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Research Paper

Design Optimization and Experimental Validation of Low-Cost Flat Plate Collector Under Central Qasssim Climate

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Abstract. In Saudi Arabia, hot water for domestic uses consumes a great portion of home electricity. Thus, solar collectors can be considered as an important alternative to reduce the amount of consumed electricity. Therefore, in recent researches, a great attention was given to develop flat plate collector (FPC) with optimal performance. In this paper, a multi-objective modified imperialist competitive algorithm (MOMICA) was employed for optimizing the performance of a FPC. The optimization results showed a capability to reach higher FPC efficiency with a relatively small collector area and hence lower price. It has also been proved that the change of the insulator depth from 0.02 to 0.05 m has a strong influence on the system's efficiency.

Keywords: Flat Plate Collector, Solar energy, Design optimization, Efficiency, Cost, MOMICA.

1. Introduction

The fast growing in energy demands combined with high costs of consuming electrical energy have highlighted the need to use the renewable energy resources [1]. Despite that renewable energy can be considered as one of important alternative to reduce the amount of consumed electricity, it has not been fully utilized in many countries around the world. In this context, solar energy from the sun can be used directly in various applications including heating of water for domestic use. FPC can be considered as a one of the most commonly used devices in converting solar thermal energy into useful heat which is much appropriate for small application including small hotels, houses, hospitals, etc.

Numerous literature studies on FPC characterization and utilization were conducted recently. Kraemer et al. [2] propose a flat plat solar thermoelectric generator in order to convert the sunlight into domestic electricity. Its shown that this kind of solar collector improve the thermal concentration in an evacuated environment. Dalvi et al [3] propose the integration of solar thermal systems into ranking-cycle power plants in order to improve the solar to electricity efficiencies. In order to investigate the performance of a small size FPC, Alghafiss et al. [4] have fabricated and tested a FPC under central Qassim climate for a different hours operating mode. The experimental investigation showed that the highest achievable absorber plate temperature was found to be 113.8°C for four hour operating mode while for six hour operating mode the highest achievable temperature was 110.9oC. Another experimental investigation on FPC performance was done by Koffi et al. [5]. The study was conducted in Ivory Coast. The average energetic efficiency collected in this work was an approximately 50% which proved the capability of the constructed system to be utilized in converting solar energy into heat. An investigation on the effect of using different materials on the performance of FPC was conducted by Chen et al. [6]. In this study, a traditional FPC was compared with a polymeric material one. As compared with polymeric material one, the collected results showed an improve in traditional collector's efficiency with 8–15%. Khedher [7] conducted an investigation on FPC system performance under different flow rates including 1.5, 2, 2.5 and 3 Liter/min. The experimental investigation showed that the maximum achievable tank temperature was found to be 82.5°C which was collected at a water flow of 2.5 Liter/min. In order to transfer the solar radiations energy to water, Cooper et al [8] fabricate and test a floating structure. To improve the floating structure performances, the authors try to ensure a contactless steam generation and superheating under one sun illumination.

Due to the fast improvement in computer science, huge efforts were conducted to implement such sciences to investigate and find the operating conditions of the FPC. Several literature works were focused on the parametric analysis of the FPC performances. A analysis study is developed by Yousef and ADAM [9] to study the effect of the mass flow rate and the geometrical design parameters (DPs) on the performances of the FPC with and without porous media. A numerical parametric analysis of FPC performances with single and double cover glass was conducted by Fahim et al. [10]. It is shown that the doubling of the cover glass improve the FPC efficiency. The thermal analysis of the evacuated FPC was studied by [11]. In this work, the authors analyze the effect of the variation in weather conditions on the evolution of the FPC performances. In order to heat the industrial building, a numerical parametric analysis of an evacuated FPC was developed by Mos et al. [12]. the effect of the heat loss and the cover glass temperature on the evacuated collector performances were studied. Picón-Núñez et al. [13] adopt the parametric study of an evacuated FPC in order to determine the best thermal performance design by considering the mass flow rate and the pressure drop as a DPs.

Besides the importance of the parametric analysis, it is shown that this strategy cannot address the coupling effect among all the DPs [14,15]. As an alternative, numerous research works were concentrated on optimizing the DPs which affecting flat plate collector performance. In this context, the perturbation technique was used by Varun, et al. [14]. The implemented technique was used to find out the best set of different parameters affecting the FPC performance including collector area, number of glass cover plate and tilt angle. In order to optimize flat plate collectors economic benefits, a genetic algorithm method was used by Kalogirou [15]. Genetic algorithm was also used by Koholé, Y.W. and Tchuen [16]. The work was focused on the optimization of three liquid type FPC which utilized as water heaters. The investigation proved the possibility of reaching higher efficiency with smaller absorber area and hence lower cost. By implementing of artificial bee colony optimization algorithm Das et al. [17] proved that the size of solar collectors can be reduced by 6-32% of the original size. In this work, the investigation was implemented by applying of inverse modeling for a double glazed cover FPC. Shojaeizadeh and Veysi [18] implemented a sequential quadratic programming to improve the efficiency of a flat-plate collector design with as function of their geometrical parameters. The same optimization algorithm was also used by [19] with an intention to minimize the FPC losses. Hajabdollahi et al. [20] develop an optimization of the FPC by considering different types of nano-particles. The objective of this optimization was to improve the thermal efficiency of the FPC by using the second version of genetic algorithm (NSGAII). The maximization of the FPC efficiency is also considered as objective function by [21] through the multi-objective particle swarm optimization method.

As mentioned previously, several stochastic optimization methods were used to investigate and improve the performance of FPC by augment of different DPs. However, the major drawback of these methods is the difficulty to alternate between exploitation (convergence speed) and exploration (solution diversity) challenges [22, 23, 24]. In fact, by increasing the convergence speed, algorithm cannot explore all feasible solutions of the search space which degrades the population diversity and vice versa [22, 23]. As an alternative, the multi-objective modified imperialist competitive algorithm (MOMICA) was recently proposed and implemented as an effective method to optimize a wide range of engineering problems with the best compromise between convergence speed and solution diversity [23]. In fact, MOMICA use the attraction and repulsion (AR) strategy in finding the optimal solutions, in order to alternate between exploitation and exploration challenges. In addition, the use of such strategy would improve the algorithm performances in reaching the global optimal position [23]. Besides its effectiveness in optimizing engineering problems, and to our best of knowledge, the available literature does not cover any research work on the optimization of the FPC by the implementation of MOMICA. Therefore, the main objective of this paper is to develop an optimal design of the FPC by using the MOMICA method. The obtained optimal results will be validated through a comparison with an experimental work conducted under the weather of Qassim city in Saudi Arabia.

2. Collector thermal analysis

2.1 Structure of the FPC

Shown in Fig. 1 is an exploded view of the FPC. After passing through the glazing cover, a large portion of the received radiation is absorbed by the absorber plate. The energy received by the absorber is then transferred to the riser tubes to heat the fluid. In order to reduce the thermal losses, the collector is completely insulated were an insulator is placed on back side and edges. The riser tubes are attached at both ends with headers.

2.2 Energetic efficiency of the FPC

The useful energy in FPC systems can be defined as the amount of heat energy gained by the working fluid inside the collector and can be expressed as following [25]:

$$Q_u = A_c F_R \left[G\tau_c \alpha_p - U_L \left(T_{fi} - T_a \right) \right] = \dot{m}_f C_f \left(T_{f0} - T_{fi} \right) \tag{1}$$

where F_R is the heat removal factor which is given by:

$$F_R = \frac{\dot{m}_f C_f}{U_L A_c} \left[1 - \exp\left\{ \frac{F' U_L A_c}{\dot{m}_f C_P} \right\} \right] \tag{2}$$

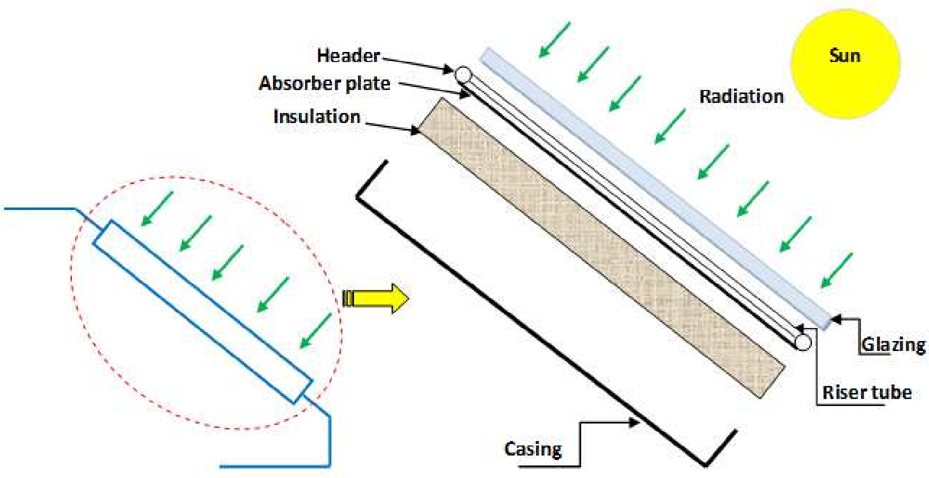

Fig. 1. Exploded view of the FPC

and the collector efficiency factor $F^{'}$ is calculated based on the following equation [25]:

$$F^{'}=\frac{1}{\dfrac{WU_L}{\pi d_i h_{c,p-f}}+\dfrac{1}{\dfrac{d_O}{W}+\dfrac{1}{\dfrac{WU_L}{C_b}+\dfrac{W}{(W-d_O)F}}}} \tag{3}$$

Since the combination of absorber plate and riser tubes are assumed as fins, the fin efficiency in this combination can be find by the following equation:

$$F=\frac{\tanh\left[\sqrt{\dfrac{U_L}{k_p\delta_p}}\left(\dfrac{W-d_O}{2}\right)\right]}{\sqrt{\dfrac{U_L}{k_p\delta_p}}\left(\dfrac{W-d_O}{2}\right)} \tag{4}$$

U_L is the overall HTC and can be evaluated by the following equation [25]:

$$U_L=\frac{1}{\dfrac{N}{\dfrac{C}{T_p}\left(\dfrac{T_p-T_a}{N+f}\right)^e}+\dfrac{1}{h_{c,c-a}}}+\frac{\sigma\left(T_p^2+T_a^2\right)\left(T_p+T_a\right)}{\dfrac{1}{\varepsilon_p+0.00591Nh_{c,c-a}}+\dfrac{2N+f-1+0.133\varepsilon_p}{\varepsilon_c}-N}+\frac{k_i}{\delta_i} \tag{5}$$

The terms f, e and C are given by:

$$f=\left(1+0.089h_{c,c-a}-0.1166h_{c,c-a}\varepsilon_p\right)\left(1+0.07866N\right) \tag{6}$$

$$e=0.43\left(1-\frac{100}{T_p}\right) \tag{7}$$

$$C=520\left(1-0.000051\beta^2\right),\ \begin{cases}0<\beta<70^{\circ}\\ \beta=70^{\circ}\text{if}\beta\geq 70^{\circ}\end{cases} \tag{8}$$

The FPC efficiency is the ratio of the useful energy gained by the working fluid (given in Eq. 1) to the incident solar irradiance. Thus, the FPC efficiency is given by:

$$\mu=F_R\left[\tau_c\alpha_p-F_RU_L\frac{\left(T_{fi}-T_a\right)}{G}\right]=\frac{\dot{m}_fC_f\left(T_{f0}-T_{fi}\right)}{A_cG} \tag{9}$$

The maximization of the energetic efficiency μ will be considered the objective function of the optimization problem.

2.3 The FPC components temperatures

2.3.1 Glass covers temperature equations

Considering an element of the FPC glass cover characterized by a specific heat capacity C_c, density ρ_c and thickness δ_c. The application of the energy balance on this element is governed by the following equation:

$$\rho_c\delta_cC_c\frac{dT_c}{dt}=G\alpha_c+h_{r,p-c}\left(T_p-T_c\right)+h_{c,p-c}\left(T_p-T_c\right)-h_{r,c-s}\left(T_c-T_a\right)-h_{c,c-a}\left(T_c-T_a\right) \tag{10}$$

where $h_{r,p-c}$ is the absorber-cover radiative HTC [25]:

$$h_{r,p-c}=\frac{\sigma\left(T_p^2+T_c^2\right)\left(T_p+T_c\right)}{\dfrac{1}{\varepsilon_p}+\dfrac{1}{\varepsilon_c}-1} \tag{11}$$

$h_{c,p-c}$ is the absorber-cover convective HTC [25]:

$$h_{c,p-c}=\left[1+1.44\left[1-\frac{1708}{R_a\cos\beta}\right]\left[1-\frac{1708\left[\sin(1.8\beta)\right]^{1.6}}{R_a\cos\beta}\right]+\left[\left(\frac{R_a\cos\beta}{5830}\right)^{\frac{1}{3}}-1\right]\right]\frac{k_a}{l_a} \tag{12}$$

$h_{r,c-s}$ is the Glass cover-sky radiative coefficient:

$$h_{r,c-s}=\varepsilon_c\sigma\left(T_c^2+T_s^2\right)\left(T_c+T_s\right)\left(\frac{T_c-T_s}{T_c-T_a}\right) \tag{13}$$

where $T_s = 0.0552 T_a^{1.5}$ and $h_{c,c-a}$ is the wind convection coefficient, given by [25]:

$$h_{c,c-a} = 5.7 + 3.8V \tag{14}$$

2.3.2 The absorber plate and the working fluid temperatures equations

Considering an element of the absorber plate characterized by a specific heat of C_p, material density ρ_p and plate thickness of δ_p. The application of the energy balance to this element yields the following relation:

$$\rho_p \delta_p C_p \frac{dT_p}{dt} = G\tau_c \alpha_p + h_{r,p-c}(T_p - T_c) - h_{c,p-c}(T_p - T_c) - h_{c,p-f}(T_p - T_f) - \frac{k_i}{\delta_i}(T_p - T_a) \tag{15}$$

In addition, the energy balance on an element of the working fluid can be written as follows:

$$\rho_p C_f \frac{\pi d_i^2}{4} \frac{dT_f}{dt} = h_{c,p-f}(T_p - T_f) - \frac{\dot{m}_f C_f}{n_t} \frac{\partial T_f}{\partial y} \tag{16}$$

where $h_{c,p-f}$ is the convective HTC between the absorber and working fluid inside riser tubes.

2.3.3 Computation of the components temperature T_c, T_p and T_f

Since the FPC components temperatures are non-linear, an iterative numerical code under Matlab software is used to calculate T_c, T_p and T_f. In fact, at initial time (t = 0), the initial values of T_c, T_p and T_f are defined to be equal to T_{fi}. Then, using of HTC mentioned earlier combined with the available climatic data and based on equations 10, 15 and 16, the values of T_c, T_p and T_f are updated. For each iteration, the new obtained values of T_c, T_p and T_f are compared with the old ones, if the difference less than 0.0001, the numerical code stops and displays the values of T_c, T_p and T_f. Else, the HTC are updated based on the new T_c, T_p and T_f values and the numerical code starts new calculation iteration.

3. Collector optimization

3.1 Formulation of the optimization problem

The objective of the optimization problem is to seek the best combination set of the FPC DPs, which maximizes its energetic efficiency. This is achieved under constraints that the DPs are defined in given search domains. The optimization problem formulation can be given by:

$$\begin{cases} \text{Maximize} \quad \mu \\ \text{under constraints :} \\ \qquad \text{DP} \in \text{D(DP)} \end{cases} \tag{17}$$

The optimized DPs and their corresponding search ranges D(DP) are presented in Table 1. The other DPs (presented in table 2) were considered constant.

Table 1. DPs and their search ranges.

DP	$w(m)$	$Ac(m^2)$	$d_i(m)$	$d_o(m)$	$\delta_i(m)$	$\delta_p(m)$	$\beta(°)$
D(DP)	[0.03,0.2]	[0.75, 2]	[0.005,0.011]	[0.012,0.022]	[0.02,0.05]	[0.001,0.02]	[10,60]

Table 2. Constant DPs.

DPS	values
Glass cover transmittance, τ_c	0.88
Absorber plate thermal conductivity, k_p	400 W/m°C
Apparent sun temperature, T_s	6000 K
Fluid specific heat, C_f	4182 J/ kg°C
Number of glass cover	1
Wind speed, V	2.5 m/s
Solar radiation, G	500 W/m2
Mass flow rate, $\dot{m}_f$	0.002 kg/s
Ambient temperature, T_a	30°C
Inlet water temperature T_{fi}	27°C
Absorber emissivity, ε_c	0.17
Absorptivity of the Absorber plate, α_p	0.95
Thermal conductivity of insulation, k_i	0.038 W/m°C

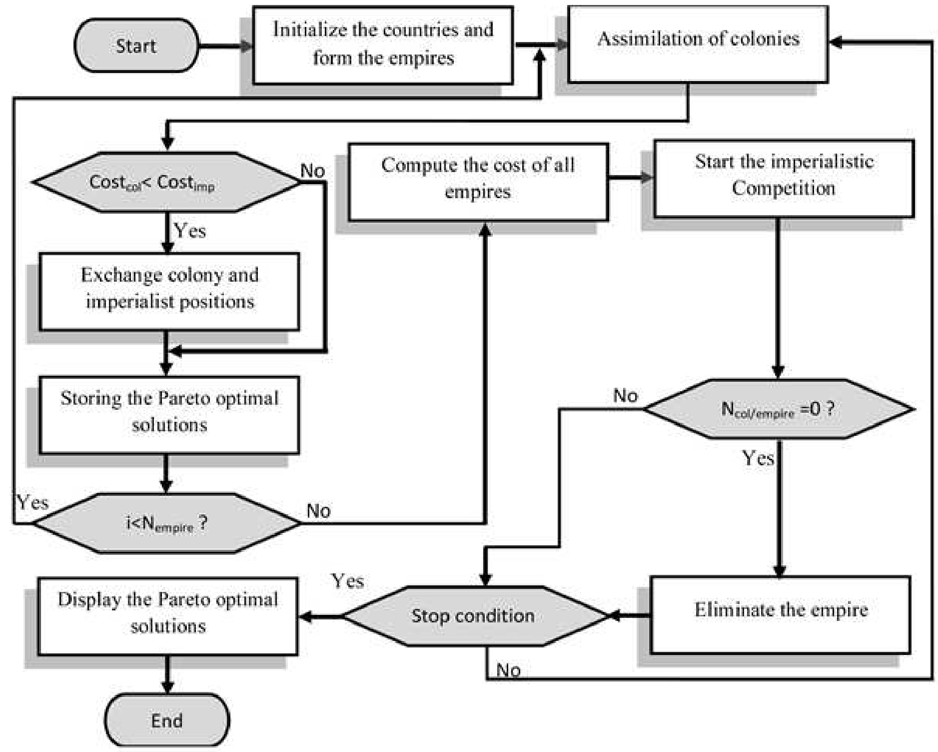

Fig. 2. The MOMICA flow chart.

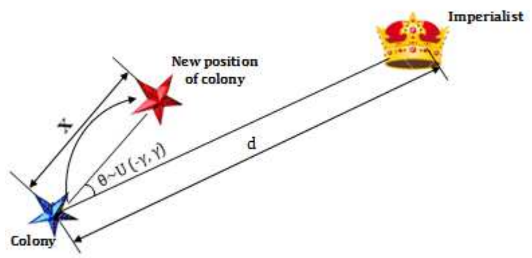

Fig. 3. The assimilation step

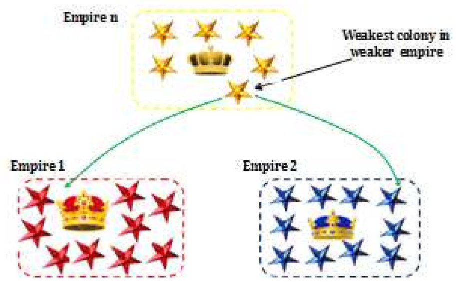

Fig. 4. Empires competition

3.2 The MOMICA method

Recently, The MOMICA is developed [23] in order to optimize the engineering problems. Firstly, the MOMICA starts a random generation of the initial population formed by many countries (each FPC design vector called country). The evaluation of different objective functions corresponding to each country yields to the determination of the countries costs. Based on this cost, some of powerful countries (with elevated costs) are considered as "imperialist" and the other countries are called "colonies". Each imperialist with some colonies form an empire. Thus, several initial empires (equal to the number of imperialists) are formed.
Secondly, the assimilation step begins where colonies move towards their imperialists as illustrated in Figure 3 [23]. Then, and in order to ameliorate their powers, colonies conduct crossover and mutation between each others. These operators can yields to new colonies more powerful than the existing imperialist. In this case, imperialist and colony permute their position. Thirdly, the powers of the different empires are evaluated based on the sum of the imperialist power and a percentage of the colonies mean powers.
After evaluation empires powers, imperialistic competition starts. In this step, all imperialists attempt to control the weakest colony of other weaker empires (Fig. 4).
Finally and after several competitions, the weak empires will lose all their colonies and they will be collapsed. This process will be repeated until remain only one empire which represents the global optimum of this optimization.

4. Results and discussion

The MOMICA algorithm was utilized to maximize the FPC energetic efficiency. The obtained optimization results are illustrated in Fig. 5 which presents the evolution of the FPC energetic efficiency of the best imperialist (representing the set of optimal DPs) as function of iteration's numbers.
From Fig. 5, one can note that the imperialist competition has required 216 iterations for the best imperialist to control and own all the colonies. This best imperialist represents the set of optimal DPs offering the maximum FPC energetic efficiency. The obtained optimal DPs are detailed in table 3.

Table 3. The obtained optimal DPs.

DP	$w(m)$	$Ac(m^2)$	$d_i(m)$	$d_o(m)$	$\delta_i(m)$	$\delta_p(m)$	$\beta(°)$	$\mu(\%)$
Optimal results	0.03	0.75	0.011	0.012	0.05	0.001	32	61.5
Fahim et al [10]	0.11	1.62	0.010	0.012	0.03	0.0009	32.06	45.63

Table 4. Optimization results for a more practical case.

DP	$Ac(m^2)$	$d_i(m)$	$d_o(m)$	$\delta_i(m)$	$\delta_p(m)$	$\beta(°)$	$\mu(\%)$
Value	0.75	0.011	0.012	0.05	0.001	32	60.94

Table 5. Comparison between experimental and optimal results.

	Experimental results [4]				Optimal results				E(%)
	Q_u (W)	T_p (°C)	F_R	μ_{exp} (%)	Q_u (W)	T_p (°C)	F_R	μ_{exp} (%)	
$\beta = 31°$	320	88.6	0.77	56	324.17	90.2	0.79	59.88	6.9
$\beta = 26°$	262	NA	0.68	48.2	271.1	81.35	0.71	51.23	6.2
$\beta = 21°$	267	NA	0.67	47.6	270.7	79.88	0.7	50.17	5.3

As shown in table 3, it is very clear that all the optimal values of the construction parameters are at their minimum values except the riser tubes internal diameter and the insulator thickness which are fixed at their maximum value. By using this FPC optimal design, the efficiency can be improved almost 30% compared to the conventional non optimized design presented in [10]. On the other hand, it is noted that the distance between two successive riser tubes "W" is very small. This implies that larger number of riser tubes must be implemented in the manufacturing of the system which would increases the cost. As an alternative solution for this issue, the obtained optimal distance was replaced by a more practical distance of 8 centimeters. Table 4 shows the results which obtained by considering $w = 8\,cm$.

Shown in (Table 4) is the results of a practical FPC system. By comparing the results shown in (Table 4) with the corresponding values obtained at the optimal design shown in Table 3, it can be concluded that the energetic efficiency is not too affected. This case has less economically benefit since it associated with greater distance between the riser tubes which leads to decrease the number of used tubes and, therefore, the collector will cost less.

4.1 Comparison with experimental results

The optimal results obtained by MOMICA have been compared with a literature experimental results [4] conducted under the weather of Qassim city in Saudi Arabia. By varying the tilt angle for three values 21, 26 to 31°,the optimal results obtained by MOMICA have been compared with the experimental literature design of FPC in terms of collected useful energy, absorber plate temperature, heat removal factor and energetic efficiency. To build a comparison, the relative error between optimal and experimental energy efficiencies has been calculated as follows:

$$E(\%) = 100\left|\frac{\mu_{exp} - \mu}{\mu_{exp}}\right| \tag{18}$$

Table 5 summarizes the comparison of different obtained results. As it can be observed from Table 5, the obtained optimal results are with in high agreement with the experimental ones. In fact the energetic efficiency relative errors between optimal and experimental results do not 7%. This validates the optimization results and confirms the effectiveness of the MOMICA method.

4.2 Effect of the DPs variations on the optimal collector efficiency

The evolutions of the optimal FPC efficiency as function of the DPs variations (such as the collector surface area, absorber tube inner diameter, absorber tube outer diameter, insulator thickness and absorber plate thickness) are investigated in this section. One can note from Fig. 6, that the energetic efficiency decreases with the increase of the FPC surface area. In fact, the energetic efficiency and the collector surface area are inversely proportional as it is shown in Eq. 9.

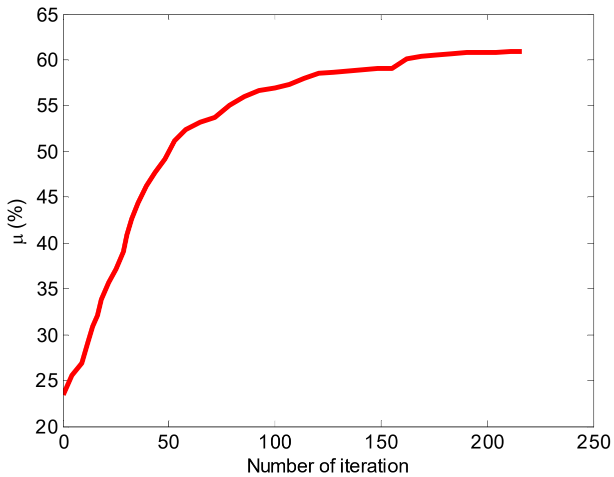

Fig. 5. Optimization results

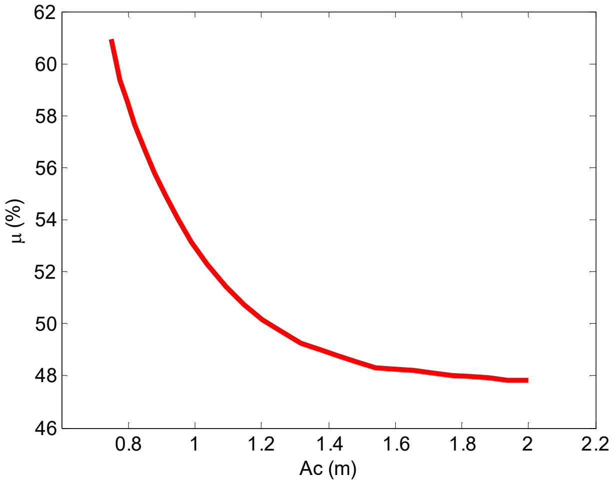

Fig. 6. Effect of the collector area surface

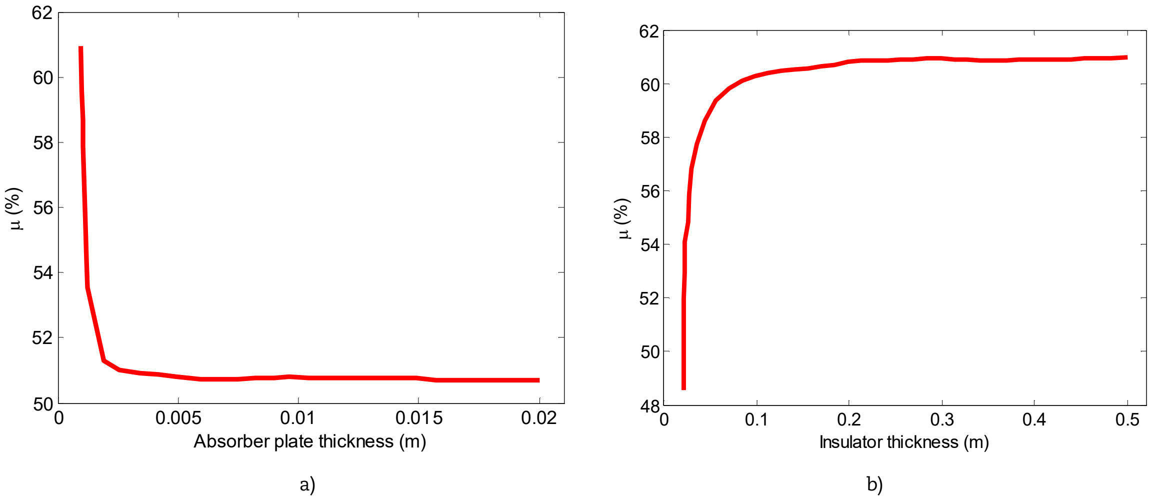

Fig. 7. Effect of the insulator and absorber plate thicknesses on the FPC efficiency; a) absorber plate thickness, b) insulator thickness

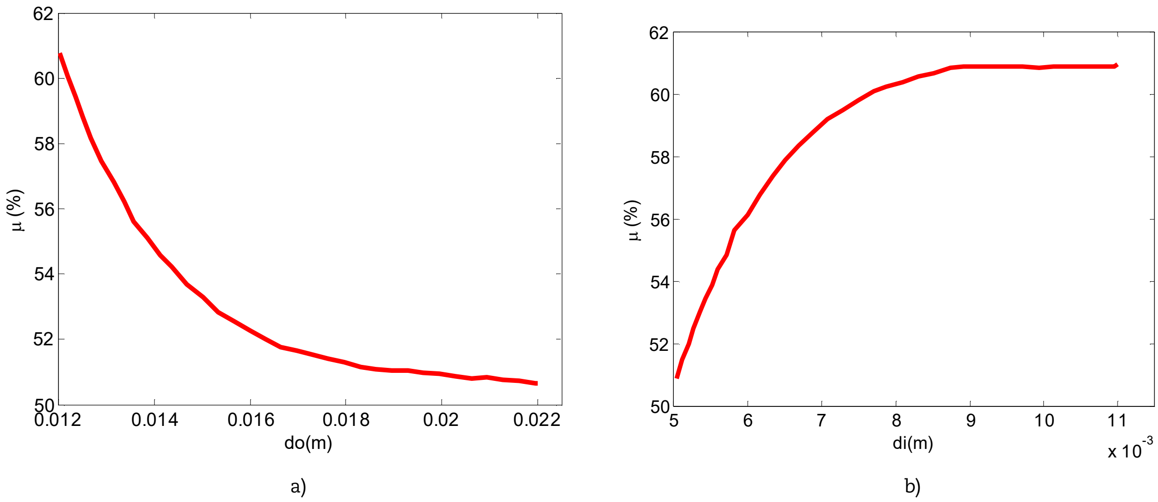

Fig. 8. Effect of the tubes outer and inner diameters on the collector efficiency; a) outer diameter b) inner diameter

Figure 7 presents the effect of the absorber plate and insulator thicknesses on the FPC efficiency. From Fig. 7 (a), one can note that the increase of absorber plate thickness would affect positively in improving of the energetic efficiency of the FPC especially in plate thickness range of 0.0001 to 0.002 m. On the other hand, the increase of absorber plate thickness would affect in increase of its temperature, which in turn would increase the temperature difference between the plate and the ambient. This result leads to a higher values of loss coefficient a plate collector which would affect negatively on the energetic efficiencies of the system. Fig. 7(b) represents the effect of the insulator thickness on the energetic efficiency of the FPC. It is noted that the increase in insulation thickness leads to an increase in energetic efficiency especially in the insulation thickness range of 0.0001 to 0.002 m. It is very clear that the increase of thermal insulation thickness would affect positively on the system's performance since it would reduce heat losses and hence efficiencies are expected.

Fig. 8 illustrates the effect of the tubes outer and inner diameters on the FPC. From Fig 8 (a), One can note that the increase of the tube outer diameter (d_O) decreases the FPC efficiency. In fact the absorber temperature decreases when the distance between the tubes decreases. From Fig. 8 (b), it is very clear that the increase of tubes inner diameters (d_i) increases the system efficiency. This is due to the fact that the increase of d_i increases the water mass flow rate in the collector. On the other hand, and according to Darcy equation for frictional losses in pipelines, the higher pipe diameter is associated with lower friction losses. Thus, increasing of inner riser tubes diameters would affect in increasing of energetic efficiency of the system.

5. Conclusions

This work presented a design optimization of a FPC used as a solar water heater. The optimization strategy was conducted by using MOMICA algorithm recently developed in the literature. The optimal results represented the best set of DPs that would maximize the energetic efficiency of the FPC. The obtained optimal results were compared with an experimental results given by an experimental rig constructed and tested at Unaizah-Qassim in Saudi Arabia. The comparison results showed a high agreement with those of experimental measurements. In fact, the relative error between optimal and experimental results did not exceed 7%. Moreover, the effect of a number of DPs like the collector surface area, absorber plate thickness, insulator thickness and the inner and outer absorber tubes diameters were investigated. It has been noted that the FPC energetic efficiency were almost constant for an absorber plate thickness greater than 0.002 m. However, the strong influence was noted from 0.001 to 0.002 m of absorber plate thickness. It has been also noted that the change of insulator thickness from 0.02 to 0.05 m has strong influence on the FPC efficiency. The collected results from this study showed the possibility to utilize a small FPC surface area to replace electrical water heater in Qassim region of Saudi Arabia which consequently would reduce electricity consumption. As a future work, we will address the robust optimization of the FPC by incorporating the DPs uncertainties.

Author Contributions

M. Nejlaoui suggested the basic idea of this paper and conducted the simulation work. A. Alghafis analyzed the obtained results and proposed the experimental comparison. H. Sadig examined the mathematical model and the validation theories. The redaction, the revision and the approval of the final version of this paper were developed through the participation of all authors.

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Conflict of Interest

The authors declared no potential conflicts of interest with respect to the research, authorship, and publication of this article.

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Nomenclature

A_c	Surface Area of the collector [m^2]	T_p	Absorber plate temperature [°C]
C_c	Specific heat capacity of the glass cover [J/kg°C]	U_L	Overall heat loss coefficient [W/m$^{2°}$C]
C_f	Specific heat capacity of the working fluid [J/kg°C]	V	Speed of the wind [m/s]
C_p	Specific heat capacity of the absorber plate [J/kg°C]	w	Distance between two consecutive tubes [m]
d_i	Absorber tube inner diameter [m]	ε_c	Glass cover emissivity
d_O	Absorber tube outer diameter [m]	ε_p	Absorber plate emissivity
DPs	Design parameters	τ_c	Glass cover transmissivity
FPC	Flat plate Collector	ν	Kinematic viscosity [m^2/s]
F_R	Heat removal factor [m]	δ_p	Absorber plate thickness [m]
G	Solar intensity [W/m^2]	k_i	Thermal conductivity of the insulation [W/m°C]
HTC	Heat transfer coefficient	l_a	Absorber plate and glass cover distance [m]
k_a	Air layer between absorber plate and glass thermal conductivity [W/m°C]	α_c	Absorptivity of the glass cover
$\dot{m}_f$	Mass flow rate in the collector [Kg/s]	α_p	Absorptivity of the absorber plate
N	Number of glass cover	β	Collector inclination angle [°]
Q_u	Collector useful energy [W]	δ_c	Glass cover thickness [m]
T_a	Ambient temperature [°C]	δ_i	Insulator thickness [m]
T_c	Glass cover temperature [°C]	μ	Flat plate collector efficiency
T_f	Working fluid temperature [°C]	σ	Stefan-Boltzman constant [W/m$^{2°}$C^4]
T_{fi}	Inlet water temperature [°C]	R_a	Rayleigh number
T_{fo}	Outlet water temperature [°C]		

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