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Investigation of annual thermal performance and techno-economical analyses of direct absorption solar collector by using nanofluids

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Abstract

In this study, the annual thermal performance and techno-economic analyses of a direct absorption solar collector (DASC) using nanofluids were investigated. According to the results of numerical analysis the difference between the specific heat gains was 126.5 W/m^2, where difference for annual energy saving or enhancement for solar energy converting to useful was 224 kW/m^{2}a. To sum up utilization of MWCNTs (0.05%) based nanofluids as heat transfer fluids in PTC supported the 13,5% of thermal efficiency in comparison of water. Furthermore, when nanofluids are used as a heat carrier in a solar collector, the cost of 1 kWh of thermal energy is 0.029 $/kWh, and when water is used, it is 0.034 $/kWh. The payback period of the initial investment amount of the nanofluid solar collector is 3.96 years, where the interest rate of the bank is calculated at 23%, and the payback period of the initial investment amount of the water solar collector is 3.99 years.

Keywords: direct absorption solar collector, nanofluid, MWCNT, annual thermal performance, tecno-economic analysis, cost of energy.
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1. Introduction

Since the technological evolution, the demand for energy utilization has been increasing dramatically, namely in the industrial sectors. According to the (IEA) - International Energy Agency report fossil fuels still dominate the global energy supply, accounting for about 82% of the total. Renewable energy sources accounted for about 18% of the total, with solar and wind being the two largest sources [1]. Application of solar thermal collectors, namely DASCs (Direct absorption solar collector) support to get a primary enviro-economic energy in domestic and industrial sectors. Furthermore, enhancement of thermal efficiency of solar thermal systems also remaining actual and provide to get more thermal energy. As solutions of improving the thermal performance of DASCs are replace the materials of collector parts to enviroeconomic one or place of water using heat transfer fluids with the high thermal conductivity. In works [2], [3] provided the preference of using polymeric materials to make a direct irradiate solar collectors. Accordingly, polymeric solar collectors showed the same thermal performance with metal based solar collectors, which working temperature reaches up to 95^{o}C, where thermal efficiency appointed 84-92%. Due to their good thermophysical properties, nanofluids are considered as promising coolants for many branches of science and technology [4], for example, in the field of transport - the use of nanofluids as coolants in coolers of transport power plants will significantly reduce their volume and weight. Moreover, it is shown that the using nanofluids as heat transfer fluid will increase the efficiency of such devices by 30% compare to water, which is given in [5], where a nanofluid based on water with silver particles was used for the solar collector, the maximum volume content is 0.04%: the maximum efficiency of solar collectors when using nanofluid reaches 70%. In [6] have been carried numerical simulation that the thermal efficiency was about 69.73-72.24%, which decreases with the high synthetic oil fluid temperatures and increases in the lower water temperature by 2%. However, using nanofluids as a heat transfer fluid in solar thermal collectors, thermophysical properties should be studied, clearly. As given in [7], [8] works thermal conductivity and viscosity of nanofluids, accordingly enhancement of thermal conductivity and viscosity of nanofluids with the comparison of water leads to increasing of thermal efficiency of solar collector by 14 %. Moreover, thermal analysis of solar thermal systems when using nanofluids as a heat transfer is also important and by this can be evaluated the heat transfer ability of nanofluids. In works [9]– [11] carried out investigations, devoted to modelling and 4E (Energy, Exergy, Economical, Environmental) analysis. Respectively, using of hybrid and mono types of nanofluids could save 40.44 GJ, 39.01 GJ, 30.8 GJ embodied energy as well as 59.03 KL, 56.95 KL, and 44.96 KL embodied water. In addition, in [10] established exergoenvironmental (EXEN), exergoenviroeconomic (EXENEC) analyses are performed to a solar collector. Regarding of results, the EXEN result (0.0727 kg CO_2/day) is lower than the corresponding environmental one (0.0777 kg CO_2/day). The enviroeconomic result (0.00112 $/day) is higher than the EXENEC result (0.00105 $/day). Based on the literature review, the main ideas are to conduct the annual thermal performance and tecno-economic analyses of DASC (Direct absorption solar collector) by using nanofluids (MWCNT, 0.05%) as heat carrier for the climate conditions of Tashkent. To establish the proposed ideas set tasks such as preparation nanofluids based on MWCNT (vol, 0.05%), modelling the proposed DASC, analyzing the thermal performance and carrying the tecno-economic analysis.

2. Methodology

2.1. Preparation

There are several methods for preparing nanofluids by dispersing nanoparticles in base fluids, such as the widely used “single-step method” and “two-step method”. For current investigation, the “two-step method” is considered preferable for preparing nanofluids based on MWCNTs with varied concentrations at room temperature and atmospheric pressure. As a base fluid, distilled water (DW) and proposed MWCNT nanoparticles with a 0.05% volume concentration were mixed into the base fluid. Mechanical blending was used, and the suspension was dispersed under ultrasonic processing (sonication power and frequency were 400 1200 W and 40 kHz, respectively) for 30 min at 25°C. Figure 1 presents the algorithm of nanofluid preparation by the “two-step method”.

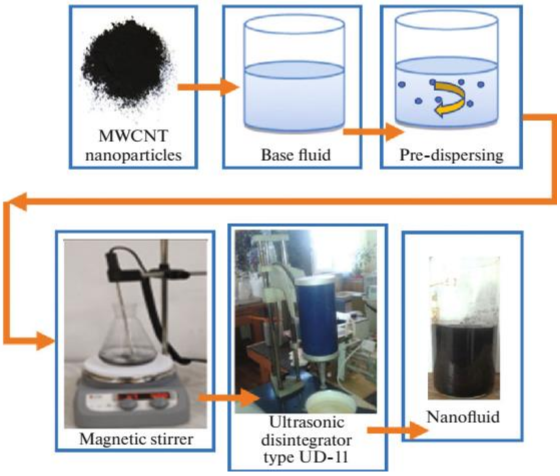


Figure 1. Algorithm of nanofluid preparation by the “two-step method”

2.1. Modelling.

In order to evaluate the thermal performance of DASC have been created mathematical model of the solar collectors given in [12], which expressed the results of numerical and experimental investigation. In order to select the most technical solution for direct absorption solar collectors with nanofluid coolant based on modeling their thermal regime, the following existing design option was considered figure 2.

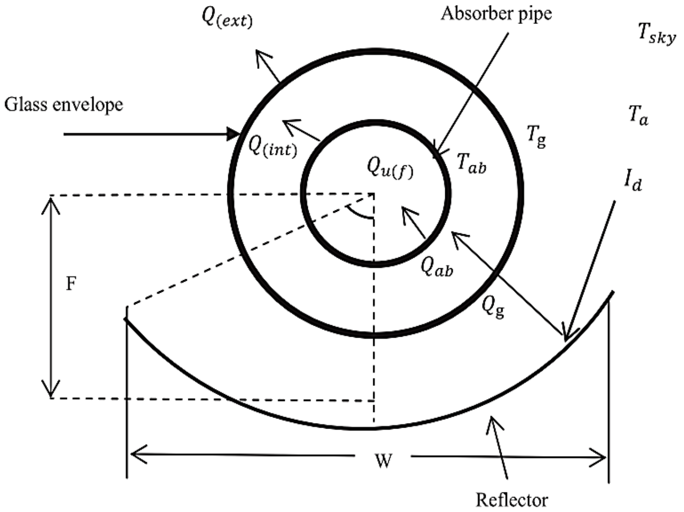


Figure 2. Schematic diagram of a direct absorption solar collector with heat transfer

When compiling a mathematical model of the thermal regime of this object and its elements, the following assumptions were made [13], [6], which do not distort the picture of the physical processes occurring in the elements of the direct absorption solar collector:

The absorber pipe, which is part of the solar collector, is divided into several layers in the control volume.

– the thermal conductivity of the absorber tube and glass shell is constant.
– cross conductivity in the absorber pipe and glass is ignored.
– slight conductivity losses at the end of the absorber tube.
– incompressible fluid with unidirectional flow.
– pressure in the ring between the absorber and the glass bulb.
– uniform redistribution of solar radiation in the absorber tube.

In the control volume, the heat balance on the glass casing can be written as follows:

$$m_g Cp_g \frac{dT_g}{dt} = WI_d \rho_0 \propto_g \gamma K + A_g k_g \frac{d^2 T_g}{dx^2} + \pi D_{ab(ext)} h_{(int)} (T_{ab} - T_g) - \pi D_{g(ext)} \left[h_{c(ext)} (T_g - T_a) + + h_{r(ext)} (T_g - T_{sky}) \right] \tag{1}$$

Heat balance equation for absorber tube;

$$m_{ab} Cp_{ab} \frac{dT_{ab}}{dt} = WI_d \rho_0 \propto_0 \gamma K + A_{ab} k_{ab} \frac{d^2 T_{ab}}{dx^2} - \pi D_{ab(ext)} h_{(int)} (T_{ab} - T_g) - \pi D_{ab(int)} h_u (T_{ab} - T_f) \Big) \tag{2}$$

Analogically the heat balance equation for heat carrier can be written as following;

$$m_f Cp_f \frac{dT_f}{dt} + \left(\frac{\dot{m}_f Cp_f}{\Delta x}\right) \frac{dT_f}{dt} = A_f k_f \frac{d^2 T_f}{dx^2} + \pi D_{ab(int)} h_u (T_{ab} - T_f) \Big) \tag{3}$$

Boundary conditions for a nonlinear differential equation (3)

$$\left.\begin{aligned} T_f &= T_{f.in} \;\; for\ \mathrm{x} = 0 \\ T_f &= T_{f.out} \;\; for\ \mathrm{x} = L \end{aligned}\right\} \tag{4}$$

Carrying out the numerical calculations for created differential equation have been used numerical implicit method of splitting [13]. Also have been chosen the coefficient if heat transfer between the parts of collector and in fluid layers as follows;

$$h_{c(ext)} = \left[0.6 + 0.387\left(\frac{Ra_{air}}{\left(1+\left(\frac{0.559}{Pr_{air}}\right)^{\frac{9}{16}}\right)^{\frac{16}{9}}}\right)^{\frac{1}{6}}\right]^2 \frac{k_{air}}{D_{g(ext)}} \tag{5}$$

$$h_{c(int)} = \frac{2k_{eff}}{D_{ab(ext)} ln\left(\frac{D_{g(int)}}{D_{ab(ext)}}\right)} \tag{6}$$

$$h_{r(ext)} = \varepsilon_g \sigma \left[\left(T_{sky} + 273\right)^2 + \left(T_g + 273\right)^2\right]\left(T_{sky} + T_g + 546\right) \tag{7}$$

$$h_{r(int)} = \varepsilon_{int} \sigma \left[(T_{ab} + 273)^2 + \left(T_g + 273\right)^2\right]\left(T_{ab} + T_g + 546\right) \tag{8}$$

$$h_u = \frac{k_f}{D_{ab(int)}} Nu_f \tag{9}$$

With laminar flow, fully developed, with uniform heat flow, all criteria for the thermal regimes of fluid flow given in works [14-15].

2.3. Economic analyses.

The cost of energy produced is obtained by using LCOE relation, which clearer given in [9]. The relation for LCOE expressed by (10).

$$LCOE = \frac{crf \cdot Z_{investment} + Z_{O\&M}}{Q_{u.annual} \cdot t_{annual}} \tag{10}$$

Where, crf is the capital recovery factor (11),

$$crf = \frac{i \times (i+1)^n}{(1+1)^n - 1} \tag{11}$$

$Z_{investment}$- is the investment cost, $Z_{O\&M}$is the cost of operation and maintenance, usually 2.5% of the initial investment for solar installations, $Q_{u.annual}$ is the collector annual useful energy received, t_{annual}- the total annual operating time of the collector. An i is the percentage of the bank rate, n is the service life of the collector, in which the service life of the heating device is considered to be 20 years or more.

$$Q_{u.annual} = \frac{\int_0^t \dot{Q}_u dt}{A} \tag{12}$$

2.3. Ecological analysis.

When using nanofluids based on MWCNTs as a heat carrier in the proposed collector, to obtain useful heat energy the annual amount of CO_2 released is calculated (13), where μ_{CO_2}- is the specific CO_2 emission when fuel is used, in this case gas and electricity are used as fuel. The price saved from annual CO_2 emissions is calculated as equation (14). The c_{co_2}- is the specific cost of CO_2 released when fuel is burned.

$$M_{CO_2} = \mu_{CO_2} \cdot Q_{u.annual} \tag{13}$$

$$C_{CO_2} = c_{co_2} \cdot M_{CO_2} \tag{14}$$

The payback period is calculated using the simple payback period method (SPP), based on the cost of useful thermal energy obtained from the initial investment amount for the proposed solar collector (15) where C_{fuel} is the specific price of fuel.

$$SPP = \frac{Z_{investment}}{Q_{u.annual} \cdot C_{fuel}} \tag{15}$$

3. Results and discussion

After discretizing the nonlinear differential equations, the system of algebraic equations is solved using one of the iterative Gauss-Seidel method [16], which is more stable and accurate for nonlinear equations (1-3). Numerically solving the proposed equations mathematical model of solar collector was validated [17] with the results of experiment, which were given in [12], as a result of validation root-mean-square error and the coefficient of determination were $RMSE = 0.61\ K$, $R^2 = 0{,}99995$. All data from the numerical analysis shown in figure 3, which illustrate the annual weather data of Tashkent region.

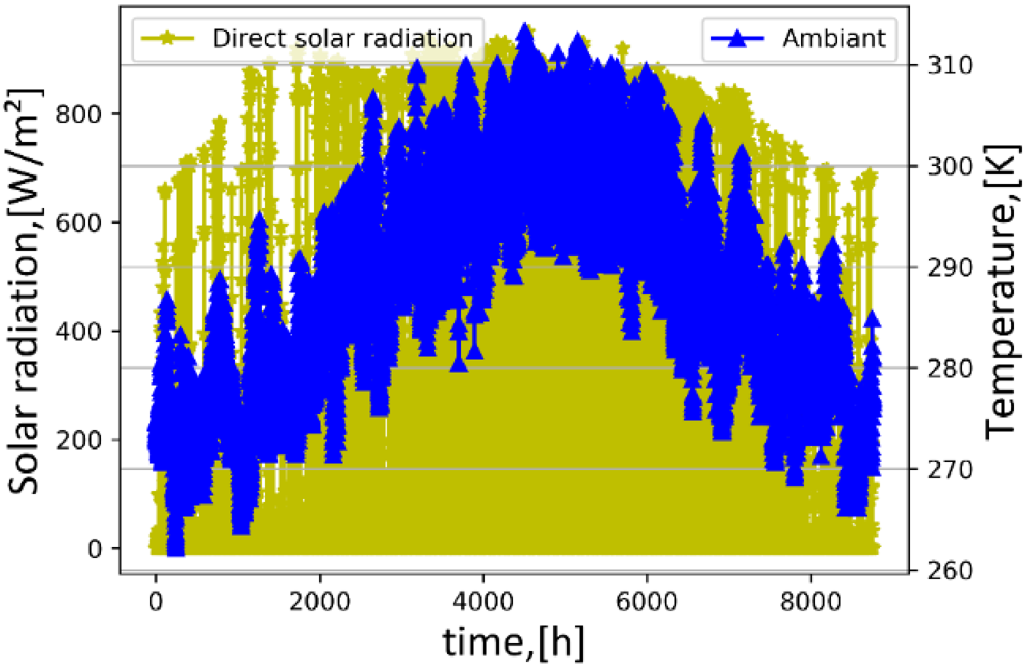
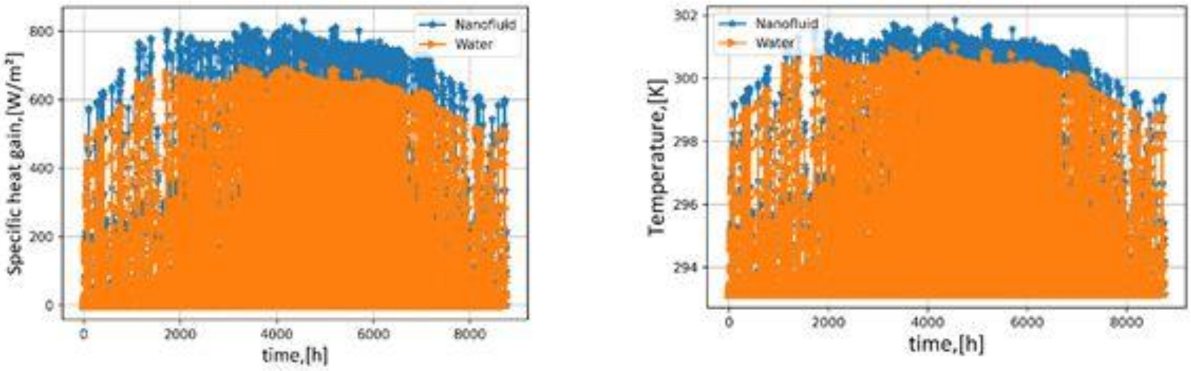


Figure 3. Direct solar radiation and ambient temperatures through the one-year period

As shown in figure 3 direct solar radiation has been changed form 0.001W/m^2 to approximately 1000 W/m^2, where the ambient temperature changed from 260 K to about 315 K.



a) **b)**

Figure 4. a) Comparison of specific heat gain of PTC by using MWCNT based nanofluids and water as a heat transfer fluid, b) Comparison of outer temperatures by using MWCNT based nanofluids and water as a heat transfer fluid

As shown in figure 4 a specific heat gain of PTC was changed from 0 up to 800 W/m^2 for heat transfers as MWCNT based nanofluids, where this value was reached up to about 650 W/m^2. The value of zero for specific heat gain, which means zero solar radiation. The difference between the specific heat gain for nanofluid based PTC and water based was reached 126.5 W/m^2, which illustrate 126.5 W energy saving for each m^2 are of PTC. Moreover, in fig.4.b given the difference between the outer temperature from PTC for nanofluids and water during the one-year period. The difference between the temperatures were reached to about 3 K at maximum values of solar radiation, as shown in figure 4 b Moreover, in figure 5 shown the comparison of thermal efficiencies of DASC by using MWCNT based nanofluids and water, with the respect of $T_m$value.

$$T_m = \frac{T_{in} - T_{amb}}{G_{direct}} \tag{16}$$

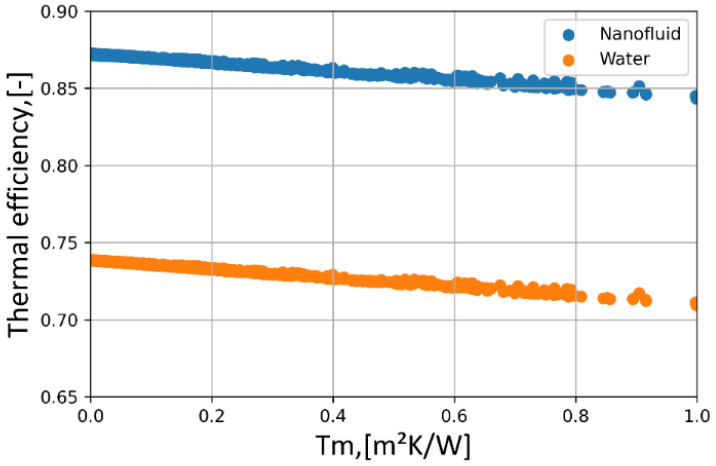


Figure 5. Comparison of the annual thermal efficiency of PTC by using MWCNTs based nanofluids and water, with the respect of T_m value.

As shown in figure 5 the thermal efficiency of PTC by using nanofluids changed from about 84.5% to nearly 88.5%, where this value for water-based DASC fluctuated between approximately 70% and nearly 75%.

Furthermore, have been carried economic and ecologic analyses for the performance of DASC by using MWCNT based nanofluids as heat carrier. Technical and economical indicators were given in table 1. Results from the economic and ecologic investigation were announced in table 2.

Parametres	**Units**	**Amount**
i-interes rate	%	14,19,23
Amount of initial investment	USD/m^2	169-Nanofluid based collector
		165-Water based collector
n- collector lifetime	year	20
μ_{CO_2}- is the specific CO_2 emission	kg/kWh	0.369-fuel is gas
		0.489- fuel is electricity
c_{co_2}- is the specific cost of CO_2 released when fuel is burned	USD/tCO_2	14.5
C_{fuel}- is the specific price of fuel	USD/kWh	0.004- fuel is gas
		0.029- fuel is electricity

Table 1. Technical and economic indicators

Solar collector type	***Annual useful heat gain*** $\left[\frac{kWh}{m^2\cdot a}\right]$	***Cost of energy*** $\left[\frac{USD}{kWh}\right]$	***Annual amoun of*** CO_2 $\left[\frac{kg}{m^2\cdot a}\right]$	***Amount of saved money from released*** CO_2 $\left[\frac{USD}{m^2\cdot a}\right]$	***Payback period* [year]**
Nanofluid based solar collector	1469	0.029	542-gas	10.411	3.96
			718-electricity		
Water based solar collector	1244	0.034	459-gas	8.818	3.99
			608-electricity		

Table 2. Technical and economic effects

4. Conclusion

It can be concluded that the thermal efficiency difference between the using of MWCNT (0.05%) based nanofluids and water as a heat transfer fluid supports about 13.5% enhancement. In terms of annual specific heat gains nanofluid used in PTC as heat carrier fluid owned 1469.9 kW/m^{2}a, where water supplied the 1244 kW/m^{2}a. From point of view the energy saving using nanofluids in DASC showed 224 kW/m^{2}a useful heat gain more than water. As a result of tecno-economic and ecologic analyses the annual amount of useful energy obtained from 1 m^2 surface of the collector was 1469 $\left[\frac{kWh}{m^2\cdot a}\right]$, and when water is used as a heat carrier, the annual amount of useful energy obtained from 1 m^2 surface is 1244 $\left[\frac{kWh}{m^2\cdot a}\right]$, which leads to an increase in useful heat energy obtained by 225 $\left[\frac{kWh}{m^2\cdot a}\right]$. When nanofluids are used as a heat carrier in a solar collector, the cost of 1 kWh of thermal energy is 0.029 $\left[\frac{USD}{kWh}\right]$, and when water is used, it is 0.034 $\left[\frac{USD}{kWh}\right]$. The payback period of the initial investment amount of the nanofluid solar collector is 3.96 years, where the interest rate of the bank is calculated at 23%, and the payback period of the initial investment amount of the water solar collector is 3.99 years.

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