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Experimental Investigation on the Effect of Partially Metal Foam inside the Absorber of Parabolic Trough Solar Collector

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A B S T R A C T

In the present work the efficiency of a solar parabolic trough has been investigated experimentally. Parabolic trough solar collectors constitute a proven source of thermal energy for industrial process heat and power generation. The impact of using the partially porous media in the absorber on the efficiency of PTC (parabolic trough collector) has been investigated. The porosity of copper foam is 0.9 and its pore density is 30 PPI (pores per inch). The experiments were performed for different volume flow rates from 0.5 to 1.5 L/min. and the ASHRAE 93 standard was used to test the solar collector's performance. Results illustrate that using metal foam in the absorber has a positive impact on the collector efficiency and increases the pressure drop in the absorber. When absorber is filled with metal foam, the overall loss coefficient U_L decreases 45% and it causes to increase efficiency because less energy is lost.

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1. INTRODUCTION

Heat transfer is the main phenomena in many industrial devices such as heat exchangers in petroleum engineering, filtration, aeromechanics, and solar energy [1-5]. Metal foams have been used in the aerospace and ship-building industries where convection and radiation heat transfer are critical. The cost of foam manufacturing have declined recently and a wide range of industries have applied metal foam in heat and mass transfer applications. Since flow paths through the foam are interlinked, the flow moves in all areas. Hence smaller and lighter heat exchangers can be fabricated by using metal foam [6, 7]. There are several different types of solar collectors used today in homes and industries to cater for a variety of applications such as water heating or electricity generation. Parabolic trough collector (PTC) is the most common linear concentrating solar collectors which is used in high temperature application [8, 9]. A parabolic trough collector is made of a parabolic-curved mirrors that focus direct radiation from the sun onto a receiver in the focal line of the reflector. The receiver is made of an absorber tube which is surrounded by a glass envelope and the space between them is evacuated to limit heat losses from the absorber tube to the surrounding environment. Hence, the working fluid that moves through the absorber tube is heated by concentrated radiation [10]. Ajay and Kundan [11] studied experimentally and numerically the efficiency of parabolic solar collector when nanofluids is used as a working fluid. Al_2O_3/water is prepared in four different concentrations and CFD simulation has been done by ANSYS FLUENT 14.5 software. They found that nanofluids had positive effect on PTC's efficiency and it was enhanced by increasing mass flow rate. Wang et al. [12] studied the impact of a secondary reflector which used as a homogenizing reflector on the efficiency of a parabolic trough solar collector. The Monte Carlo ray-trace (MCRT) method is applied in order to estimate the concentrated solar flux distribution and uniform solar flux distribution on the absorber tube was found. Results illustrated that the efficiency of PTC declines

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because of enhancement optical loss. Another investigation about the effect of nanofluids on the thermal performance of parabolic trough collector was done by Ajay et al. [13]. They confirmed that nanofluids increases the thermal performance of solar collector. The numerical study of the flat and tubular solar collectors were investigated by Nimr and Alkam [14]. Porous media partially inside the duct of the solar collectors and water was heated while flowing through it. An improvement in the thermal dispersion was observed and interface between the fluid and solid increased when metal porous media such as copper and aluminium used. On the other hand, increasing the pressure drop of flow is the main obstacle which increases energy demand for pumping [15]. This fact has been declared in the earlier works that concerned with the combination of porous medium in a forced convective flow system and an improvement in heat transfer can be observed with a pulsating flow through a pipe partially filled with a porous foam [16, 17]. Forced convection in a system in which a fluid porous material occupies only a part of the passage has been the subject of numerous investigations [18]. Analytical solution illustrates that there is an enhanced heat transfer in an annular duct partially filled with a porous medium.

In this study, the performance of a parabolic trough collector (PTC) using a copper foam absorber has been studied. A new solar trough collector was designed and fabricated in order to study the collector efficiency and its effective parameters and water is applied as a working fluid. The absorber of solar collector is a steel tube 28 (mm) in diameter coated with black chrome and filled by a copper metal foam. ASHREA 93 standard has been applied in order to measure the efficiency of solar collector and the effect of using three configurations of metal foam inside absorber have been examined and compared. Finally, the evidence for enhancement of the solar collector efficiency is explained.

2. EXPERIMENTAL SETUP

A parabolic trough reflector with two types of absorbers with, and without metal foam is investigated experimentally. A parabolic reflector was designed with the length of 1.28 m and aperture width of 1 m. The reflector was made of 1 mm thick steel mirror with (Table1). The rim angle of this prototype was selected as 90; this degree represents a suitable rim angle as reported by Valan Arasu and Sornakumar [19],. Seven polyglass fixtures are applied in order to support the parabolic reflector. The reason is that the density of polyglass is 1.19 gr/cm^3 which is very close to that of water, as well as having perfect resistance against wind.

A copper tubes is applied in order to connect polyglass fixtures to the body of the collector. The absorber tube is the most important part of a parabolic trough collector which is responsible for absorbing solar heat and conducting it to the fluid.

For this aim, outer surface of a copper tube was coated with black chrome and a glass tube enveloped it. A pyrex glass tube has been used as an envelope. It is clear that the quality of coating and space between copper and glass tube have significant effect on the thermal and optical performances of collector. In this study, three different absorbers were tested: a copper tube filled with metal foam, absorber filled with partially metal foam and conventional (free porous media) absorber. Two PT100 type thermocouples were inserted into the flow at the inlet and exit of the test section to measure the bulk temperatures of the water. Also, a portable thermocouple used to measure the ambient temperature. All thermocouples were calibrated and their error at measuring temperatures is 0.60 ^{o}C. A rotary flow meter use to measure the flow rate of the fluid in the absorber and it is mounted in a vertical position. The solar radiation flux density was measured by using a Solar Power Meter TES-1333R. The working flow in the cycle was circulated by using a pump which is located at the outlet of the tank. Table1 lists the specifications of the mirror reflector.

In order to evaluate the efficiency of solar collector, the ASHRAE 93 standard [20] has been used according to the specific environmental conditions which are introduced by standard. It is important to mention that all data should be collected under steady-state conditions. ASHRAE 93 suggests the maximum variation of variables for defining a steady-state condition during the testing period which is demonstrated in Table 2.

TABLE 1. The detailed specifications of the mirror reflector

Parabola length (Lc) (m)	1.28
Parabola aperture (w) (m)	1
Thickness (mm)	1
material	steel
Focal distance (f) (mm)	250
Aperture area (Aa) (m^2)	1.28
Rim angle (ϕ)	90

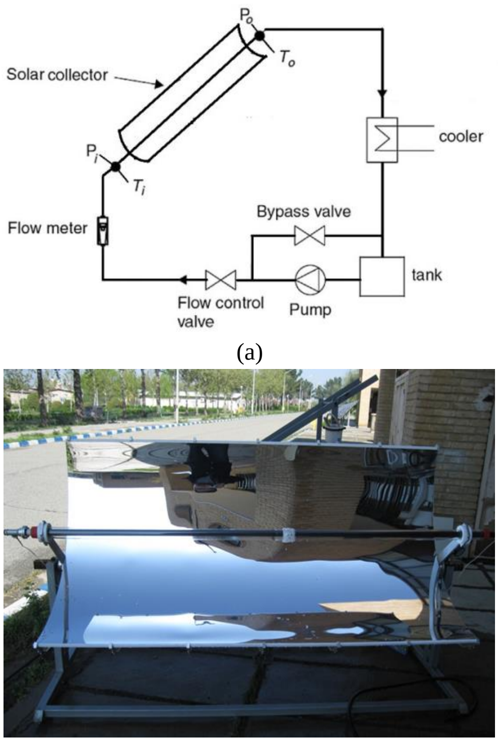
TABLE 2. the allowed maximum variation of key variables [20]

Variable	Maximum variation
Total solar irradiance normal to surface (W/m^2)	±32
Ambient temperature (K)	±1.5
Volume flow rate	The greater of ±2% or ±0.005 (gpm)
Inlet temperature	The greater of ±2% or 1 (K)

A schematic of experimental setup which is prepared for testing a parabolic solar collector is illustrated in Figure 1a. Moreover, a real photo of parabolic solar collector which is fabricated in the Material and Energy Research Centre is shown in Figure 1b.

Porosity ε and the PPI (number of pores per inch) are two main parameters used to describe the foam structure. Porosity ε is defined as the ratio of total void volume to the total volume occupied by the solid matrix and void volumes, while PPI is easily calculate by counting the number of pores in one inch. It is worthwhile to mention that the pressure drop is a function of permeability (K) of the metal foam which in turn depends on the pore density (PPI) and porosity (ε). Consequently, the pressure drop of single-phase flow through the pipe increases exponentially with pore density.

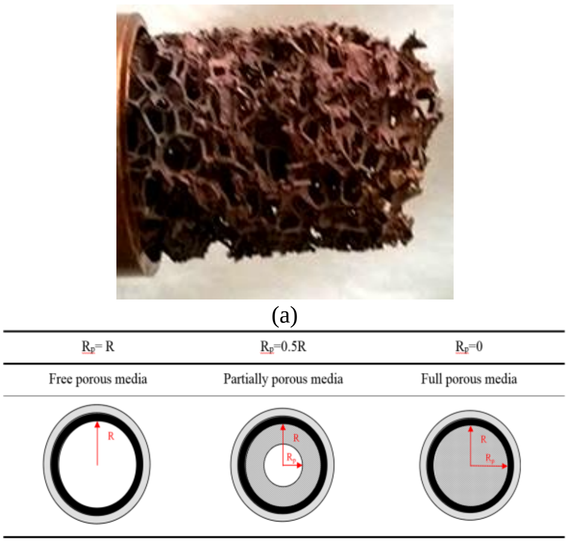
The porous medium that filled the test section is copper foam with one geometric specifications: 30 PPI and it is shown in Figure 2a. Copper foam has excellent heat transfer due to its considerable advantages of large specific area, high solid thermal conductivity, and strong flow-mixing capability. Also, three different configurations of metal foam full, partially and free porous media are illustrated in Figure 2b. Meanwhile, the properties of metal foam which were measured at the solar laboratory of material and energy researcher center (MERC), is demonstrated in Table 3.



(a)

(b)

Figure 1. a) Schematic of closed loop test system for solar collector. b) parabolic solar collector trough



(a)

(b)

Figure 2. a) Copper foam as a porous media; b) three different configuration of absorber

TABLE 3. Thermophysical parameters and dimensions of copper foam

Material	Copper
Porosity	0.90
Permeability, K (m^2)	1.37E-11
Legends, Lf (mm)	250
Diameter, D (mm)	28
Thermal conductivity (W/m.K)	399

The advantage of PTC with porous absorber is the fact that it has high heat transfer coefficient due to large specific area. However, the major disadvantage is that the pressure drop increases significantly. Copper foam characteristics should be selected based on the least pressure drop and the most heat transfer. Pore density 30 PPI and porosity 0.9 cause strong flow-mixing and enhancement heat transfer area while there is a slight increase in pressure drop. The main reason is that the flow can cross through the porous media without trap into cavity.

3. EFFICIENCY CALCULATIONS AND ANALYSIS

ASHRAE Standard suggests carrying out the tests in various inlet temperatures. The theory of solar parabolic trough collector is well established and can be found in the basic works [21-23]. The collector performance test is performed under steady state condition, including steady radiation energy falling on the collector surface, steady fluid flow rate, constant wide speed and ambient temperature. The useful energy gain from the collector is defined by the following equation:

$$Q_u = \dot{m}C_p\left(T_o - T_i\right) \quad (1)$$

The useful energy collector from a solar collector is given by:

$$Q_u = F_R\left[A_a G_t \eta_o - U_L A_r\left(T_i - T_a\right)\right] \quad (2)$$

where Q_u is the rate of useful energy gained, $\dot{m}$ is the volume flow rate of fluid flow, C_p the heat capacity of water, and To and Ti are the outlet and inlet fluid temperature of solar collector, respectively. Also, A_a denotes the appropriate areas for the absorbed solar radiation, F_R is the heat removal factor, η_o the optical efficiency, G_t the global solar radiation, U_L the overall loss coefficient of solar collector, and Ta the ambient temperature.

Moreover, the thermal efficiency is obtained by dividing Q_u by the energy input as in Equation (3)

$$\eta = F_R\left(\eta_o - U_L\left(\frac{T_i - T_a}{G_t C}\right)\right) \quad (3)$$

where C is the concentration ratio and F_R the heat removal factor which is defined as:

$$F_R = \frac{\dot{m}c_p}{A_r U_L}\left(1 - Exp\left[\frac{U_L F' A_r}{\dot{m}c_p}\right]\right) \quad (4)$$

where F' is the collector efficiency factor. On the other hand, thermal efficiency was calculated by experimental data according to Equation (4)

$$\eta = \frac{\dot{m}C_p\left(T_o - T_i\right)}{A_a G_t} \quad (5)$$

If the efficiencies are plotted against $T_i - T_a / G_t C$, a straight line will result. Intersection of the line with the vertical efficiency axis illustrates the $F_R\eta_o$, and the $F_R U_L$ can be found from slope of the line. This slope determines that the amount of energy has eliminated from the solar collector and the intercept shows that maximum collector efficiency.

4. RESULT AND DISCUSSION

The effect of using absorber filled with porous media on the performance of the PTC solar collector was investigated. Copper metal foam has been used as the porous medium. Using copper foam causes the thermal conductivity of absorber to increase and the ability of absorber for transferring heat from surface to fluid to enhance. The effective thermal conductivity of metal foam is explained in reference [24]. Boomsma [24] illustrated that the effective thermal conductivity has two different manner for $k_f/k_s \le 10^{-3}$ and $k_f/k_s \ge 10^{-3}$ which k_s and k_f are the thermal conductivity of solid and fluid phases, respectively. Although a constant value has been observed for $k_f/k_s \le 10^{-3}$, there is a considerable increase when $k_f/k_s \ge 10^{-3}$. It means that, k_f is the dominant term as compared with k_s.

Experimental tests have been performed at various temperatures and solar conditions and all results are plotted with efficiency as the vertical axis and $x = T_i - T_{amb}/G_t$ as the horizontal axis. The collector performance is presented by finding the best straight line through the data points. The maximum value of the collector efficiency occurs when $T_i = T_{amb}$. The intersection of the line with horizontal axis where the collector efficiency is zero specifies a low radiation level or high temperature of the fluid inside the collector. In order to reach more accuracy, each test was repeated three times. Values of the uncertainties of the mass flow rate, temperature, solar irradiation anemometer and differential pressure are shown in Table 4. The uncertainty associated with each of the variables (x) used in determining the thermal efficiency is given by the square root of the sum of the variances of the statistical distributions of each component (i) involved in the process, namely:

$$\psi_c(y) = \sqrt{\sum_{i=1}^{n} \psi(x_i)^2 . \left(\frac{\partial y}{\partial x_i}\right)^2} \quad (6)$$

The values determined during the test and used in the calculation of the instantaneous thermal efficiency of solar collector are the following

- Mass flow rate ($\dot{m}$)
- Solar irradiance (G)
- Temperature (T)

The combined uncertainty of instantaneous thermal efficiency $\psi(\eta)$ is:

$$\psi(\eta)^2 = \psi(\dot{m})^2 . \left(\frac{\partial \eta}{\partial \dot{m}}\right)^2 + \psi(T)^2 . \left(\frac{\partial \eta}{\partial T}\right)^2 + \psi(G)^2 . \left(\frac{\partial \eta}{\partial G}\right)^2 \quad (7)$$

Besides the measurement of uncertainty described above, it was considered that the uncertainty emanated from the regression analysis.

TABLE 4. Measurement of uncertainties from a specific data point

Variable	Qty.	Unit	Uncertainty	Conf. (%)
Mass flow	1	kg/s	±5% of value	95
Temperature	2	ºC	0.1 ºC	95
Solar Irradiance	1	W/m^2	±32	95
Anemometer	1	m/s	±5% of value	95

Figure 3 shows the solar insolation and ambient temperature for absorber without metal foam in single test. All the tests were carried out around the solar noon between 10:30 and 14:30.

Figure 4 shows the outlet temperatures of the absorber for three cases which are shown in Figure 2b. The inlet temperature is 20 ^oC and constant according to ASHREA 93 standard. It is clear that the outlet temperatures enhance when the copper foam occupies more space of cross section of tube and it means that the efficiency of PTC increases by using copper foam. Moreover, water reaches the highest temperature, around 38 ^oC, when absorber is filled with porous media.

The effect of the variations of mass flow rate on the collector efficiency is illustrated in Figure 5. Three different mass flow rates: 0.5, 1 and 1.5 L/min have been tested and the results show that the collector efficiency increases as the mass flow rates enhance. It is worthwhile to mention that similar pattern has been seen in previous works [25-27].

Figure 6 demonstrates that using metal foam in the absorber have enhancement effect on the efficiency of the collector. As expected, a reduction trend has been observed for three cases with increasing x value. At high values of x, the effect of metal foam on thermal performance of solar collector is more significant. According to Equation (3) the collector performance is presented by finding the best straight line through the data points.

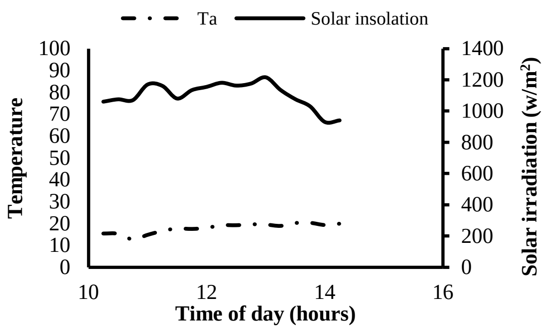


Figure 3. Experimental curve for 1 day

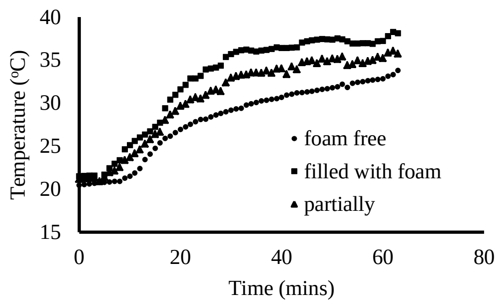


Figure 4. Variation of the average temperatures of the water at the outlet of the absorber for three cases

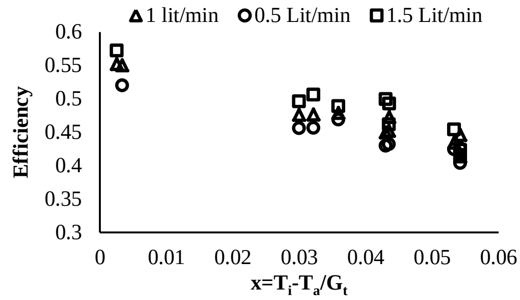


Figure 5. Variations of collector efficiency versus the reduced temperature

The intersection of the line with vertical axis where $T_i = T_{amb}$, depicts $F_R \eta_o$ and slope of line shows $F_R U_L$. By knowing optical efficiency F_R and U_L can be calculated. Table 5 illustrates the values of the efficiency parameters F_R and overall loss coefficient of solar collector U_L for three cases. A comparison between them shows that the overall loss coefficient U_L decreases 45% when absorber filled with metal foam and it causes to increase efficiency because less energy is lost. Moreover, a slight decline has been observed in the heat removal factor.

The collector efficiency is very sensitive to the heat transfer enhancement in collector and it increases when heat transfer coefficient in the absorber enhances. The local heat transfer coefficient, h, can be defined as k/ δ_t where k and δ_t are thermal conductivity and the thickness of thermal boundary layer, respectively [28]. It is obvious that the heat transfer coefficient increases when the fluid thermal conductivity enhances and thermal boundary layer thickness declines.

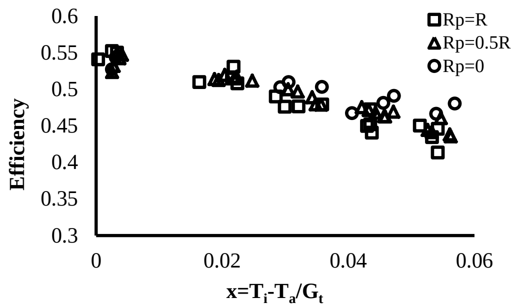


Figure 6. efficiency of PTC for three cases

TABLE 5. Efficiency parameters for the three cases

	U_L	F_R	Equation
Rp=R	28.33	0.88	$\eta = -2.256x + 0.5547$
Rp=0.5R	23.36	0.872	$\eta = -1.852x + 0.5494$
Rp=0	15.44	0.854	$\eta = -1.193x + 0.5381$

For absorber filled with metal foam, thermal conductivity increases because solid thermal conductivity increases and thermal boundary layer thickness decreases.

5. CONCLUSION

In the present work, the effect of copper foam on the thermal performance of PTC has been investigated experimentally. ASHREA 93 standard is applied in order to evaluate the thermal performance of PTC and the efficiency parameters F_R and U_L have been considered. This investigation is studied for first time and has not been mentioned in previous literature. Using metallic foams for heat transfer enhancement is a novel method. Copper foams have great potential in heat-transfer-related applications such as solar collectors where the enhancement of heat transfer cause to increase the thermal performance of the collector. The mass flow rate varied from 0.5 to 1.5 L/min and the ASHRAE 93 standard was used to calculate the efficiency of the collector. The highlights of the study could be stated as following:

- The solar collector efficiency declines with decreasing the mass flow rate.
- The absorber filled with metal foam has a positive effect on collector efficiency due to thermal conductivity enhancement.
- The removed energy and absorbed energy parameter of the solar collector decreases by using porous media.

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Thermal Conductivity

چکیده

در این مقاله بازده انرژی کلکتور سهموی خطی به صورت آزمایشگاهی مورد مطالعه قرار گرفته است. کلکتور سهموی خطی معمولا برای کاربرد های صنعتی و نیروگاهی که نیاز به دمای بالای سیال دارند استفاده می‌شود. تاثیر به‌کارگیری محیط متخلخل قطعه‌ای در داخل جاذب بر روی عملکرد این نوع کلکتور مورد بررسی قرار گرفته است. برای این منظور از فوم مسی با تخلخل ۰/۹ و چگالی حفره ۳۰ PPI استفاده شده است. آزمایش‌ها تحت قیود استاندارد ASHRAE 93 و منطبق با دستورالعمل آن در دبی‌های مختلف سیال از ۰/۵ تا ۱/۵ لیتر بر دقیقه انجام شده است. نتایج نشان می‌دهد که استفاده از فوم متخلخل در داخل جاذب سبب افزایش بازده کلکتور و همچنین افزایش افت فشار در داخل جاذب می‌شود. به‌علاوه، هنگامی که جاذب با محیط متخلخل پر شده است، ضریب افت حرارت کلی ۴۵٪ کاهش یافته که به معنی کاهش اتلاف حرارت و افزایش بازده خواهد بود.

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