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Investigation of thermal Performance of a parabolic trough solar collector (PTSC) with different fluids using CFD method

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Abstract

This study was aimed to examine the effect of fluid type on the thermal performance Parabolic Trough Solar Collector (PTSC) was investigated. The simulation process was performed using Computational Fluid Dynamic (CFD). The experiments were conducted at the air flow rate of 0.08 m/s. Four fluid types including water, glycerin, engine oil (10W40) and Nano-fluid (Al_2O_3, 9%) were considered for the performance analysis. At the end of the day the final fluid temperature which stored in the storage tank was about was about 64.9, 79.2, 83.5 and 90.8, respectively. Moreover, thermal obtained energy for water, glycerin, engine oil and Nano-fluid was 34.19 MJ, 37.79 MJ, 43.18 MJ and 50.76 MJ, respectively. CFD simulation of the storage system showed that there is a good agreement between the simulated and experimental data at different air flow rates. Using PCM has no adverse effect on the quality of the dried product.

Keywords: CFD simulation, Nano-Fluid, Solar dryer, Storage system, Thermal efficiency

INTRODUCTION

More than 12% of the overall energy demeaned by manufacturing industry, supplied by fossil fuels. But the negative environmental and health effects of fossil fuels combustion as the main energy sources must be taken into account in considerations. Moreover, the source of fossil fuel is ending up and after a while there will be limited for the future [1-2]. Due to these reasons, using the renewable energy such as solar energy could be a good solution to supply energy sources. Typically, solar collectors are connected with the thermal systems such as drying systems, heating and cooling systems. However, due to the lower thermal efficiency, the solar systems are less considered for thermal usage. Therefore, much effort such as combining system, using phase change materials, and using fluid with higher heat capacity have been carried out for improving the performance of the solar systems.

Among the solar collectors which are connected with the storage system, Parabolic Trough Solar Collectors (PTSC) are more efficient collectors with lower maintenance and lower cost. There are some advantages with PTSC such as having a good performance during the year (especially for the days with lower solar radiation due to the sun tracking system) [3-4]. Various studies have been performed to increase the efficiency of evacuated tube solar collectors such as: using nanofluid[5][3], changing the shape of the absorber tubes [6], evaluation of optimal tilt-angles of all-glass over the tubes [7], using water in glass cover of the tubes [8] and using individual single walled evacuated tube with direct flow [9].

The low efficiency of solar system could be improved using fluids with higher heat capacity and storing thermal energy inside storage tank. With the using fluid inside the thermal system, the amount of thermal energy stored by the fluid during the day (especially when the solar radiation intensity is in maximum level) increases. There are some materials used in Parabolic Trough Solar Collectors such as hydraulic oil [10], CeO_2/water [3], Al_2O_3 [11], CuO [12], and TiO_2 [13].

Computational fluid dynamics (CFD) is a powerful tool for fluid dynamics and thermal design in industrial applications, as well as in academic research activities [14]. In this method to simulate fluid flow and heat transfer process inside the system, powerful computers and applied mathematics was used [15]. Since the heat transfer and the behavior of the PTSC is depending on the geometrical design of the collector and the type of the fluid which flows inside the system, experimental validation of the system at different condition is very difficult and time consuming [16]. Thus using CFD method increases the accuracy of the project and decreases the cost and the time used for thermal analysis of the system. There are a bunch of numerical investigations dealing with effect analysis of using different fluids on the thermal efficiency of the PTSCs such as [17-20]. In the present work the validation of a CFD model developed for the transient simulation of the energy performance was investigated. Also the CFD simulated model was validated using experimental data which were collected at the same condition applied for simulation process.

MATERIALS AND METHODS

A. Fundamentals of CFD theory

The amount of heat generated by the solar radiation on a surface is calculated using Eq.1:

$$Q_{rad} = A_e \sigma (T_c^4 - T_a^4) \quad (1)$$

Where Q_{rad} is the thermal radiation power (W), A_e is radiation area (m^2), σ is Boltzmann constant 5/669×10[8] (W m^{-2} K^{-4}) and T_c and T_a are the temperature (°C) of the tube and the ambient air, respectively [21].

The relation between radiation and absorption for the collector plate is obtained by Eq. 2:

$$\theta + \alpha + \tau = 1 \quad (2)$$

Where θ is reflection coefficient, α is absorption coefficient and τ is diffusion coefficient. Most of the objects used in nature do not emit solar and thermal radiation, so its value is negligible. To model the solar systems, we need to calculate the spectral coefficient as Eq. 3:

$$SF = \frac{I_{visible}}{I_{visible} + I_{IR}} \quad (3)$$

$I_{visible}$ is the flux of visible beams to the surface and I_{IR} is the fluxes of infrared rays.

Considering the reflection and absorption in the position r and direction s, the Eq. 4 can be used to calculate the radiant heat transfer equation.

$$\frac{dI_{(\vec{r},\vec{s})}}{ds} + (\alpha + \theta) I_{(\vec{r},\vec{s})} = \alpha n^2 \frac{\sigma T^4}{\pi} + \frac{\theta}{4\pi} \int_0^{4\pi} I_{(\vec{r},\vec{s})} \varphi_{(\vec{s},\vec{s}')} d\Omega' \quad (4)$$

Where n is the refractive index of light, φ is the light fuzzy functions and Ω' is the solid angle of the sun's motion.

By ignoring the effect of gravitational acceleration, the conjugation and displacement equations are solved in the form of Eq. 5 and Eq. 6.

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho U) = 0 \quad (5)$$

$$\frac{\partial \rho U}{\partial t} + U.\nabla \rho U = -\nabla P \quad (6)$$

A. Modeling solar absorber tube

To analysis the fluid dynamics of the collector, ANSYS workbench 14.2 and Solid works 2014 were first installed on a computer. Then, the 3D model of collector was fully detailed in the Solid works software, stored in a separate folder as an independent part and each separately was imported to ANSYS fluent subprogram. After applying the 3D mesh, the type of materials used in the collector (Table 1) and the boundary conditions were applied to the models and the model was solved based on the turbulence condition.

Table 1. The characteristics of the working fluids and copper tube as the receiver of the collector

Fluid type	Properties			
	specifit heat (J/kg.K)	termal conductivity (W/m.K)	density (kg/m^3)	viscosity (kg/m.s)
Water	4182	0.6	998.2	1.001×10^{-3}
Glycerin	2428	0.284	1261	0.799
Engine Oil	1980	0.96	917	0.96
NanoFluid	2750	1.22	1097	0.01
Copper	390	401	8920	-

The quality of the mesh and grid for the model were checked statistically using skewness criteria. Generally, the best mesh was related to those with the skewness of zero and the worst was related to meshing system with the skewness of 1 [22-23]. The medium mesh was considered for collector and the storage tank and the reports of the evaluation of the meshing process showed that the skewness for the system tank was about 0.32 and it was suitable for any progress in CFD simulation. Moreover, the grid independency test showed that the fine distribution grid is the most suitable mesh for this study. For validation of the model friction factor was considered and the results showed that the model with the maximum error of 3.2% has a good agreement with the theoretical outputs.

BOUNDARY CONDITIONS:

The following boundary conditions were investigated for simulation the receiver tube:

Inlet: the fluid velocity was about 0.01 m/s with uniform velocity and uniform temperature. Wall: the top and bottom half periphery of the tube are subjected to the radiation. The concentration ratio of the collector is assumed about 25. Outlet: the pressure gradient at the outlet section is assumed equal to zero.

HEAT TRANSFER ANALYSIS

The heat transfer from the absorber to the fluid which flows in the system can be estimated by Eq. 7.

$$Q_s = A_a . G_b \tag{7}$$

In which Q_s is the available solar irradiation, A_a is the collector aperture and G_b is solar radiation utilized by the collector.

The useful thermal energy obtained by the fluid flows in the collector estimated according to:

$$Q_u = \dot{m} . c_p . (T_{out} - T_{in}) \tag{8}$$

The efficiency of solar collector ($\eta_{collector}$) can be estimated as follow:

$$\eta_{collector} = \frac{Q_u}{Q_s} \tag{9}$$

The heat transfer coefficient for collector is defined according to the Nusselt number relationship Eq. 10:

$$Nu_x = \frac{h_x D_1}{k} \tag{10}$$

The friction factor calculated using the following equation considering pressure drop along the absorber tube [11]:

$$f = \frac{2 \Delta P}{\rho_f u^2}\left(\frac{D_1}{L}\right) \quad or \tag{11}$$

$$f = (0.79 . \ln Re - 1.64)^2$$

Where is the pressure drop, is the tube length, u is the fluid velocity and Re is Reynolds number.

In order to reduce thermal energy losses at the end of the absorber plate, 456 holes with a diameter of 6 mm were made with a square model and the distance of 2.5 cm between the holes. The porosity coefficient was 0.0314 (calculated by Eq. 12) [14]:

$$\sigma = \frac{\pi D^2}{4 p^2} = \frac{A_{hole}}{A_{plate}} \tag{12}$$

Where σ is the porosity coefficient of the absorber plate, A_{hole} is the area of each hole (cm^2), A_{plate} is the total surface area of the absorber plate (cm^2), D is the diameter of the hole (cm) and p is the interval of the holes (cm).

Experimental set up

A laboratory scale solar PTSC, equipped with receiver tube, with storage tank was designed and constructed in “Pakdasht, Tehran, college of aboureyhan”. All the experiments were carried out with the mentioned solar dryer in July 2016. The main component of the dryer showed in Fig. 1.

Fig 1. The schematic of solar dryer equipped with: chassis, reflector, receiver tube, thermal controller, centrifugal pump.

Fluid has the main role for transmitting the thermal energy through the collector. The fluid heated inside the receiver tubes and moved from the collector to the storage tank using a pump. By the time the fluid temperature inside the storage tank increases. Due to have the storage system the drying process can be continued during the night time. The details of the system showed in table 2.

Table 2. Details of solar cabinet dryer

Components	Details
Receiver tube	A copper tube, with diameter of 30mm, the length 2100mm, thickness of1mm
Solar concentrator	A stainless steel with the reflection 0.88 and absorption of 0.1, the concentration factor of 25.
Transferring tube	PVC tubes insulated by glass wool
Storage tank	A poly ethylene cubic tank, 200 liter, insulated by 40 mm thick of glasswool
Fluid circulator	An Axial pump, 12 volt, 10 Ampere (NM, 32-60-180), with flow rate of 0.2 l/min

An automatic temperature controller with an accuracy of ±0.1 °C was used to control the temperature of selected points of the dryer. For this purpose, K type calibrated thermocouples were installed at different points of the collector. The sensors were connected to a digital data-logger (DL-9601A, Lutron) and recorded the temperature during the drying process. The environmental relative humidity was recorded every 30 minute by a digital hygrometer (HT, 3600, Lutron, Taiwan) with an accuracy of 0.1%. The ambient air relative humidity and air temperature was about 12-17% and 25-39 ºC. For controlling the solar radiation intensity during the experiments a pyranometer (TES-1333R, Taiwan) with an accuracy of ±1W/m^2 was used. The airflow at different points of the dryer was controlled by an anemometer (AM- 4206, Lutron, Taiwan). The flow rate of the fluids was controlled using a flowmeter (PROMAG - 53P).

RESULTS AND DISCUSSIONS

Variations of solar radiation for drying system during the experimental days showed in Fig. 2. The amount of solar radiation increases with the time and reaches its maximum level at around 14:00 and then decreases. The mean solar radiation was fluctuating along the days and varied from 40 to 880 W/m^2. The variation of solar radiation during the drying days is not significant.

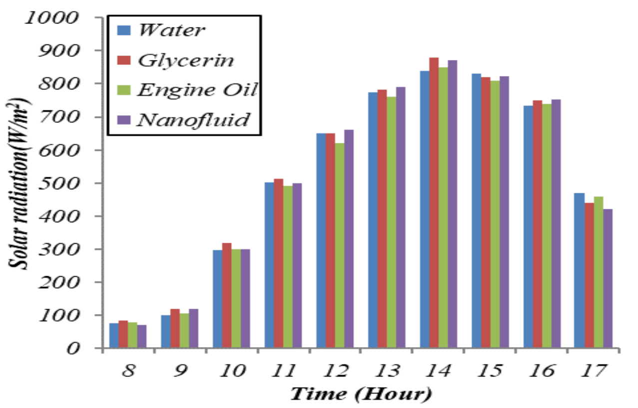


Fig. 2. Variation of solar radiation for different fluids during the experimental days

Fig.3. shows the variation of the ambient temperature ambient temperature and relative humidity versus the local time during the experimental days. The ambient air temperature was varied from of 18 ºC to 35.7 ºC and he relative humidity of the environment varied from 14.4 to 21.4% during the drying days.

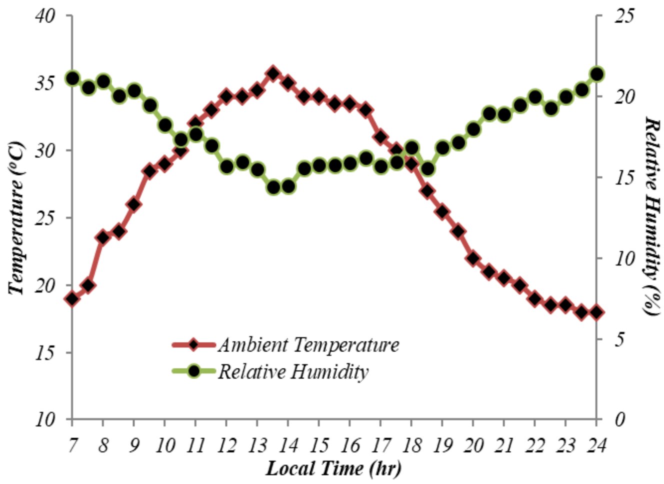


Fig. 3. Variation of ambient temperature and relative humidity versus the local time during the experimental days

By increasing the solar radiation the average fluid temperature increases as well. At the end of the day (16:00 to 17:00) the solar radiation decreased and consequently the increasing rate decreased as well. Due to have the difference of the heat capacity of fluids the values or temperature inside the storage tank was different. The higher temperature for water, glycerine, engine oil and nanofluid were about 64.9 ºC, 79.2 ºC, 83.5 ºC and 90.8 ºC, respectively. The variations can be seen in Fig. 4.

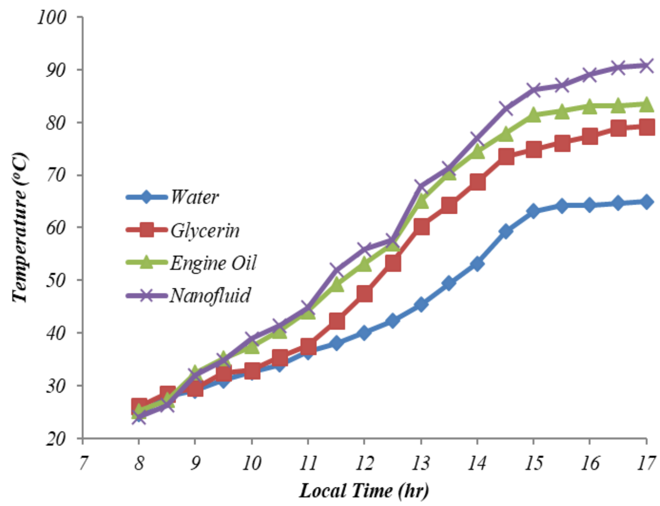
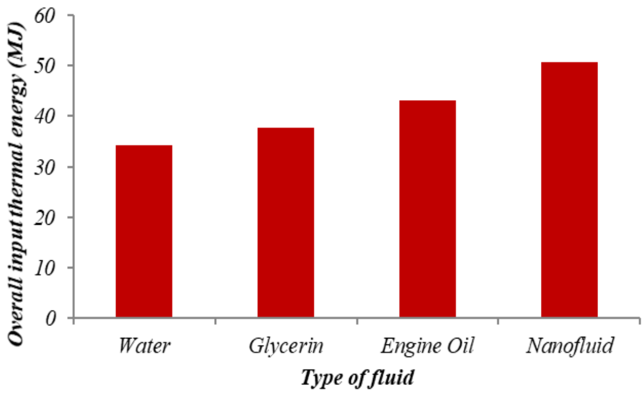
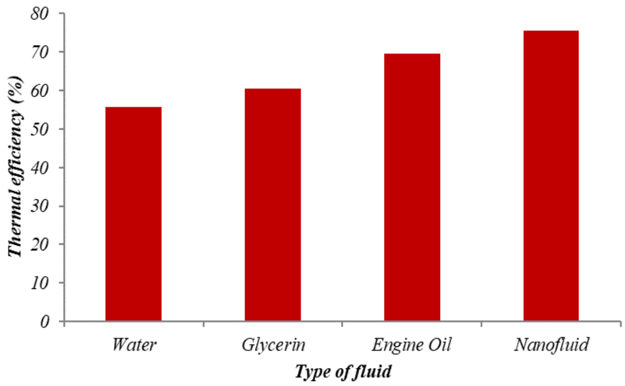


Fig. 4. Variation of temperature inside the cabinet for different fluids inside the system (water, glycerin, engine oil and nanofluid) condition during the drying experiments.

Fig.5 shows the thermal overall energy stored in the storage tank. The thermal energy which reflected to the center tube, absorbed by the working fluid entered to the storage tank. The overall thermal energy varies by changing the type of the working fluid. The highest value (50.76 MJ) and lowest value (34.19 MJ) was related to nanofluid and water as working fluids, respectively. The using submerged nanoparticles in the base fluid (water) increase the heat transfer coefficient. Also, current investigations have shown that using Al_2O_3 helps to increase local heat transfer coefficient of the collector tube and this improved the output temperature of the collector. The thermal efficiency for working fluids was 55.65%, 60.45%, 69.4% and 75.49%. It can be seen that using different types of the fluid (glycerin, engine oil and nanofluid) improved the thermal efficiency of the collector. The overall input thermal energy for glycerin, engine oil and nanofluid was 10.52%, 26.29% and 48.46% higher than water as working fluid.



(a)



(b)

Fig. 5. The variation of a) overall input thermal energy versus the drying time and b) overall input thermal energy versus drying conditions

Fig. 6. displayed the results of CFD simulation and temperature contours at the outlet of the receiver tube for different types of working fluids at 10:00 o'clock. The contours showed that the surface temperature of the tube is higher but it is homogenous for nanofluid related to the water. Due to contact the walls of the receiver with the nano-particle solution, some of the thermal energies absorbed and this decreases thermal loss [24].

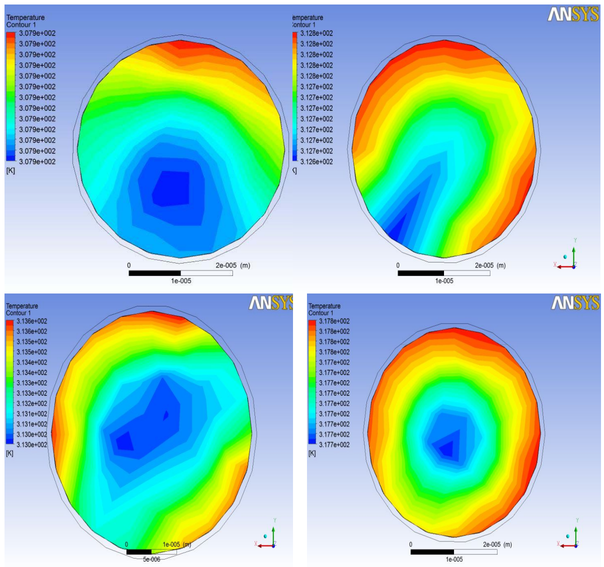


Fig.6. Temperature Counters of receiver tube for different types of working fluid

The comparison between the predicted data obtained by CFD simulation and experimental data for the outlet fluid temperature of the receiver with different working fluids showed in Fig.7. It is clear that the selected CFD model predicted the thermal behavior of the fluid with higher precision (R^2> 0.95). The level of temperate predicted by CFD simulation is higher than the level of experimental values and this is may be due to the environmental and material conditions that has effect on outlet fluid temperature. The relative error for predicted and experimental data varies from 2.9% to 6.7% and it is acceptable based on the other studies which reported similar results for solar system [25-26].

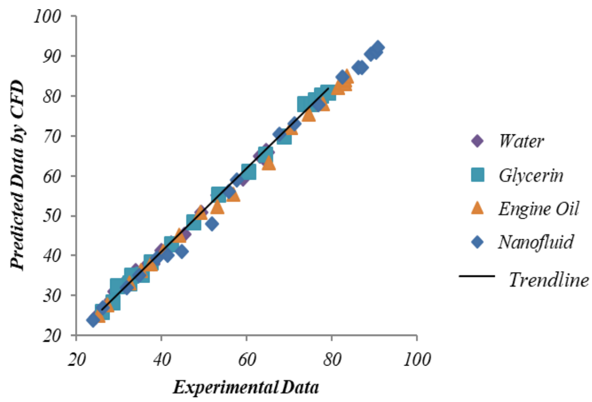


Fig. 7. Experimental versus predicted outlet fluid temperature for the receiver with different types of fluids

CONCLUSION

An experimental study was carried out to the thermal performance and efficiency consideration of PTSC with different fluids. Also the thermal behavior and temperature distribution of the receiver during the experimental days was simulated using CFD. Four types of working fluids including water, glycerin, engine oil (SAE 10w40) and nanofluid (Al_2O_3 9%) were flows in the solar system using a hydraulic pump with the flow rate of 0.01 l/s. The results illustrated that the final fluid temperature in the storage tank using water, glycerin, engine oil and nanofluid was 64.9, 79.2, 83.5 and 90.8, respectively. Moreover, thermal energy stored in mentioned fluids was 34.19 MJ, 37.79 MJ, 43.18 MJ and 50.76 MJ, respectively. Due to the nanoparticle the heat transfer coefficient of the fluid increased and consequently the thermal efficiency of the collector improved. The overall input thermal energy for glycerin, engine oil and nanofluid was 10.52%, 26.29% and 48.46% higher than water as working fluid. CFD simulation of the collector implied that there is a good agreement between the simulated and experimental data at different air flow rates. The study could be used as the cheap and efficient method to get the higher thermal energy of the solar collectors.

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