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Nanofluids: A Promising Heat Transfer Fluid for Solar Collectors

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Abstract. This study investigates how MWCNT-based nanofluids enhance the performance of direct absorption solar collectors (DASC) compared to traditional water-based systems. The findings reveal that MWCNT nanofluids keep a higher temperature range of 296-302 K, better than water 295-300 K, and achieve a specific heat gain of up to 800 W/m², which is significantly higher than water's peak of less than 50 W/m². The mathematical model used in this research, when checked against real experimental data, showed a very low error rate (RMSE of 0.61K) and a very high accuracy (R^2 of 0.99995). From an economic perspective, the cost of energy (LCOE) for systems using nanofluids dropped from 0.016 USD/kWh to 0.004 USD/kWh with higher interest rates, from 4% to 18%. Additionally, the environmental analysis showed a considerable decrease in CO_2 emissions for systems using electricity compared to those using gas. These results suggest that MWCNT nanofluids significantly improve both the efficiency and environmental impact of solar thermal systems.

Key words. Direct absorption solar collector (DASC), nanofluid, MWCNT, thermal performance.

Nomenclature.

Symbols	Description
$\dot{Q}$ [W]	Heat flow
m [kg]	Mass
Cp [J/kg·K]	Specific heat capacity
W [m]	Width of coelloctor
I [W/m²]	Solar radiation
K [W/m·K]	Thermal conductivity
T [K]	Temperature
Tm [K]	Mean temperature
D [m]	Diameter
h [W/m²K]	Heat transfer coefficient
A [m²]	Collector area
Δx [m]	Step for length
t[s]	time
Ra	Rayleigh number
Re	Reynolds number
Nu	Nusselt number
L[m]	Lenght
Gr	Grashof number
Pr	Prandtl number
f	Friction factor
Z [USD/m²]	Cost for per square are
i [%]	Discount rate
τ [%]	Interest rate
$\dot{m}$[kg/s]	Flow rate
C_{CO_2}[USD]	Saving cost from CO_2
c_{co_2}[USD/kg]	Specific cost of CO_2
$Q_{u.annual}$	Annual specific heat gain
Greek symbols	
$\propto$	Absorption coefficient
γ	Inclination factor
ε	Emittance
σ	Stephan Boltzmann coefficient
μ	Dynamics vicsosity
μ_{CO_2}[kg/kWh]	Specific CO_2 emission
Subscripts	
f	Fluid
g	Glass
ab	Absorber
in	Inner
out	Outer
ext	external
eff	effective
u	useful
Abbrevations	
$LCOE$	Levelized cost of energy
crf	Coefficient recovery factor
MWCNT	Multiwalled carbon nanotubes
DASC	Direct absorption coefficient
Al_2O_3	Aluminium dioxide
RMSE	Root mean square error

1. Introduction

As the world's fossil fuel reserves dwindle and the effects of climate change worsen, there is a need to find more sustainable methods of producing and using energy. Harnessing renewable energy like solar and wind power offers a crucial solution to the twin challenges of combating climate change and preserving dwindling fossil fuel resources. Thanks to its versatility, solar energy stands out as one of the most productive renewable sources. Solar thermal technologies are key drivers of solar energy use, playing a crucial role in both industrial and domestic sectors. Namely, application of solar thermal collectors, namely DASCs (Direct absorption solar collector) support to get a primary enviro-economic energy in domestic and industrial sectors. Moreover, other types of solar systems are also stand a crucial for eco-friendly implementation. Furthermore, enhancement of thermal efficiency of solar thermal systems also remaining actual and provide to get more thermal energy.

Due to advances in nanotechnology, nanofluids are now used preferable in various thermal systems, such as heat exchanger, fuel cells, solar collectors. Nanofluids, which are liquids that contain tiny particles called nanoparticles, have proven to be very effective in improving how well solar thermal collector’s work. These fluids can greatly increase the efficiency of solar collectors. For example, using a mixture of nanoparticles like MWCNT/Al_2O_3 (50:50%) can boost efficiency by up to 29% depending on how fast the fluid flows[1]. Nanofluids also have better thermal properties, such as improved thermal conductivity and the ability to transfer heat more effectively. For instance, Al_2O_3 nanofluids can increase thermal conductivity by up to 6.7% and enhance heat transfer by 25%[2]. While conducting studies on the thermal performance of direct absorption solar collectors using nanofluids as heat carriers, it's also crucial to conduct an economic evaluation of the energy efficiency of these systems [3]. In addition, in [4] established exergoenvironmental (EXEN), exergoenviroeconomic (EXENEC) analyses are performed to a solar collector. Regarding of results, the EXEN result (0.0727 kg CO2/day) is lower than the corresponding environmental one (0.0777 kg CO_2/day).

Driven by these findings, our main goal is to thoroughly analyze the economic and technological aspects of direct absorption solar collectors (DASC) that use polymer materials with a small amount (0.05% volume) of multi-walled carbon nanotube (MWCNT) nanofluids as the heat-carrying fluid. To achieve this, we plan to prepare nanofluids using MWCNT nanoparticles, study and analyze their physical properties related to heat, model the DASC, assess its thermal performance, and conduct economic evaluations.

2. Methodology

A. Energy balance

For our study, we have chosen the numerical method to model the thermal behaviors in direct absorption solar collectors (DASC) using MWCNT nanofluids. We developed a mathematical model that represents the heat balances within the control volume. This model uses differential equations to describe each part of the collector. These equations are then solved by discretizing them using an implicit scheme, under several assumptions: the thermal conductivity of the absorber tube and glass shell is constant; transverse conductivity in the absorber pipe and glass is not considered; there are minor conductivity losses at the ends of the absorber tube; the pressure in the space between the absorber and the glass bulb is included; there is a uniform redistribution of solar radiation within the absorber tube. This mathematical model of the DASC collector is articulated through heat balance equations for each component, detailed in equations (1-4). To identify the most effective technical solution for direct absorption solar collectors using a nanofluid coolant, we analysed their thermal regime based on an existing design, as illustrated in Figure 1.

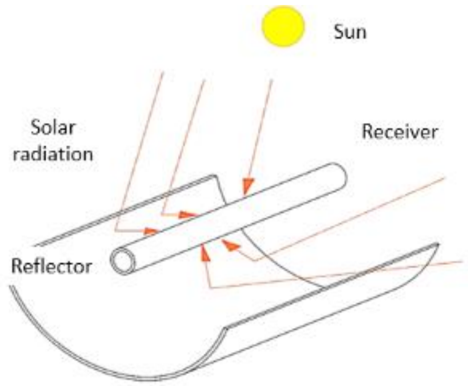

Fig.1. Schematic diagram of a direct absorption solar collector.

In the control volume, the general heat balance of DASC can be written as given in eq (1).

$$\dot{Q}_{f.in} + \dot{Q}_{solar} = \dot{Q}_{f.out} + \dot{Q}_{loss} \quad (1)$$

where $\dot{Q}_{f.in}$ is the energy of the inlet liquid, $\dot{Q}_{solar}$ is the solar energy reaching the surface of the collector, $\dot{Q}_{f.out}$is the energy of the output liquid, $\dot{Q}_{loss}$ is the energy loss from the collector. Accordingly, in the control volume, the heat balance on the glass casing can be written as follows:

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

Heat balance equation for absorber tube;

$$m_{ab} Cp_{ab} \frac{dT_{ab}}{dt} = W I_d \rho_0 \propto_0 \gamma K + A_{ab} k_{ab} \frac{d^2 T_{ab}}{dx^2} - \pi D_{ab(ext)} h_{(int)} (T_{ab} - T_g) - \pi D_{ab(int)} h_u (T_{ab} - T_f) \quad (3)$$

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

$$m_f Cp_f \frac{dT_f}{dt} + \left(\frac{\dot{m}_f Cp_f}{\Delta x}\right) \frac{dT_f}{dt} = A_f k_f \frac{d^2 T_f}{dx^2} + \pi D_{ab(int)} h_u (T_{ab} - T_f) \quad (4)$$

The proposed mathematical model is solved by numerical methods, which takes into account the boundary conditions and the initial values of the parameter under study. As a boundary condition taken the annual weather data of Tashkent such as solar radiation, ambient temperature and wind velocity. Boundary condition for fluid temperature and temperature of collector parts given by eq (5).

$$T_f = 293K, \begin{Bmatrix} x = 0 \\ t = 0 \end{Bmatrix} \quad (5)$$

B. External and internal heat losses

All physical properties of outside air are calculated on average air temperature and glass. Heat loss from the outer surface of the receiver by conventional heat transfer can be found as follows:

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

In the presence of wind, convection becomes forced and equation can be modified as follows:

$$h_{c(ext)} = C Re_{air}^n Pr_{air}^m \left(\frac{Pr_{air}}{Pr_g}\right)^{\frac{1}{4}} \frac{k_{air}}{D_{g(ext)}} \quad (7)$$

The criteria for the Reynolds number will be different coefficients as followings;

$$1 < Re_{air} \leq 40, \text{ where, } C = 0.75 \text{ и } n = 0.4$$
$$40 < Re_{air} \leq 10^3, \text{ where, } C = 0.51 \text{ и } n = 0.5$$
$$10^3 < Re_{air} \leq 2 \times 10^5, \text{ where, } C = 0.26 \text{ и } n = 0.6$$
$$2 \times 10^5 < Re_{air} \leq 10^6, \text{ where, } C = 0.076 \text{ и } n = 0.7$$

$$m = \begin{cases} 0.37 & Pr_{air} \leq 10 \\ 0.36 & Pr_{air} > 10 \end{cases} \quad (8)$$

The internal heat transfer coefficient can be calculated through the following expressions;

$$h_{c(int)} = \frac{2k_{eff}}{D_{ab(ext)} ln\left(\frac{D_{g(int)}}{D_{ab(ext)}}\right)} \quad (9)$$

Where, k_{eff}-effective thermal conductivity of absorber (receiver) can be found as follows;

$$k_{eff} = 0.386 k_a \left(\frac{Pr_{air}}{0.861 + Pr_{air}}\right)^{\frac{1}{4}} (Ra_c)^{\frac{1}{4}} \quad (10)$$

$$Ra_c = \frac{\left(ln\left(\frac{D_{g.int}}{D_{abs.ext}}\right)\right)^4}{L^3_{eff}\left(D_{абс.вне}^{-3/5} + D_{g.int}^{-3/5}\right)^5} Ra_{eff} \quad (11)$$

$$L_{eff} = \frac{D_{g.int} - D_{abs.ext}}{2} \quad (12)$$

$$Ra_{eff} = Gr_{air} Pr_{air} \quad (13)$$

Consistently, the coefficients of internal and external heat transfer by radiation are calculated according to Stefan Boltzmann's law.

$$h_{r(ext)} = \varepsilon_g \sigma \left[(T_{sky} + 273)^2 + (T_g + 273)^2\right](T_{sky} + T_g + 546) \quad (14)$$

$$h_{r(int)} = \varepsilon_{int} \sigma \left[(T_{ab} + 273)^2 + (T_g + 273)^2\right](T_{ab} + T_g + 546) \quad (15)$$

where,

$$\varepsilon_{int} = \left(\frac{D_{g(int)}}{D_{abs(ext)}}\right) \Big/ \left(\frac{1}{\varepsilon_{abs}} + \frac{1 - \varepsilon_g}{\varepsilon_g}\right) \quad (16)$$

The temperature of the sky is determined according to the ambient temperature;

$$T_{sky} = 0{,}0552 T_{amb}^{1.5} \quad (17)$$

Accordingly, the useful convection heat transfer coefficient depends on the Nusselt number at different coolant flows. The parameter of convection heat transfer from the liquid to the absorber, which determines the ability of heat transfer to the coolant, is calculated by the expression (18).

$$h_u = \frac{k_f}{D_{ab(int)}} Nu_f \quad (18)$$

Under forced internal convection, the Nusselt number for laminar and turbulent regimes can be seen as in the following expressions (19).

With laminar flows, fully developed, with uniform heat flow (q=const), Nusselt number[3], [4];

$$Nu_f = 4.36, \text{ for } Re_f < 2300 \quad (19)$$

When the flow is transient, the Nusselt number will be as follows:

$$Nu_f = \frac{(f/8)(Re_{жд} - 1000)Pr}{1 + 12.7\sqrt{f/8}(Pr^{2/3} - 1)} \text{ for } 2300 \leq Re_f \leq 5 \times 10^6 \quad (20)$$

where the friction coefficient is defined as follows:

$$f = {}^{64}/_{Re} \text{ for } Re_f < 2300 \quad (21)$$

$$f = [0.790 ln Re_f - 1.64]^{-2} \text{for } 3000 \leq Re_f \leq 5 \times 10^6 \quad (22)$$

If the flow is completely turbulent with uniform heat flow then the Nusselt number is expressed as follows:

$$Nu_f = 0.023 Re_f^{0.8} Pr_f^{0.4} \quad \text{for } Re_f > 2300, \ 0.6 < Pr < 100 \quad (23)$$

B. Heat transfer fluid and its preparation

Evaluating the economic viability of a direct absorption solar collector hinges upon its thermal performance, which is intimately linked to the thermophysical properties of the employed nanofluid. In this study all calculations carried for the prepared nanofluid based on MKN-MWCNT-RG1020 nanoparticles and water as a base fluid. There are several methods for dispersing nanoparticles in base fluids to create nanofluids, including the popular "single-step" and "two-step" methods. For this study, the "two-step" approach was chosen as the preferred technique for preparing nanofluids containing MWCNTs at different concentrations under ambient conditions (room temperature and atmospheric pressure). Briefly, distilled water (DW) served as the base fluid, into which the desired MWCNT nanoparticles (0.05% volume concentration) were introduced (Fig.2)

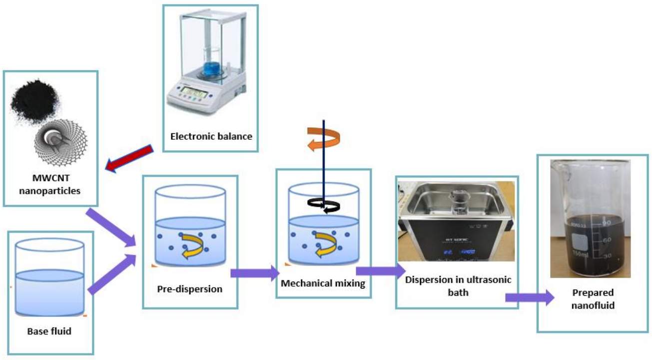

Fig.2. Steps of nanofluid preparation by using “Two-step method”

As showed in figure.2 mechanical mixing was employed to initially mix the suspension, followed by ultrasonic processing for 30 minutes at 25°C. This ultrasonic treatment utilized a power range of 400 to 1200 W and a frequency of 40 kHz.

C. Thermophysical properties (Dynamic viscosity)

Dynamic viscosity, a crucial parameter in heat transfer, significantly impacts the thermal performance of solar collectors. In direct absorption solar collectors (DASC), MWCNTs-based nanofluids serve as the heat carrier. To accurately predict the dynamic viscosity of the nanofluid as a function of operating temperature, we propose a new correlation (eq. 24). While, pursuing the new correlation was held the validation, as result the coefficient of determination R^2-value and RMSE were 0.99 and 1.18E-09 Pa·s, respectively.

$$\boldsymbol{\mu_{nf} = -1.379 \cdot 10^{-8} \cdot T^3 + 2.437 \cdot 10^{-6} \cdot T^2 - 0.0001444 \cdot T + 0.003532} \quad (24)$$

D. Solution procedure

To address this problem, a finite difference method was employed. Integrating equations (2-4) using the control volume method, using a fully implicit difference scheme. After discretizing the nonlinear differential equations, the system of algebraic equations is solved using one of the iterative Gauss-Seidel method, which is more stable and accurate for nonlinear equations. Based on the existing methodologies, the time step was 2 minutes. To implement the compiled model numerically, we proposed an algorithm and software developed in the Spyder package (Python 3.8.12).

E. Model Validation

The model created for this research was assessed by comparing it against experimental results from Dudley (SNL) over seven different conditions. This comparison highlighted a root mean square error (RMSE) of 0.61K and a coefficient of determination (R^2) of 0.99995, demonstrating that the model possesses an exceptionally high degree of predictive accuracy.

F. Boundary conditions

As boundary conditions have been chosen the one-year climate conditions of Tashkent, where Direct solar radiation was changed from 0.001 W/m^2 to approximately 1000 W/m^2, while the ambient temperature changed from -10℃ to approximately 40℃ and the speed of wind shifted up to 11 m/s (Fig.3).

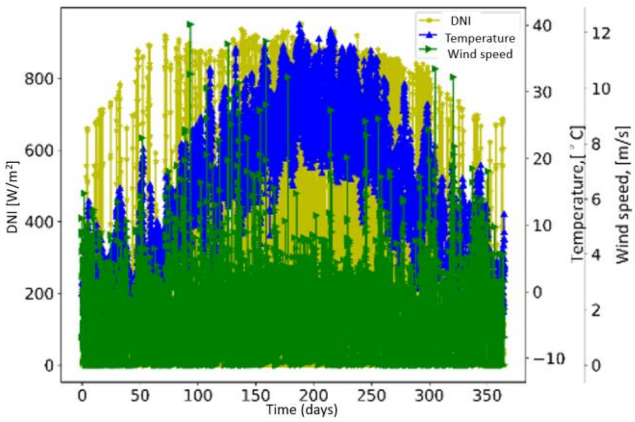

Fig.3. Annual dynamics of Direct solar radiation, ambient temperature and wind speed of Tashkent.

3. Results and Discussion

A. Thermal performance

The thermal performance of solar collectors is essential for determining how efficiently and effectively they can convert solar energy into usable heat. In our study, we looked at the thermal performance of direct absorption solar collectors (DASC) using MWCNT-based nanofluids. We analyzed temperature rise, specific heat gain, and efficiency, comparing these results with those using water as the heat carrier. Figures 4.a and 4.b display the yearly useful heat gain per square meter of collector area when using MWCNT nanofluids versus water as coolants, along with a comparison of the external temperatures.

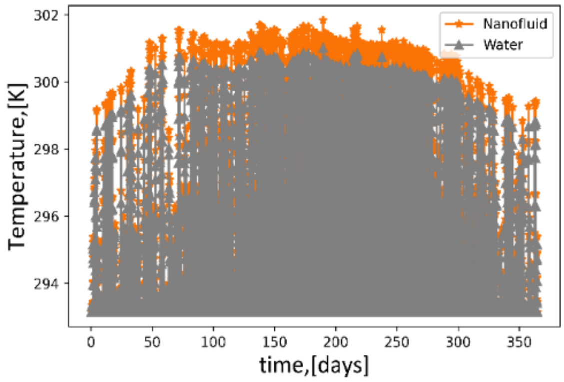

Fig.4.a. Comparison of the annual dynamics of outer temperatures of heat transfer fluids (MWCNTs-based nanofluids and water) from the DASC collector.

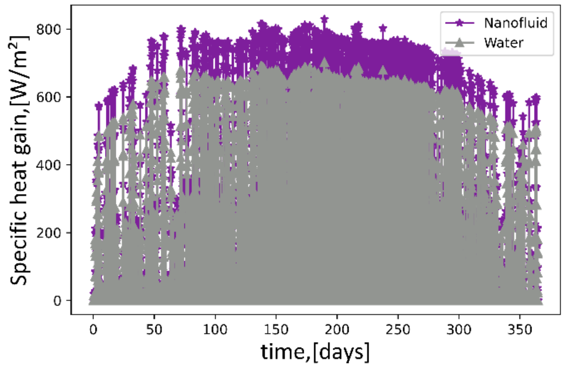

Fig.4. b. Comparison of the annual dynamics of specific heat gain of heat transfer fluids (MWCNTs-based nanofluids and water) from the DASC collector.

Figure 4.a shows a graph comparing the temperature of a nanofluid to that of water over a year. The nanofluid maintains a higher temperature range of 296-302 K, compared to water's 295-300 K, indicating better thermal stability. Figure 4.b illustrates the annual specific heat gain of a direct absorption solar collector (DASC) using both nanofluids and water as coolants. The nanofluid's specific heat gain peaks at about 800 W/m2, significantly higher than water's peak of less than 50 W/m2. The difference in specific heat gain between the nanofluid-based and water-based systems is 126.5 W/m².

B. Thermal efficiency

Thermal efficiency is a key indicator of effective performance in solar thermal applications like (DASC), especially when using (MWCNTs)-based nanofluids. It, along with specific heat gain, outer temperature, and heat transfer coefficient, plays a crucial role in evaluating performance. Figure 5 compares the thermal efficiencies of DASC using water and MWCNTs-based nanofluids, focusing on temperature reduction *Tm*, as specified in EU standards EN 12975-1:2000.

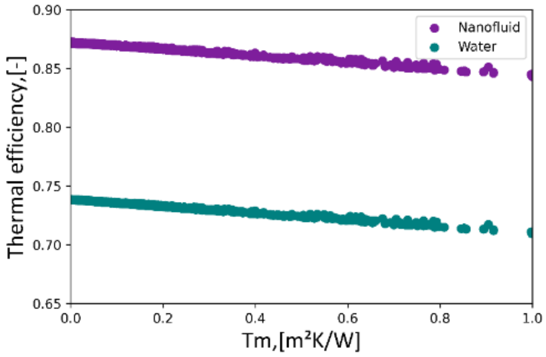

Fig.5. Comparison of the annual thermal efficiency of DASC using MWCNTs-based nanofluids and water, with respect to the reduce temperature value $\boldsymbol{T_m}$.

As shown in fig.5. the thermal efficiency of DASC 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%.

C. Economic analyses

Consequently, conducting an analysis to determine the economic feasibility of employing power plants equipped with polymer solar collectors that utilize nanofluid coolants derived from multi-walled carbon nanotubes (MWCNT) presents a critical and timely challenge. The cost of the energy produced is calculated using the Levelized Cost of Energy (LCOE). eq (25).

$$LCOE = \frac{crf \cdot Z_{investment} + Z_{O\&M}}{Q_{u.annual} \cdot t_{annual}} \qquad (25)$$

where, crf is the capital recovery factor eq (25), $Z_{investment}$- 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.

$$crf = \frac{i \times (i+1)^n}{(i+1)^n - 1} \qquad (26)$$

where, i is the appropriate discount rate, which can be calculated as following;

$$i = \frac{1+\tau}{(1+e)} - 1 \qquad (27)$$

where, τ is interes rate of bank and e is the rate of an infliation.

The useful heat energy received from the collector is calculated by following;

$$\dot{Q}_u = \dot{m} \cdot c_p \left(T_{fout} - T_{fin}\right) \qquad (28)$$

where, $\dot{m}$ is the flow rate of the heat carrier, c_p is the relative heat capacity, T_{fout} and T_{fin} are the inlet and outlet temperatures of the heat carrier.

Annual useful energy is calculated using eq (29).

$$Q_{u.annual} = \frac{\int_0^t \dot{Q}_u dt}{A} \qquad (29)$$

The collector total surface is A, $\dot{Q}_u$-useful heat gain, t-time.

In table I illustrated the techno-economic indexes, which are boundary conditions for ecenomical analysis.

Table I. Technical and economic indicators

Parametres	Units	Value
Interest rate	%	4-18
Infliation	%	8-20
Initial investment	*USD/m²*	179-Nanofluid based collector 175-Water based collector
Collector lifetime	*year*	≥ 10
Annual useful heat gain	*kWh/m²·a*	1469.9 (MWCNT) 1244 (Water)
Total surface of the Collector	*m²*	39

Regarding the methods for economic analyses and the technical and economic indicators of DASC provided in Table I, the LCOE for the collector has been evaluated considering the relevance of the bank interest rate and inflation, as shown in Figure 6.

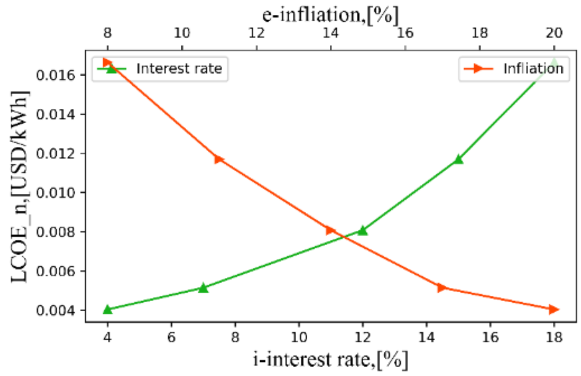

Fig.6. Effect of Interest rate and Inflation on the Levelized Cost of Energy (LCOE) from the DASC collector by using MWCNTs-based nanofluids as a heat carrier.

The graph depicts the correlation between the LCOE of a DASC using nanofluids and two economic variables: interest rates and inflation. Contrary to the previous statement, the graph actually shows a decrease in LCOE as interest rates go up, with a drop from roughly 0.016 USD/kWh to 0.004 USD/kWh when interest rates increase from 4% to 18%. In an inverse relationship, inflation's rise from 8% to 20% corresponds with a decrease in LCOE from about 0.016 USD/kWh down to 0.004 USD/kWh. These trends underscore the impact that financial factors have on the cost-efficiency of DASCs, which is a critical consideration in their implementation and financial planning.

D. Ecological analysis

The objective of the environmental analysis of the considered types of solar collectors using nanofluid heat carriers was to calculate the environmental indicators (reduction of CO_2 emissions) for the conditions of the Republic of Uzbekistan. The annual specific mass of CO_2 emissions (kg/m²·year) from the combustion of traditional types of fuel to produce as much energy as the solar installations generate is determined by the eq.30.

$$M_{CO_2} = \mu_{CO_2} \cdot Q_{u.annual} \qquad (30)$$

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 amount of money saved from emissions is determined by the following formula;

$$C_{CO_2} = c_{co_2} \cdot M_{CO_2} \qquad (31)$$

where c_{co_2} - is the specific cost of CO_2 released when fuel is burned. Calculated ecological indicates defined as follows; The provided data outlines several key parameters related to the use of gas and electricity as fuels and their environmental impacts. Specific CO_2 emissions are measured at 0.369 kg/kWh when using gas and increase to 0.489 kg/kWh for electricity. Economically, the savings from reducing CO_2 emissions during fuel combustion range between USD 14.5 to 22.5 per ton of CO_2. In terms of fuel costs, gas is more economical at USD 0.004 per kWh compared to electricity, which costs USD 0.029 per kWh. Regarding the reduction of CO_2 emissions, using electricity as fuel results in a higher reduction, achieving 718.341 kg/m² per year, as opposed to 542.061 kg/m² per year with gas. These figures are crucial for evaluating the economic and environmental benefits of different fuel types in energy production.

4. Conclusion.

In conclusion, our study demonstrated that direct absorption solar collectors (DASC) using MWCNT-based nanofluids significantly outperform traditional water-based systems in thermal performance. MWCNT nanofluids maintained a higher temperature range of 296-302 K compared to water 295-300 K and achieved a specific heat gain up to 800 W/m², far exceeding water's peak of less than 50 W/m². The mathematical model validated against experimental data showed a root mean square error (RMSE) of 0.61K and a near-perfect coefficient of determination (R^2) of 0.99995. Economically, the levelized cost of energy (LCOE) for DASC using nanofluids fell from 0.016 USD/kWh to 0.004 USD/kWh as interest rates rose from 4% to 18%. Environmental analysis also revealed a significant reduction in CO_2 emissions, with electricity-fueled systems achieving 718.341 kg/m² per year compared to 542.061 kg/m² with gas. These findings underscore the effectiveness of using MWCNT nanofluids to enhance the efficiency and sustainability of solar thermal systems.

Acknowledgement

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