COMPARATIVE ANALYSIS OF A FLAT SOLAR COLLECTOR AND FLAT SOLAR COLLECTOR WITH CHEMICAL COATING

by

Yedilkhan AMIRGALIYEV, Murat KUNELBAYEV**, Talgat ORMANOV, Talgat SUNDETOV, and Salauat DAULBAYEV

Institute of Information and Computational Technologies,
Al Farabi Kazakh National University, Almaty, Kazahstan

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The given article considers results of experimental measurements, productivity comparison and master controller executive system of flat-plate solar collector with thermosiphon circulation and flat solar collector with special chemical coating. There has been developed master controllers control module, which receives data from temperature and lighting sensors, obtained in operation process. The aim of the research is getting the solar collectors' optimal parameters, representing maximal usage performance index, controllability, as well as, construction type, allowing energy saving. In the recent years flat-plate solar collectors with chemical coating are characterized with higher efficiency in real conditions usage. The developed master controllers' executive system is used for monitoring the installation's main parameters, as well, it permits to compare characteristics of solar collector with thermosiphon circulation those of flat-plate solar collector with chemical coating. The obtained experimental data has shown, that flat solar collectors, using chemical coating as a transfer medium in solar heat supply system, have an advantage in the context of usage effectiveness. The heat output and water heating in a flat solar collector are calculated, which vary depending on the intensity of solar radiation. The thermal efficiency of a flat solar collector with a thermosiphon tank based on the Mojo V3 platform using Dallas sensors is calculated.

Key words*: flat-plate solar collector, thermosiphon circulation, chemical coating, solar collector controller, thermodynamics, thermal capacity*

Introduction

The review on studies [1-3] have offered elaboration of thermic solar installations, which include lighting sensors, designed for measuring solar irradiation, electric and relay switch of backup gas boiler, which can interpret the solar collectors' operation in case of low solar irradiation or in case of its absence. As well there has been developed control system on the base of Android mobile devices, switched on the Internet, designed for remote monitoring. In [4] the authors have developed a smart home energy control system by means of the device on ZigBee base, used for monitoring home appliances and lighting power consumption. Authors in [5] have elaborated a hybrid model for solar energy low temperature objects, consisting of solar heat flat collector field. The [6] has offered nanoliquids development, which might be used in flat solar panels to update systems performance. Colangelo *et al*. [7, 8] have elaborated the modified nanoliquid solar collector, which consists of modified cross-section both for upper

* Corresponding author, e-mail: murat7508@yandex.kz

and lower collector's parts, in which Al_2O_3 nanoliquid with nanoparticles concentration have been used. In [9] there has been studied the flat-plate solar collector with nanoliquid, using Al_2O_3 dispersion. Chaji *et al*. [10] studied flat-plate solar collector with nanoliquid on aqueous base. Authors in [11-13] have researched the solar collectors, used nanoliquid on CuO base. In [14] the authors conducted analytical research of the solar collector with nanoliquid entropy generation on Al_2O_3 base and water with turbulent convection inside the circular pipe, subjected to constant temperature. The researches in [15] have developed the method of collector testing in compliance with quasidynamic conditions according to EN12975-2 European standard. The research aim is operating characteristics experimental comparative analysis of dual circuit flat solar collector with thermosiphon circulation and flat solar collector with chemical coating by means of newly developed control system for solar heat supply systems.

Method of research

Developed master controllers' executive system has been applied to measuring the characteristics of thermal solar installations with chemical coating, which further might be compared to analogous characteristics of traditional double circuit solar installations with thermosiphon circulation.

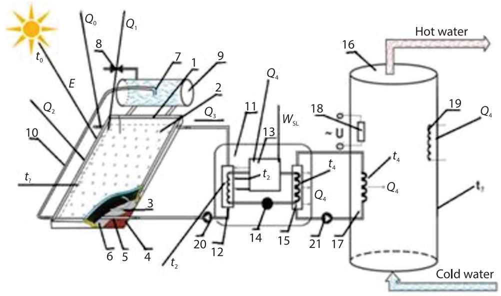

Figure 1. Principal diagram of double circuit solar installation with thermosiphon circulation

Flat solar collectors with thermosiphon circulation are used for transforming the falling solar irradiation into thermal energy. Energy thereof is accumulated as tangible energy in the reservoir, designated for liquid storage and used, as needed, for providing heat for premises and water heating. Figure 1 shows double circuit solar installation with thermosiphon circulation, proposed in the works [16, 17].

Operation of the installation, being offered, is fulfilled as follows. Solar energy, E, with temperature, t_0, is absorbed with solar collector – 1, with temperature, t_1, heated solar energy flow goes through translucent insulating double-glazing unit – 2. The heat, obtained from the solar flow, heats the liquid in coils – 3, which is removed from collector, and its place is occupied with cold water, coming from the pipe-line with a tap for cold water – 8, and in the siphon of doze meter tank – 7 there is constant thermal siphon circulation by means of circulation tube – 10. Further the liquid enters the thermal pump – 11, which consists of condenser's evaporator – 12 with temperature, t_2, in which the heat exchanger is made in a coil form. The heat exchanger, absorbing the temperature transmitter heat, decreases its temperature lower than that of atmospheric air, Q_2, using throttle valve – 14, thereby facilitating additional heat absorption from outside air. In the diagram there is also demonstrated the solar irradiation, reflected from semitransparent coating, Q_0, and absorbing panel surface, Q_1. In the thermal pump there is fulfilled transmission of heat carrier energy with relatively low temperature to the heat exchanger's transfer medium – 15. To perform that cycle there is used a compressor – 13 with temperature, t_3, with electric drive – 17. Further, by means of condenser's heat exchanger – 15 with temperature, t_4, heat from the thermal pump, Q_5, is transmitted to the heat exchanger's accumulator tank, Q_6, with temperature, t_6, of the heating system – 18. As the installation has two circuits, it is equipped with automatic circulating pumps – 19 and 20, designated for liquid circulation between solar collector and evaporator, condenser and accumulator tank. Water temperature is brought to the required technological level and delivered to a consumer for hot water supply and heating [18, 19]. Solar heat supply system with solar collector with chemical etching has been constructed at the Institute of information and computer technologies in Almaty city, Republic of Kazakhstan (latitude 45° 24′ 5″ N, longitude 9° 14′ 58″ E). The device has been designed without wiring, it is cheaper, than available solution, and easier in implementation, avoiding the problems of communicating with a device inside a building, remote from the solar panel. The system envisages the installation of external heat exchanger, designed for modelling the hot water consumption or heat dissolving, when temperature in the boiler exceeds the fixed value, set as the maximum threshold. Control system includes an external wireless solar module with autonomous power supply, which transmits the data on the temperature of solar panel, T_1, to internal control unit. The unit receives the data and controls the system, monitoring temperature value and two electric pumps conditions.

Figure 2 shows the experimental installation, designed for determining the temperature level of heated liquid and water in the tank, as well for measuring radiation level on solar panels, which can be used for comparing the double circuit solar installation with thermosiphon circulation performance to that of solar installations with chemical coating

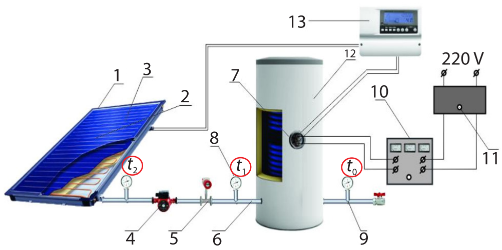

Figure 2. Experimental installation of solar heat supply with master controller: *1 – heat-insulated body, 2 – translucent coating, 3 – absorber tank, 4 – circulating pump, 5 – flowmeter, 6 – pipe-line, 7 – tubular heating element, 8, 9 – thermometers for measuring water temperature at inlet and outlet from absorber tank and environment, 10 – set of electric meters K 501, 11 – autotransformers, 12 – accumulator tank, and 13 – master controller*

Experimental installation diagram consists of heat-insulating body – 1, translucent coating – 2, absorber-tank – 3 and circulating pump – 4, flowmeter – 5, pipe-line – 6, thermal electric heater with heat regulator – 7, thermometers – 8 and 9, for measuring water temperature at inlet, T_1, and outlet, T_2, from the tank and environment, Tm, metering device K501 and autotransformer – 11, as well as master controller for executive unit [16, 17].

To achieve the set aim we have developed two principally new solar collectors, on the base of which there will be created control of heat supply solar system. Figures 3(a) and 3(b) demonstrate a flat solar collector with thermosiphon circulation, which is made of red hot glass with 1000 × 2000 mm^2 dimension, 4 mm thickness. Copper tubes with 19 mm and 4 mm diameters of 24 m total length are connected into one in parallel, copper list with 1 mm thickness is

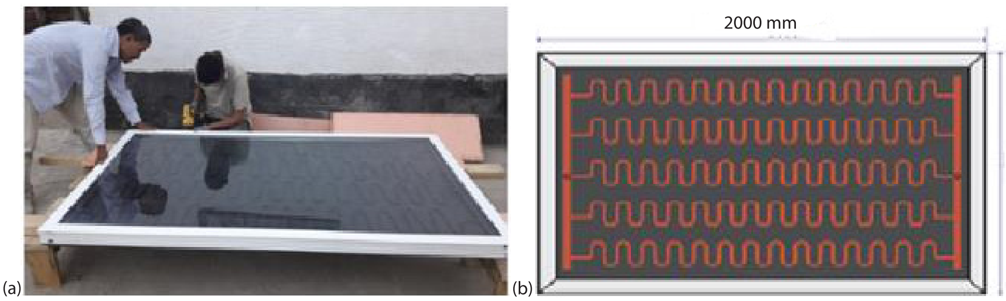

Figure 3. Solar collector manufacturing processes; (a) flat solar collector with thermosiphon circulation and (b) inner part

covered with polymer paint, solar collector's reverse side is made of 2 mm thickness Al sheet, inner part is covered with foam plexus and penofol.

Figures 4(a) and 4(b), shows the solar collector with chemical coating. It is made of red hot glass with 1000×2000 mm^2 dimension, 4 mm thickness. Spiral type copper tube with a diameter 10 mm, 4.5 m length is soldered at the rear side of absorbing copper sheet. The 1 mm thickness and 594×840 mm^2 dimension copper sheet has coatings, applied by means of chemical etching ($K_2S_2O_8$ + NaOH + H_2O + $Na_2S_2O_8$) of several microns thickness. Double layer heating up is fulfilled with foil penofol and foam plexus of 30 mm thickness. Solar collector's reverse side is made of 2 mm thickness aluminum sheet.

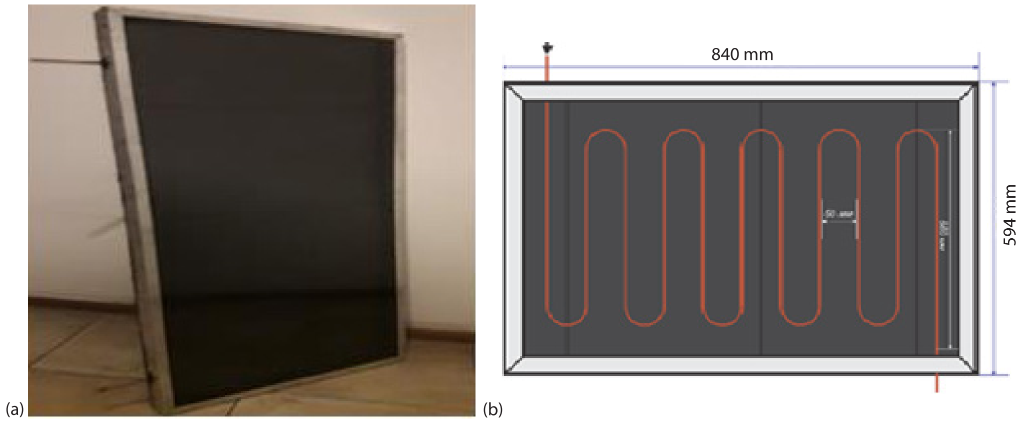

Figure 4. (a) Solar collector with chemical coating and (b) inner part of solar collector with chemical coating

Novelty of the research herein is development of double-circuit solar system with thermosiphon circulation, which has flat solar collector, representing the heat insulating transparent double glazing unit with reduced pressure, a heat carrier is made of thin-walled corrugated stainless tube. Heat, obtained from solar flow, heats the liquid in coils, which is removed from the collector, and its place is occupied with cold liquid from the siphon and there happens constant heat circulation, which upgrades heat transmission effectiveness, eliminating additional webs between the panel and heat insulation. There is, as well, a thermal pump, where a condenser and evaporator are made in the form of heat exchanger of *spiral in spiral* type, heat exchanger pipe-lines are located one over another, which increases the square and heat exchange intensity.

As well, the novelty is the development of solar collector controller, where an electric module contains programmable logical integral scheme Mojo V3, which processes sensors' temperature data, indicators of function and operating parameters are LCD display, real time clock and ETHERNET module, designated for monitoring the solar system in whole, and executive elements include a relay.

The useful energy gain, Q_U, for a flat solar collector is determined:

$$Q_U = \dot{m} C_p \left(T_0 - T_{\mathrm{i}} \right) \tag{1}$$

where $\dot{m}$ and C_p are the mass-flow rate and the heat capacity of the liquid, respectively.

In the study [20], the equation for calculating the heat capacity of water was used:

$$C_{p,\mathrm{w}} = 4226 - 3.244 T_{\mathrm{fm}} + 0.0575 T_{\mathrm{fm}}^2 \tag{2}$$

$$T_{\text{fm}} = (T_0 - T_\text{i})^2 \tag{3}$$

where T_{fm} [°C] is the average temperature of the working fluid inside the collector.

The heat capacity of the nanofluid is calculated [21]:

$$C_{p,\text{nf}} = C_{p,\text{np}}(\varphi) + C_{p,\text{w}}(1-\varphi) \tag{4}$$

The useful energy gain was expressed [22]:

$$Q_U = A_C - F_R\left[G_t(\tau\alpha) - U_1(T_\text{i} - T_\text{a})\right] \tag{5}$$

For each test, the instantaneous efficiency Q_U was determined from the ratio of the useful energy gain, Q_U, to the incident radiation, $A_C G_t$:

$$\eta_\text{i} = \frac{Q_U}{A_C G_t} = \frac{\dot{m}C_p(T_0 - T_\text{i})}{A_C G_t} = F_R(\tau\alpha) - F_R U_1\left(\frac{T_\text{i} - T_\text{a}}{G_\text{t}}\right) \tag{6}$$

Despite these difficulties, a long-term assessment of the performance of many solar heating systems, collectors can be characterized by interception and inclination [23].

According to the Second law of thermodynamics, the work can be obtained by determining the capacity of the tank to implement a reversible process [18]. Thus, the expression of the work between the time, t, and the final time, t_{final}, for the thermally tightened mass in the tank, developed [19], is obtained:

$$E_{t,t_{\text{final}}} = \rho Ac\int_0^H \left[T(z,t) - T_{\min}\right]\text{d}z \tag{7}$$

Transient thermal efficiency according to the First thermodynamics law for a ton of liquid in the tank is obtained by the ratio:

$$\eta = \frac{\int_0^H \left[T(z,t) - T_{\min}\right]\text{d}z}{H(T_{\max} - T_{\min})} \tag{8}$$

where $E_{\max}$ is the energy maximum, allowed, *i.e.*, when $T(z, t)$ equals to $T_{\max}$:

$$W_{\text{t-t final}} = \rho AC_p\int_0^H \left\{\left[T(z,t) - T_{\min}\right] - T_0 \ln\frac{T(z,t)}{T_{\min}}\right\}\text{d}z \tag{9}$$

We can compute the thermal system performance from the Second thermodynamics law for the liquid in the tank, according to the ratio:

$$\varepsilon = \frac{W_{t,t_{\text{final}}}}{W_{\max}} = \frac{\int_0^H \left\{\left[T(z,t) - T_{\min}\right] - T_0 \ln\frac{T(z,t)}{T_{\min}}\right\}\text{d}z}{H\left[(T_{\max} - T_{\min}) - T_0 \ln\left(\frac{T_{\max}}{T_{\min}}\right)\right]} \tag{10}$$

where $W_{\max}$ is the maximum of the work, obtained in the reversible process, when the mass of liquid in the tank reaches a uniform temperature, *i.e.*, and $T(z, t)$ is equal to $T_{\max}$.

This study evaluates the performance of solar air heaters (SAH) with inserted porous baffles using energy and exergy analysis methods. Using the First and Second laws of thermodynamics, the energy and exergy efficiencies of SAH are calculated and presented for various parameters. In the course of experiments, five types of SAH are tested and compared with each other in terms of their efficiency [24]. The present study examines previous research and applications in terms of design, performance evaluation, heating methods for increasing transmission, experimental and numerical work, heat storage, compassion efficiency, and recent advances [25]. Local and average Nusselt numbers calculated. The results show that heat transfer increases with increasing Rayleigh number and aspect ratio and decreases with increasing wavelength [26]. The effects of the thermal Rayleigh number and the buoyancy coefficient along streamlines, isotherms, is concentration, as well as local and average rates of heat and mass transfer for the aforementioned parameters are presented. Comparison with previously published papers and found to be excellent agreement [27]. The article [28] discusses the resources of the Republic of Kazakhstan based on solar energy. Estimates of solar systems when assessing solar energy resources on the territory of Kazakhstan are based on quantitative characteristics of direct solar radiation on a horizontal surface from which conversion from a horizontal plane to an inclined plane of any orientation can be performed. As a result of the study, statistical processing of the average values of direct, total irradiation and duration of solar radiation was compiled, five zones were identified and a histogram was compiled characterizing the possibility of introducing solar installations in Kazakhstan.

Prototype of modular master controller for solar thermal system

Master controllers are designed for monitoring the solar thermal installations and, in particular, can be characterized by modular structure. It allows renew controller's functionality in respect to further development of installation. In this section we present the modular controller prototype, based on freely programmable platform.

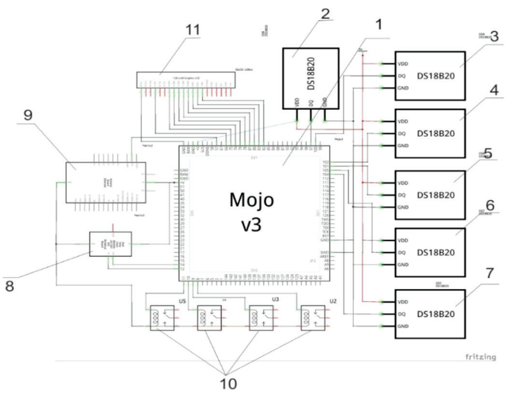

Figure 5. Principal diagram of connecting ESP-WROOM-32 with sensors of system's controller monitoring

In the research herein six digital temperature sensors (Dallas DS18B20) 2-7 register different temperatures of the flat solar collector with thermosiphon circulation. Sensors are controlled by programmable logistical integral Scheme 1 ESP-WROOM-32, containing dual core 32-bit microprocessor. Temperature readings recordings, saved at ETHERNET module 9, every 5 seconds interval send temperature data and valves states 10. Real time clock 8 records data and time of temperature data measuring, sending them to programmable logistic integral scheme ESP-WROOM-32. Six sensors are switched on the plate ESP-WROOM-32 by means of electric wires, programmed in VHDL language, which after processing temperature data, date and time, received from RTC 8, accordingly, save them in XML, figs. 5-7.

Language XML facilitates processing of that data by means of automatic or manual interpreting the programs of data electronic tables. Temperature data, date, time and valves state of installation operation system are shown on display 11.

Table 1 presents technical specifications of solar system controller, which have been used upon conducting experimental research.

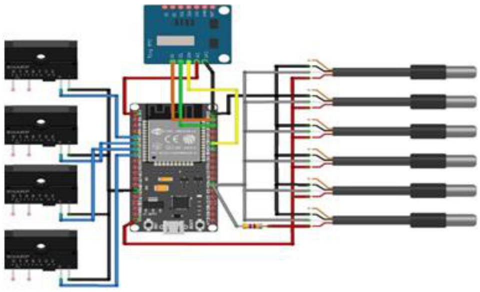

Figure 6. Principal diagram of controller on platform ESP-WROOM-32

Figure 7. Solar system controller display

Table 1. Technical specifications of solar system controller

Dimensions [mm]	120 × 120 × 23
Power supply [V]	AC110/AC220
Consumption [Wt]	<3
Temperature measuring accuracy [°C]	–/+2
Collector's temperature measuring range (°C)	–10…220
Tank temperature measuring range [°C]	0…+110
Pump maximum capacity [Wt]	3 pc < 300
Inputs	1 pc pt1000, 2 pc ntc10k
Outputs (relay for pump, valve THE)	10 A
Operating temperature [°C]	–10 +50
Water protection class	IP40

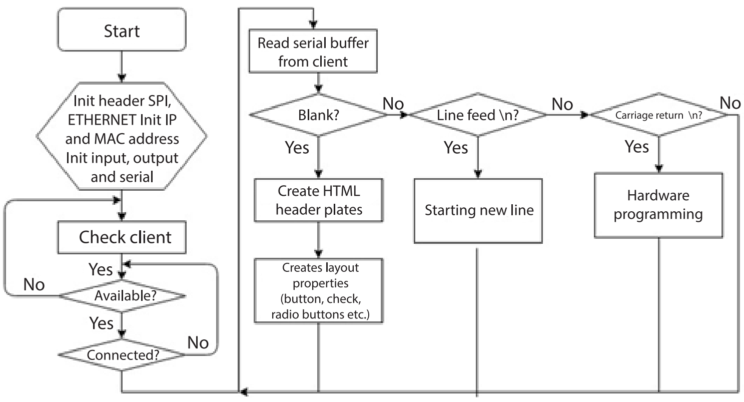

Figure 8. Algorithm flow-chart of solar collector control

Solar collector master controller is built-in with an optimal algorithm to correlate the signals, being obtained from various subsystems and to monitor controllers. At the start of algorithm the program activates libraries and constants, afterwards there is switched on the real time clock module, activated temperature sensors and communication with a server, fig. 8. Provided all devices are activated, there is established communication, otherwise there is started the work on activation. If communication with a server is set, then xml file is saved in Ethernet module. Then the sensor temperature data is read out and data on temperature is recorded in Ethernet module.

Results and discussion

To compute the solar collector's efficiency there is used the standard EN 12975-2, described in [15]. Experimental researches have been conducted to study thermal performance, using both the flat solar collector with thermosiphon circulation and solar collector with chemical coating ($K_2S_2O_8$ + NaOH + H_2O+ $Na_2S_2O_8$). Research on studying collector's efficiency was conducted during several months under different reduced temperature drops.

An important component of experimental work is measuring the main parameters, necessary for computing the solar collector's performance at fixed temperature at the inlet, which is monitored by a master controller. Upon experimental tests there was conducted condensing about 15-20 minutes.

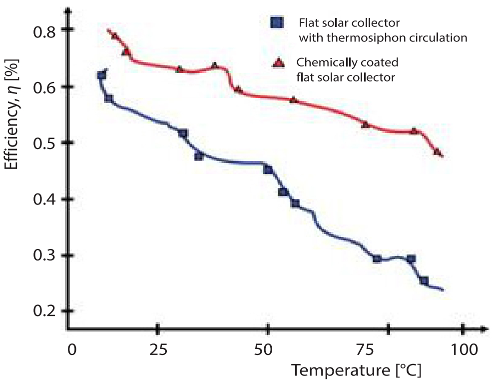

Figure 9. Efficiency dependence of flat-plate solar collector with thermosiphon circulation and solar collector with chemical coating $K_2S_2O_8$ + NaOH + H_2O+ $Na_2S_2O_8$

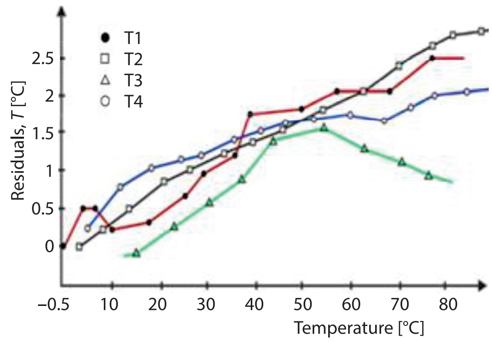

Figure 10. Assessing the accuracy of temperature external control unit

As it is seen from fig. 9 the highest obtained efficiency value of flat solar collector with thermosiphon circulation amounts to 57.89% at reduced temperature 30 °C, while at increased temperature the efficiency constituted 60.45%. Water temperature in the inlet of flat solar collector with thermosiphon circulation constituted 68.56 °C, air temperature 31.44 °C and solar energy flow 750.50 Wt/m^2. Water temperature from the outlet from flat solar collector with thermosiphon circulation constituted 75.76 °C, air temperature 31.44 °C and solar energy flow 750.50 Wt/m^2. In clear day the solar energy flow, reaching earth's surface at local midday, usually is in the interval from 700-1300 Wt/m^2 depending on latitude, longitude, altitude and season. In particular, for our region, Almaty, Republic of Kazakhstan the solar energy flow amounts to 750.50 Wt/m^2.

According to outcome of conducted experimental work we can draw a conclusion, that the efficiency of flat solar collector with chemical coating $K_2S_2O_8$ + NaOH + H_2O+ $Na_2S_2O_8$ has increased for 6.5%, comparing to solar collector with thermosiphon circulation.

Figure 10 shows the outcomes of assessing the accuracy of temperature external control unit T1 and four sensors Dallas DS18B20 (T2-T4). Controller can operate under the temperature range from −30 °C +100 °C and can maintain relative moisture from 10-90%. Sensor T_1 shows readings within the range from 35 to 55 °C. Temperature sensor T_2 demonstrates temperature values from 45-85 °C. Temperature sensors T_3 and T_4 show the value 85 °C.

Figure 11 shows temperature adjusting for different ranges, which was necessary for using in monitoring system. For every sensor there exists a linear equation. Equations have been included into Arduino plate code, installed inside master controller. In the result of the research it should be mentioned, that the sensors assure good accuracy along the whole range, fixing, in particular, abnormal temperature readings in the system.

As can be seen from fig. 12, the thermal power and water heating in a flat solar collector varies according the intensity of solar radiation. The higher the solar radiation, the higher the power and heating of the water throughout the solar heating system. Also, the thermal efficiency of a flat solar collector with a thermosiphon tank, based on the Mojo V3 platform, using Dallas sensors was used for experimental studies.

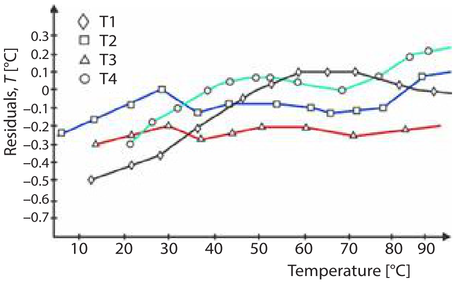

Figure 11. Correcting for various temperature ranges

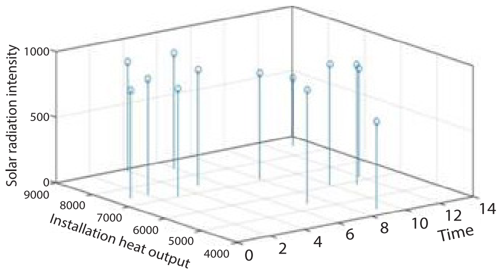

Figure 12. Dependence of solar radiation on installation thermal capacity and water heating time

Conclusion

In the work herein we have conducted experimental works to compute and compare the performance of a flat-plate solar collector with thermosiphon circulation and solar collector with chemical coating $K_2S_2O_8 + NaOH + H_2O + Na_2S_2O_8$. In the course of work there has been computed the efficiency under various reduced temperature drops with different solar lighting and temperature at the inlet to the solar collector. From experimental outcomes it is seen, that at using the solar collector with chemical coating $K_2S_2O_8 + NaOH + H_2O + Na_2S_2O_8$ the performance of the flat solar collector thereof is upgraded. As well, it has been computed, that the effectiveness of the solar collector with chemical coating $K_2S_2O_8 + NaOH + H_2O + Na_2S_2O_8$ is for 6.5% higher, than that of a flat plate solar collector with thermosiphon circulation. There has been assessed master controller's accuracy, which can operate within the temperature range from −30 °C to +100 °C and can maintain the relative moisture from 10-90%. Sensor T_1 shows values in the range from 35-55°C. Temperature sensor T_2 demonstrates temperature values from 45-85 °C. Temperature sensors T_3 and T_4 have values 85 °C. According to the research outcomes it can be noted, that the sensors provide desirable accuracy along the whole range, fixing and correcting, in particular, deviated behavior at temperature rise.

Nomenclature

A_C – surface area of solar collector, [m^2]
C_p – specific heat at constant pressure, [Jkg^{-1}K^{-1}]
$C_{p,\mathrm{np}}$ – capacity of nanoparticles ($K_2S_2O_2$ + NaOH + H_2O+ $Na_2S_2O_8$), [Jkg^{-1}K^{-1}]
$C_{p,\mathrm{nf}}$ – heat capacity of nanofluid, [Jkg^{-1}K^{-1}]
$E_{\max}$ – energy maximum, [W]
G_t – global solar radiation, [Wm^{-2}]
$\dot{m}$ – mass-flow rate of fluid-flow, [Ls^{-1}]
Q_U – rate of useful energy gained, [W]
T_a – ambient temperature, [C)]
T_i – inlet fluid temperature of solar collector, [C]
T_0 – outlet fluid temperature of solar collector, [C]
t – working temperatures, [°C]
U_l – overall loss coefficient of solar collector, [Wm^{-2}K^{-1}]

Greek symbol

η – efficiency, [%]

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