe methods that were used for estimation of efficiency.

In the research (Maldonado et al., 2014) there was a research of construction and efficiency of solar hot water heating system. Geometry and dimension of a solar system were defined on the based of the result of the materials thermal properties. Authors (Nogueira et al., 1991) showed a software developed in Matlab and own algorithms for calibration of small a solar hot water heating system.

Thermal performance can be calculated based on the first law of thermodynamics (energy) but that does not allow estimating losses of a solar flat collector (Farahat et al., 2004). The second law of thermodynamics (exergy) is used to estimation of the various losses in the solar flat collector and allow to estimate the efficiency of a solar hot water heating system (Luminosu & Fara, 2005; Park et al., 2014).

Now in Kazakhstan, it is big attention for developing a solar hot water heating system, the price of system is expensive therefore it is not available for all costumers. To solve the issue it is to develop a new hybrid energy system with mathematical methods and computer simulation, software's and hardware's. One of the ways to the efficiency of using energy is to use a new source of energy (renewable and environmentally friendly) in the fuel and energy system of Kazakhstan. So 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 solar energy potential, in the article (Amirgaliyev et al., 2018; Amirgaliyev, Kunelbayev, Merembayev, Daulbayev Irzhanova, 2019) based on actual observations and theoretical calculations generalizing there are the most favourable period and region to use the solar energy in Almaty region. In this article solar collector with storage tank, heat exchanger and pump stations for hot water have been considered. Simulation has been performed for different temperature conditions and solar irradiance for Almaty region. Simulation is done in Matlab and Simulink, the tool is often used for simulation different processes and in particular for simulation solar hot water heating system (Morini & Piva, 2007; Morini & Piva, 2008; Amirgaliyev, Merembayev & Kunelbayev, 2018). The simulation can allow to evaluate a technical possibility of solar water heating system and indicate system nodes which to be modified and improved for Kazakhstan weather condition.

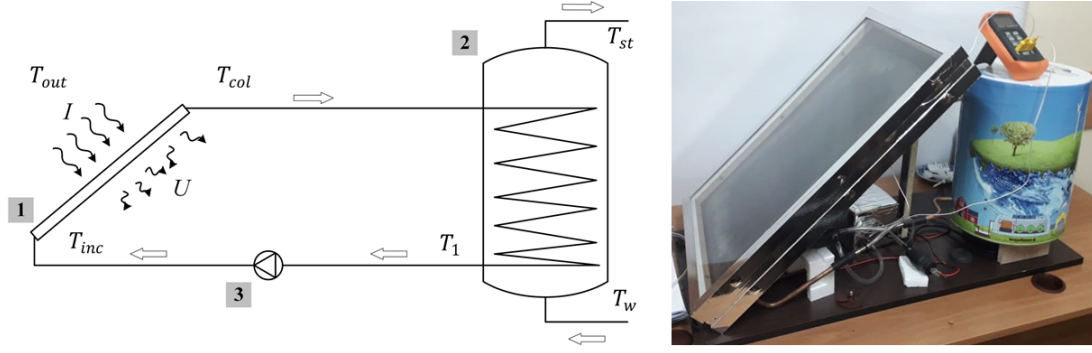


Figure 1. Schema of solar hot water heating system. Constructed solar hot water heating system. The solar hot water heating system. 1 – solar flat collector; 2 – storage tank with a heat exchanger; 3 – pump.

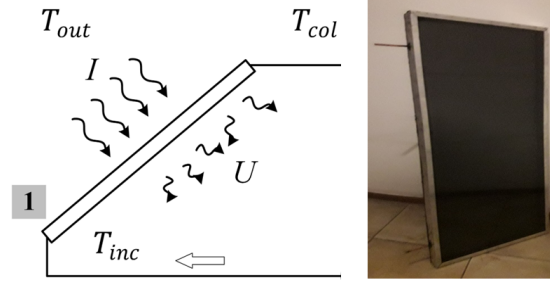


Figure 2. Schematic diagram of solar flat collector. Constructed solar flat collector. The solar hot water heating system.

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. Figure 1 showed below a solar hot water heating system with a heat exchanger coil in a storage tank. The heat exchanger coil is installed inside the storage tank and it allows to heat water for consumption: heating and domestic hot water.

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

3. Energy analysis

Based on solar energy absorbed by the plate of collector, heat loss coefficient of a collector and heat absorbed by the fluid the energy balance equation can be given by (Wengang et al., 2018):

Table 1. Input values of solar flat collector.

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

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

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

Input values of solar flat collector are described in Table 1. We used these parameters of the collector to make analysis of heat loss coefficient.

To simplify the calculation of differential equations for calculating the heat loss, it was proposed to use common loss factors for the solar collector, similar calculations were performed in (Jafarkazemi & Ahmadifard, 2013). We consider the solar flat collector for a system with a single glass coating. The calculation of the loss coefficient for the upper surface is carried out using the formula:

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

The convection coefficient between absorbed and glass coating $h_{c,p-c}$ is 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 usually correlated in terms of two or three dimensionless parameters: the Nusselt number Nu, the Rayleigh number Ra, and the Prandtl number Pr.

$$Nu = \frac{hL}{k} \quad (3)$$

The dependence of the parameters Nu and Ra was calculated in (Hollands et al., 1993).

$$Nu = 1 + 1.44 \left[1 - \frac{1708(\sin 1.8\beta)^{1.6}}{Rac\cos\beta} \right] \left[1 - \frac{1708}{Rac\cos\beta} \right]^+ + \left[\left(\frac{Rac\cos\beta}{5830} \right)^{1/3} - 1 \right]^+ \quad (4)$$

$$Ra = \frac{g\beta'\Delta TL^3}{v\alpha} \quad (5)$$

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

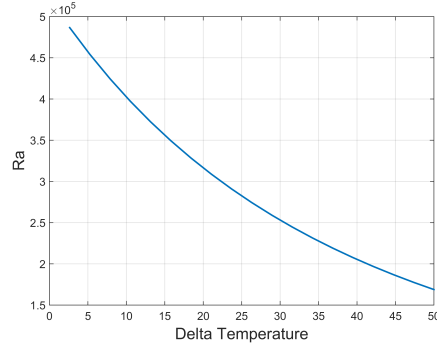


Figure 3. The dependence of the temperature difference and Ra.

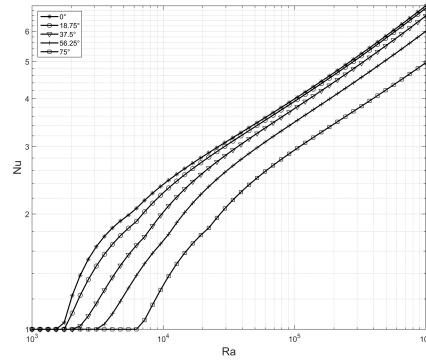


Figure 4. Dependence between Ra and Nu.

$$h = Nu \frac{k}{L} \quad (6)$$

The dependence of the temperature difference between the receiving surface and Ra, calculated by the formula (5). From this formula, we can build a relationship between the number Ra and the temperature difference between the receiving surface and absorbed Figure 3. From this graph, it can be noted that with a large difference between the surface, the Ra number is minimal, which affects the calculation of the Nu number.

The correlation between Ra and Nu are calculated through the formula (4). The Figure 4 is displayed 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.

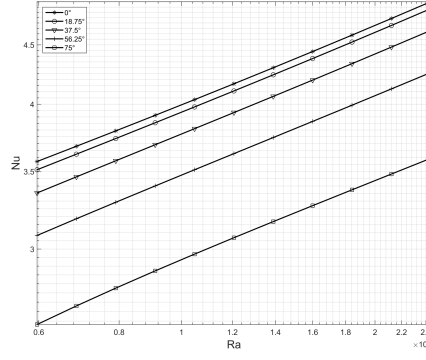


Figure 5. Dependence between Ra and Nu in small scale

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

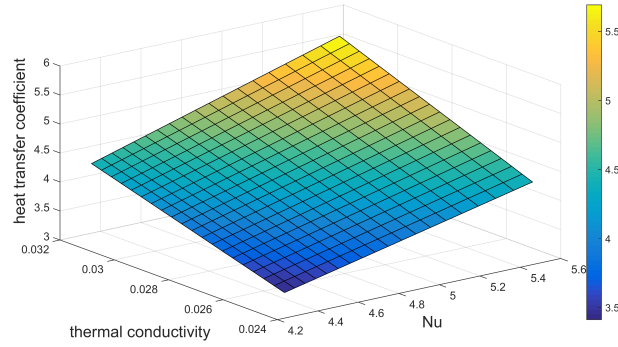


Figure 6. Dependence between the thermal conductivity, Nu and heat transfer coefficient.

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

$$h_{r,p-c} = \frac{\sigma(T_p^2 + T_c^2)(T_p - T_c)}{\frac{1}{\epsilon_p} + \frac{1}{\epsilon_c} - 1} \quad (7)$$

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

$$h_{r,c-a} = \epsilon_c \sigma (T_c^2 + T_a^2)(T_c + T_a) \quad (8)$$

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

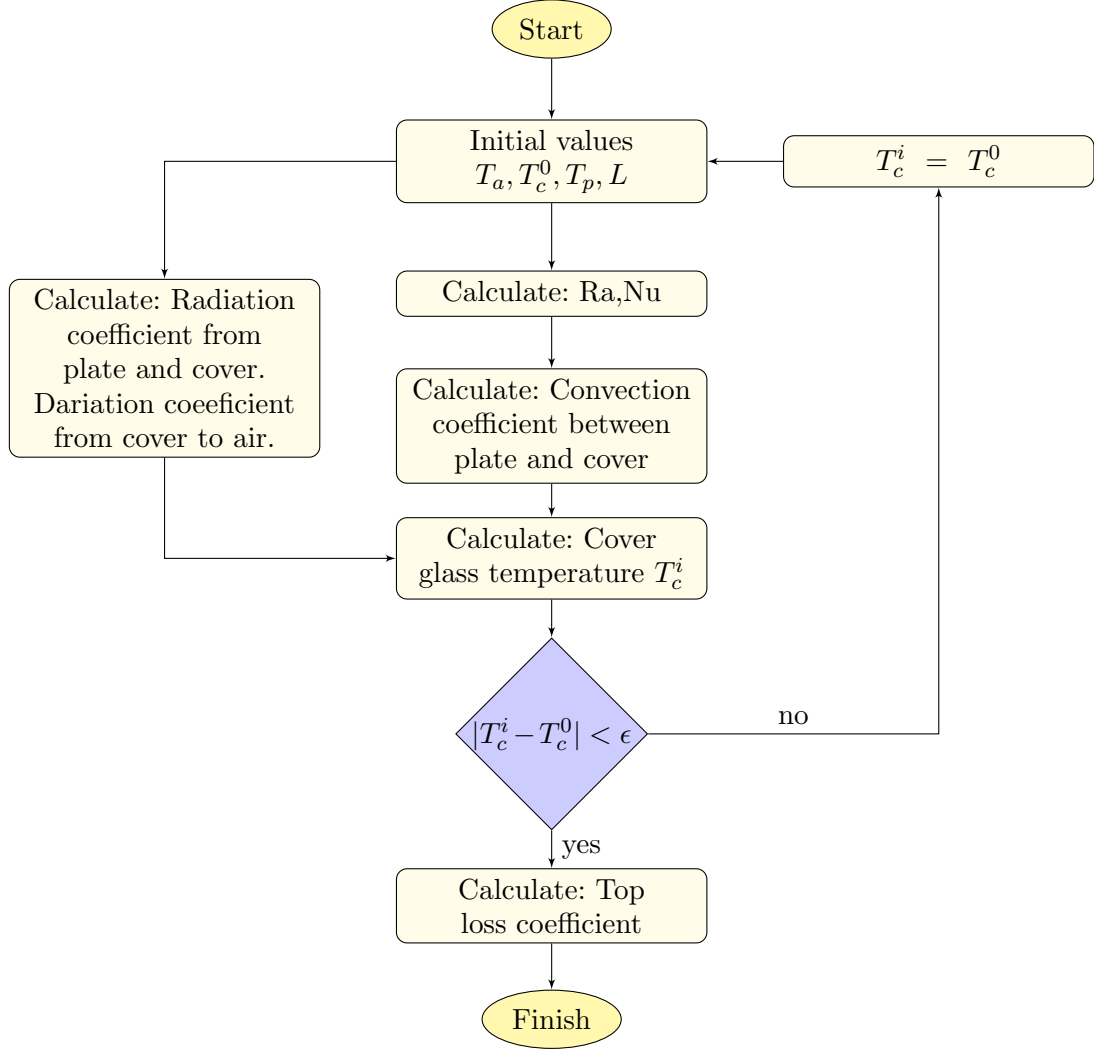


Figure 7. The flow-chart of calculation a top loss coefficient.

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

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

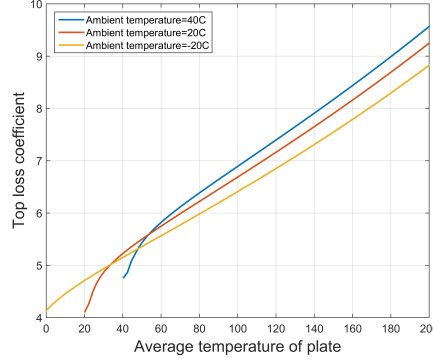
During calculation, we get the following result for the top loss coefficient in Table 2.

Result of calculation is the top loss coefficient from the collector plate to the ambient, W/m^2C and equal to 7.528.

On the basis of formula (2) we have got the range of loss coefficient for the upper surface (one surface of glass), it was calculated for different ambient temperature indicators [40; 20; -10], plate temperature has the range from 0 to 200 °C with h_w wind heat transfer coefficient of 10 W/m^2C . In Figure 8 we got a dependence between the average temperature of plate and top loss coefficient. We can notice that a temperature

Table 2. Result of calculation the top 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, $W/m^2\text{ }^\circ C$	4.8829
Space between cover and plate, m	0.03	Radiation coefficient from the plate to the cover, $W/m^2\text{ }^\circ C$	8.6584
		Radiation coefficient for the cover to the air, $W/m^2\text{ }^\circ C$	6.9555
		Cover glass temperature, °C	66.6

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

and loss coefficient increases almost linearly except from 0 to 60 °C. Our calculated coefficient is 7.528, on the figure this value is equivalent to the average temperature of plate about 120 °C. This fact can be possible in the summertime.

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

$$U_b = \frac{k}{L} \quad (10)$$

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 are not calculated for the total heat loss coefficient. If it is necessary to calculate the exact values of heat loss, the calculation will be performed using the formula (Tabor, 1958).

$$U_e = \frac{(UA)_{edge}}{A} \quad (11)$$

Where U is calculated using formula (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.

$$U = U_t + U_b + U_e \quad (12)$$

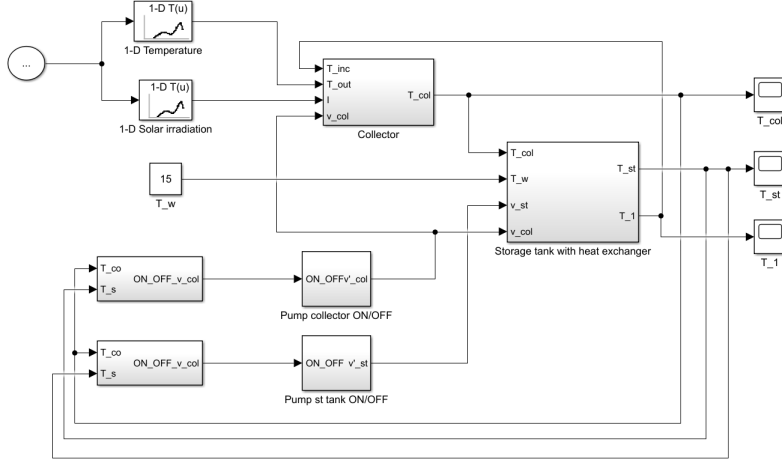


Figure 9. General block schema of the solar hot water heating system.

4. Result of simulation and discussion

MatLab/Simulink has done a simulation of the model and used model was taken from research (Amirgaliyev et al., 2018). The created model has been simulated full solar hot heating water system: flat collector, storage tank and pumps. Based on the mathematical model of the solar flat collector formula (1) a block schema has been developed by Simulink, block schema of the collector model is showed in Figure 9. The result of the simulation is a temperature of outlet fluid from the collector.

We selected data for one year and for Almaty region. Input data: solar irradiance and ambient temperature. The result of the simulation is displayed in Figure 10. Based on the figure we can note that for the region the solar hot water heating system will not provide acceptable temperature in flat collector and storage tank, the period from December to March. The best result (high temperature) of the system will be provided from June to the middle of October. Figure 10 shows a high correlation between solar irradiance and temperatures in the collector and storage tank. If the density of solar radiation is higher, then 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 reached temperature in the collector cycle, we used same a limit values for activation the pump like in research (Amirgaliyev et al., 2018). Figure 10 showed that pump turned to operate regularly in summertime to transfer reached temperature from the collector into storage tank. In wintertime, the pump does not evidently work.

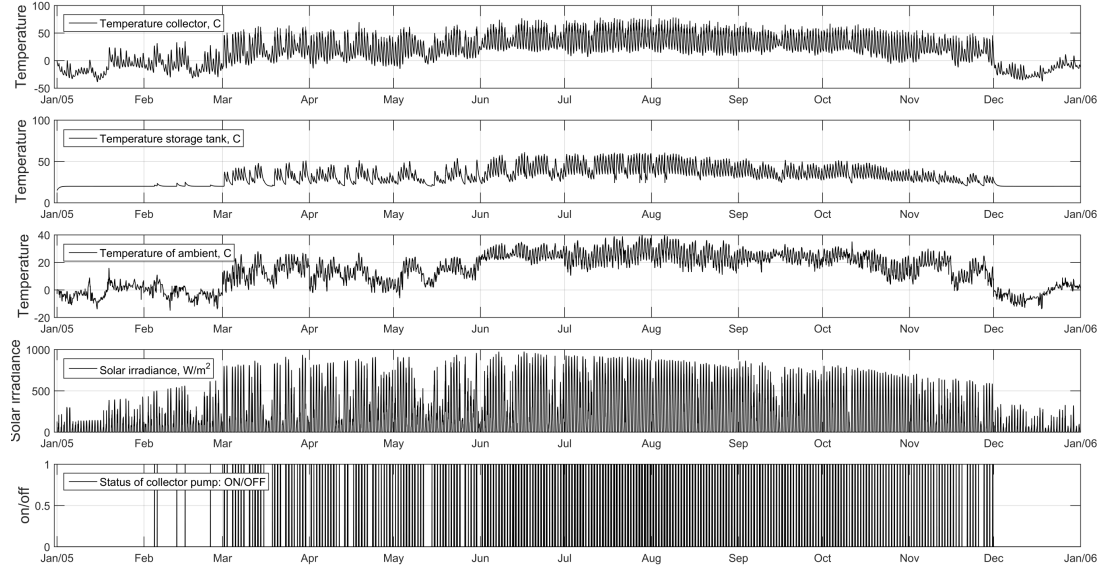


Figure 10. The result of simulation for one year.

To analyze simulated results in detail we scaled simulated data to 3 days (1st July – 3rd July). The result of simulation showed the maximum temperature of water in storage tank 56.9 °C in Almaty region and in collector is 60.5 °C (Figure 11 and 12). In figure temperatures in the collector, storage tank and pump operation mode are displayed. We can see a correlation between ambient temperature and heating water temperature. When temperature in collector reaches 40 °C then 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 the cooling of fluid in the cycle is due to weather conditions (decrease in ambient temperature, sunset).

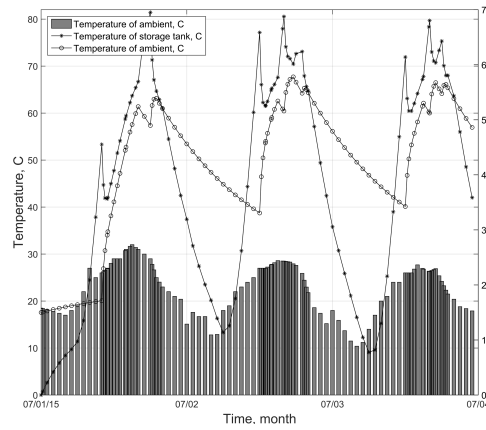


Figure 11. Ambient temperature, temperature in collector and storage tank.

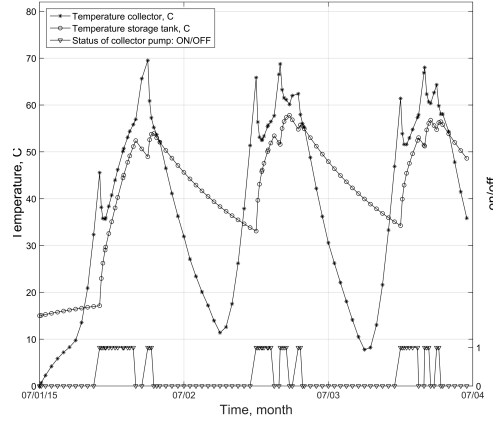


Figure 12. Temperature in collector and storage tank with pump operational mode.

5. Conclusion

Before performing a water heating simulation, it is necessary to analyze the technical characteristics of the solar flat collector, such as the heat loss of the collector. This analysis takes more time but allows simulating results that are more accurate. 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 various individual system parameters to increase the system efficiency in various climatic conditions of Kazakhstan. The result of the simulation showed that during the daytime, the temperature of the water in the collector is 70 °C and during this period, it can be used at home. The main problem is the storage of heated water since at night the heated water is cooled. Another task we can define from analysis of the simulation is to find a way to extend a work period of the system with high efficiency (April – October), maybe it will be engineering, technical or programming of controller solutions. This point needs to investigate and improve. 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 the machine learning algorithms to adjust the parameters. We will conduct an experiment and a comparative analysis of simulated and experimental data.

6. Acknowledgement

This work is supported by the program – targeted funding from the Ministry of Education and Science of the Republic of Kazakhstan within the framework of the Project BR05236693 "Mathematical and computer models, hardware and software tools and experimental development on creation of network combined effective dual-circuit solar collectors with thermosiphon circulation and monitoring of their functioning".

Nomenclature

α	Thermal diffusivity (m^2/s);
β'	Volume expansion coefficient;
δT	Temperature difference between the boards;
ϵ_c	Absorbent emission (0.88);
ϵ_p	Glass emission (0.95);
η	Efficiency (percentage);
ρ_{col}	Density of fluid in collector (kg/m^3);
σ	Stefan - Boltzmann constant ($5.670367 \times 10^{-5} Wm^2K^{-4}$);
c_{col}	Specific heat capacity in a collector cycle (J/kgK);
g	Gravitational constant ($g=9.81 m/s^2$);
h	Heat transfer coefficient (W/m^2K);
$h_{c,p-c}$	Thermal conductivity coefficient (W/m^2C);
$h_{r,c-a}$	Radiation coefficient between the glass surface and the air (W/m^2C);
$h_{r,p-c}$	Radiation coefficient from the glass coating to the absorber (W/m^2C);
h_w	Wind heat transfer coefficient (W/m^2C);
I	Solar irradiance (W/m^2);
k	Heat conductivity of the insulating material (W/m^2K);
L	Distance between the absorbent and the glass;
Nu	Nusselt number;
Pr	Prandtl number;
T_1	Temperature of output fluid from a heat exchanger ($^{\circ}C$);
T_c	Glass surface temperature ($^{\circ}C$);
T_p	Absorbent temperature ($^{\circ}C$);
T_{col}	Temperature of outlet fluid from collector ($^{\circ}C$);
T_{inc}	Temperature of inlet fluid into collector ($^{\circ}C$);
T_{out}	Temperature of collector ambient ($^{\circ}C$);
U	Heat loss coefficient of collector (W/m^2C);
ν	Kinematic viscosity (m^2/s);
V_{col}	Volume of fluid in a collector cycle (m^3);
v_{col}	Volumetric flow rate in collector cycle (m^3/s);
A	Area (m^2);

References

- Yoo, Jung-Hyun. (2015). Evaluation of solar hot water heating system applications to high-rise multi-family housing complex based on three years of system operation. *Energy and buildings*, 101, 54–63.
- Chow, TT and Fong, KF and Chan, ALS, & Lin, Z (2006). Potential application of a centralized solar water-heating system for a high-rise residential building in Hong Kong. *Applied Energy*, 83(1), 42–54.
- Badescu, V. (2005). Simulation analysis for the active solar heating system of a passive house. *Applied Thermal Engineering*, 25(17–18) 2754–2763.
- Siddiqui, MU, & Said, SAM (2015). A review of solar powered absorption systems. *Renewable and Sustainable Energy Reviews*, 42, 93–115.
- Kalogirou, Soteris A. (2004). Solar thermal collectors and applications. *Progress in energy and combustion science*, 30(3). 231–295.
- Maldonadoa RD., Huertab E., Coronab JE, Cehb O, León AI. & Henandez I. (2014). Design and construction of a solar flat collector for social housing in México. *Energy Procedia*, 57. 2159–2166.
- Nogueira, C., Vidotto, M., Toniazzi, F. & Debastiani, G. (2016). Software for designing solar water heating systems. *Renewable and Sustainable Energy Reviews*, 58, 361–375.
- Farahat, S., Sarhaddi, F., Ajam, H. (2004). Exergetic optimization of flat plate solar collectors. *Renewable energy*, 34(4), 1169–1174.
- Luminosu, I., & Fara, L. (2005). Determination of the optimal operation mode of a flat solar collector by exergetic analysis and numerical simulation. *Energy*, 30(5), 731–747.
- Park, SR., Pandey, AK., Tyagi, VV. & Tyagi, SK. (2014). Energy and exergy analysis of typical renewable energy systems. *Renewable and Sustainable Energy Reviews*, 30, 105–123.
- Amirgaliyev, Ye., Kunelbayev, M., Wójcik, W., Kalizhanova, A., Auelbekov, O., Kataev, N., Kozbakova, A. & Irzhanova (2018). Solar-driven resources of the Republic of Kazakhstan. *News of the national academy of sciences of the Republic of Kazakhstan-series of geology and technical sciences*, 4, 18–27.
- Morini, GL. & Piva, Stefano (2007). The simulation of transients in thermal plant. Part I: Mathematical model. *Applied Thermal Engineering*, 27(11-12), 2138–2144.
- Morini, GL. & Piva, Stefano (2008). The simulation of transients in thermal plant. Part II: Applications. *Applied Thermal Engineering*, 28(2-3), 244–251.
- Yedilkhan, Amirgaliyev, Merembayev, Timur & Kunelbayev, Murat(2008). Dynamic Simulation of a Solar Hot Water Heating System for Kazakhstan Climate Conditions. *2018 14th International Conference on Electronics Computer and Computation (ICECCO)*, 206–212.
- Wengang, Yifeng, Yanhua, Hongwen & Mingxin (2018). Research on operation strategy and performance prediction of flat plate solar collector with dual-function for drying agricultural products. *Renewable Energy*, 127, 685–696.
- Hollands, KGT., Unny, TE., Raithby, GD. & Konicek, L. (1976). Free convective heat transfer across inclined air layers.
- Jafarkazemi & Ahmadifard (2013). Energetic and exergetic evaluation of flat plate solar collectors. *Renewable Energy*, 56, 55–63.
- Tabor, H. (1958). Radiation, convection and conduction coefficients in solar collectors, *CBull. Res. Counc. Isr., Sect. C* 6(3).
- Amirgaliyev, Y.N., Kunelbayev, M., Merembayev, T., Daulbayev, S., Irzhanova, A. (2019). The graphic analytical method of flat solar collector energetic and optical characteristics. *International Journal of Mechanical and Production Engineering Research and Development*, 9(3), 1749–1760.