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THERMAL-HYDRAULIC EVALUATION OF VARIOUS STRIP SHAPES AND NANOFLUIDS ON THE PERFORMANCE OF PARABOLIC TROUGH COLLECTORS

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ABSTRACT

The thermal and thermodynamics performances of the parabolic trough collectors can be improved by using swirl generators as inserts for the solar receiver. Inserts improve the mixing of the flow by not only enhancing the delivery of higher heat transfer rates to the working fluid but also by reducing the convection and radiation losses from the external receiver walls. Furthermore, mixing nanoparticles to this setup results in better thermal properties than those of the pure fluids which in turn helps in increasing the fluid output working temperature and reducing the outer wall temperature. The main objective of the current study is thus to comprehensively assess the effect of various straight strip shapes with and without nanoparticles taking into account different thermal-hydraulic parameters. Four different strip arrangements were considered in the present setup; large conical-shape strips, small conical-shape strips, rectangular-shape strips and elliptical-shape strips. All considered cases were then examined with the presence of nanofluid using 6% SiO_2 nanoparticles mixed with Therminol® VP-1 (TO) at an inlet temperature of 400K. The Monte Carlo Ray Tracing (MCRT) model was used to apply the non-uniform heat flux over the solar receiver in the circumferential direction for the simulations which were performed over a range of Reynolds numbers (10^4-10^5) using two different low-Reynolds number turbulence closures; $k-\omega$ SST and Launder and Sharma.

1. INTRODUCTION

Fossil fuel depletion and global warming are still a challenge that needs to be resolved. Among various renewable and sustainable energy sources, solar energy can be described as one of the most significant approach that can be utilized to solve energy demand requirements without affecting the environment. Amongst the Concentrating Solar Power (CSP) systems, the most commercially developed and widely cost-effective technology is the Parabolic Trough Collector (PTC) technology; especially, for the medium-temperature industrial and engineering applications. There are several proposed techniques that have been used to enhance the thermal performance of the PTC systems such as: changing the operating conditions of pure working fluids; the addition of nanoparticles to the base working fluid and the insertion of metallic turbulators inside the solar absorber. However, the combination of any or all of the aforementioned techniques together to improve the performance has not been well studied in the literature. In the previous studies, various types of inserts have been investigated such as fins, cylindrical inserts, star flow inserts, internal toroidal rings, inclined conical strips, eccentric pipe inserts, wire coils, typical twisted tapes, and straight conical strips attached to the core rod Abed and Afgan (2020a) etc. These inserts presented different levels of increases in thermal energy, pressure drop, overall collector efficiency and thermal exergy. In the present study, we combine the nanofluids with different optimized shapes of swirl generators which act as turbulators to enhance the mixing, thereby improving the thermal performance without considerably increasing the pressure drop across the solar receiver.

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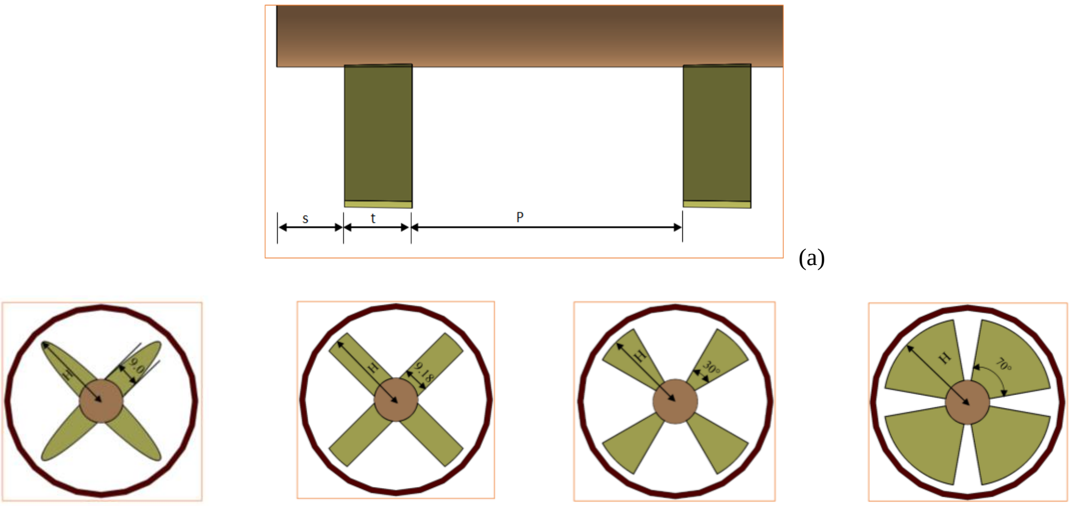
2. PHYSICAL MODEL AND VALIDATION

The strip shapes used in the current work are presented in Figure 1. All strips have a constant thickness (t) of 10 mm and constant horizontal pitch (P) between strip sets which is 486 mm. The first set of strips is positioned 10 mm downstream of the absorber tube inlet (s). Each examined shape set has four strips that have a constant height (H = 30 mm) and located in the major and minor diagonals of the absorber tube. The elliptical geometry has a small diameter of 9 mm and a large diameter of 60 mm whereas the rectangular geometry has a width of 9.18 mm and a length of 60 mm with curved ends. However, the small conical geometry has an angle of 30° as opposed to the large conical strip which has an angle of 70°. Both strip configurations have a constant height of 30 mm. The strip inserts are connected to the centre of the absorber tube.



(a)

(b) (c) (d) (e)

Figure 1: The examined straight strips of inserts in the current study. (a) Lateral view of half examined inserts, (b) Elliptical strips, (c) Rectangular strips, (d) Small conical strips, (e) Large conical strips.

The properties, environmental characteristics and geometrical values are given in Table 1.

Table 1: The PTC model parameters used in the current work.

Property	**Value**	**Property**	**Value**
Inner diameter of absorber tube, D_i	0.066 m	Focal length, f_L	1.84 m
Outer diameter of absorber tube, D_o	0.07 m	Aperture width, w_a	8.0 m
Solar receiver length, L	4.0 m	Ambient temperature, Tam	300 K
Solar beam irradiation, G_b	1000 W/m^2	Wind speed, V	0.5 m/s

In the current study, the Therminol® VP-1 is used as the heat transfer fluid with an inlet temperature of 400 K with the thermal properties summarized in Table 3. The nanofluid is obtained by adding silicon dioxide (SiO_2) nanoparticles to the Therminol® VP-1. The thermal properties of the nanoparticle are also given in Table 2.

Table 2: Thermal properties of Therminol® VP-1 and nanoparticle used in the present study.

Type	μ (Pa.s)	ρ (kg/m^3)	C_p (J/kg.k)	k (w/m.k)	Pr	Reference
Therminol® VP-1	0.000732	975.8	1851	0.1243	10.89	Abed et al. (2020a)
SiO_2	-	2200	765	1.4	-	Abed et al. (2020b)

The thermo-physical properties of nanofluids are normally estimated using empirical or semi-empirical models provided in the literature. The models selected for use here are summarized in Table 3.

Table 3: The thermo-physical properties models for nanofluids used in the present study, Abed et al. (2020c).

Property	Model
Density (ρ_{nf})	$\rho_{nf} = \rho_s \varphi + \rho_f (1-\varphi)$
Specific heat capacity ($C_{p,nf}$)	$C_{p,nf} = \frac{1}{\rho_{nf}}\left[\rho_s C_{p,s}\varphi + C_{p,f}\rho_f(1-\varphi)\right]$
Dynamic viscosity (μ_{nf})	$\mu_{nf} = \mu_f(1 + 7.3\varphi + 123\varphi^2)$
Thermal conductivity (k_{nf})	$k_{nf} = 0.25\left[(3\varphi-1)k_s + (2-3\varphi)k_f + \sqrt{\Delta}\right]$, $\Delta = [(3\varphi-1)k_s + (2-3\varphi)k_f]^2 + 8k_s k_f$

For the parabolic trough collectors, the numerical predictions of thermal efficiency were validated against the experimental data of Dudely et al. 1994 as shown in Figure 2a. On the other hand, for the nanofluids, the numerical results were compared to Pak and Cho (1998) as presented in Figure 2b below for the comparisons of thermal efficiency and Nu number over a range of Reynolds number and ambient temperatures. The SST k-ω performed better than the LS k-ε model as shown in Figure 2a and was thus chosen as the model for all validation and further analysis as shown in Figure 2b.

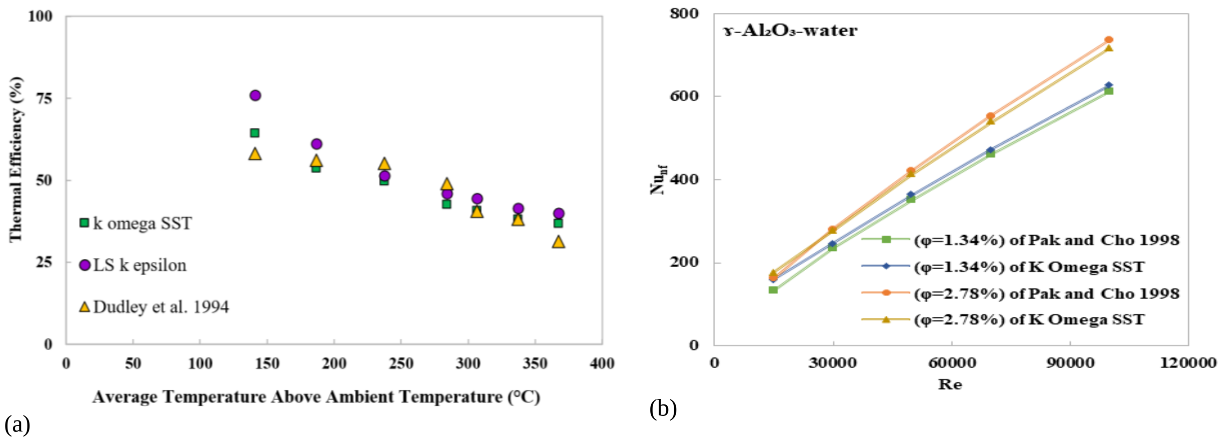


Figure 2: (a) The thermal efficiency predicted from the current study validated with experimental data of Dudley et al. 1994. (b) Nanofluid Nusselt number predicted by the present study compared with the empirical correlation proposed by Pak and Cho (1998).

3. RESULTS AND DISCUSSIONS

All the examined cases showed different levels of heat transfer enhancement and reduction in thermal losses. For example, using nanofluids alone in the solar receiver could only enhance the heat transfer by about 15.57%. Similarly, using the optimized shape of inserts (large conical strips) increased this enhancement to up to 57.49%. However, when the two techniques were combined the heat transfer enhancement was found to be around 62.53%. The numerical simulations were also used to optimize the shape and size of the inserts and it was found that the large conical-shaped strips were the most efficient with the elliptical-shaped strips being the least efficient as far as enhancement of the heat transfer and reduction of the heat losses are concerned; see Figure 3 for the various shapes of the inserts that were tested in the study. The same trend of the overall thermal efficiency enhancement was observed with the maximum argumentation in the thermal exergy efficiency being 15.32% for the large conical strips with nanofluids whereas this enhancement was only 11.25% for swirl generators within pure working fluid. On the other hand, the enhancement with the use of nanofluids alone was only 9.02%.

All results attained by the present work are summarized in Figure 3. It can be observed that inserting different swirl generators and nanofluids, results in enhancement of the convection heat transfer as represented by the maximum Nu number for the large conical shape configuration. This is due to the increased contact surface of the inserts that leads to enhanced mixing of the working fluid and thereby improving the heat transfer. Moreover, the presence of nanofluid and swirl generators also leads to better energy absorption from the absorber wall thereby reducing the thermal losses. These improvements resulted in enhancing the overall collector efficiency and thermal exergy in all cases. The maximum improvements were observed with the larger conical shape with 6% SiO2-Therminal oil nanofluid. However, using nanofluids increases the fluid properties, i.e., dynamic viscosity and fluid density, which increases the pumping power required to force the fluid to move through the solar absorber. Moreover, inserting the swirl generators inside the solar receiver also acts as a barrier against the flow direction thereby further increasing the pressure drop and required pumping power.

A comparison between the best candidate represented by the large conical shape strips and the worst choice represented by the Elliptical shape strips are presented in Table 4, which shows the effects of these techniques on the thermal and hydraulic performances with/without the presence of nanofluids.

Table 4: Summary of the results obtained, LC: Large conical strips, ES: Elliptical strips.

Enhancement Technique	Nusselt Number Enchantment	Thermal Losses Reduction	Thermal Efficiency Improvement	Exergy Efficiency Improvement
Nanofluids (6% SiO2-TO)	16%	16%	9%	9%
Swirl generator (LC)	57%	24%	11%	11%
Swirl generator (ES)	10%	15%	5%	5%
Swirl generator (LC) with Nanofluids	63%	27%	15%	15%
Swirl generator (ES) with Nanofluids	24%	21%	12%	11%

It is evident that the use of nanofluids results in various enhancements in the PTC system includes higher thermal energy, larger overall collector efficiency and thermal losses reduction compared with the typical system. However, the usage of nanoparticles may cause organisms’ diseases and environmental risk from their production to their disposal. The environmental effect of nanoparticles is based on the separation process in the base fluids, how the nanoparticles are utilized in the workplace, nanoparticle stability and their mobility in the base fluids etc. Therefore, the life cycle assessment of nanoparticles and their environmental risk assessment are essential, Taghavi et al. (2013). Moreover, the use of nanofluids increases the pumping power requirements as increase the volume fraction of nanoparticles which resulted in a higher cost for the pumping system.

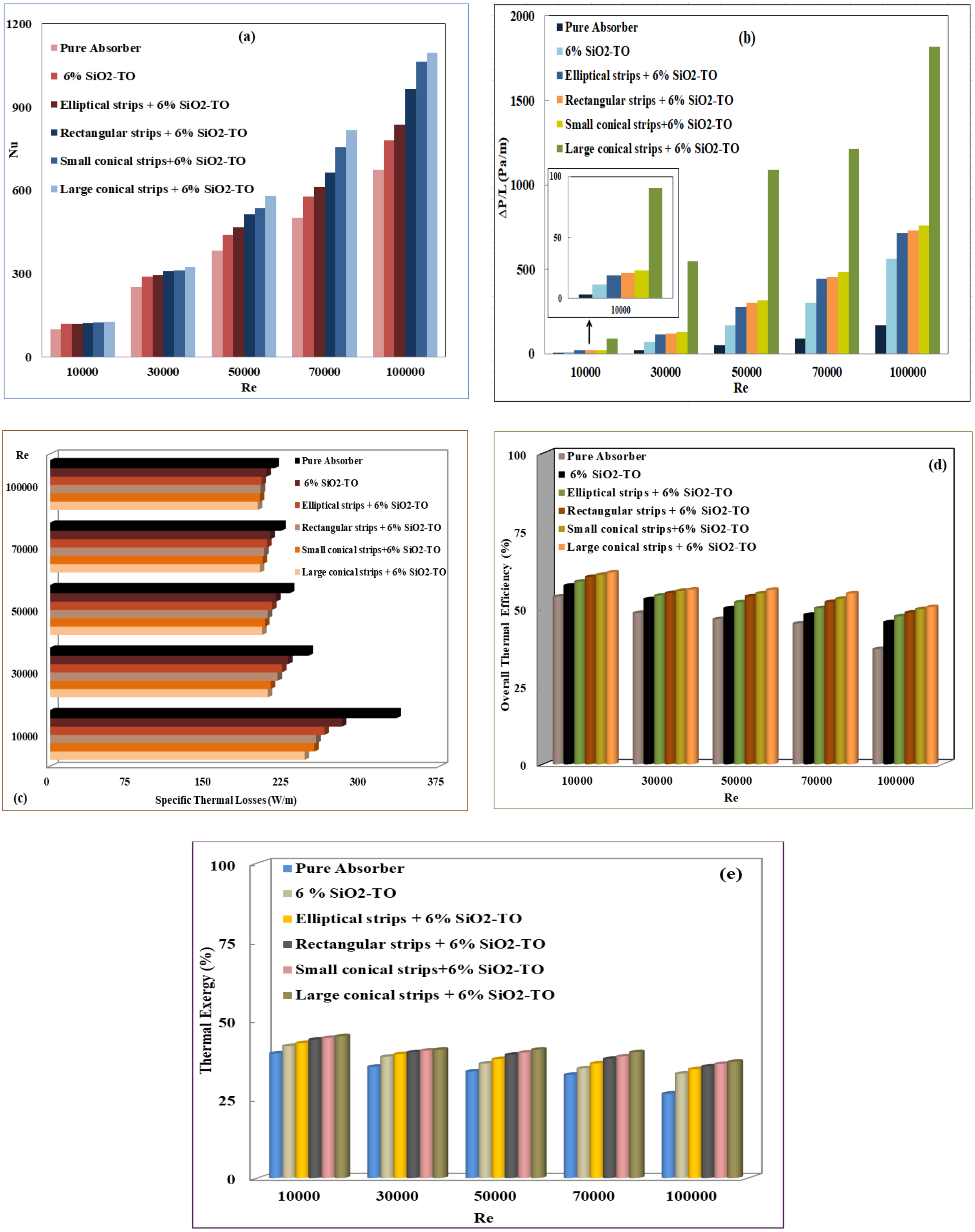


Figure 3: The effect of used technologies on the thermal-hydraulic performances of the PTC system; (a) Nu number, (b) pressure drop, (c) thermal losses, (d) overall collector efficiency and (e) thermal exergy.

4. CONCLUSIONS

The current study examined the effect of different shapes of swirl generators with and without nanofluids on the thermal performance of parabolic trough collectors. Out of the chosen different configurations, the large conical shape was found to be the best and the elliptic shape was the worst when it came to performance improvements. Results showed that the largest improvement in all examined parameters was achieved by the large conical strip geometry swirl generator when combined with nanofluids. For this optimized configuration, the overall thermal efficiency improvement was 15.41%, with the Nusselt number enhancement of about 62.53%, whereas the thermal efficiency and exergy improvements were both found to be just over 15%. From a thermal-hydraulic perspective, the augmentation in the specific pressure drop across different swirl generators was found to be about 11.78% higher than that recorded by the addition of nanofluids alone.

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