Experimental Study of Solar Collector Performance with Serpentine Mini-Channel

Zainab H.Naji1

Mechanical Engineering Department, University of Technology, Baghdad, Iraq

dr_alnaji_z@yahoo.com

Mohammed Fowzi M

Mechanical Engineering Department, University of Technology, Baghdad, Iraq

mohammed2007msc@yahoo.com

Maryam Ali A. Ameer

Mechanical Engineering Department, University of Technology, Baghdad, Iraq

mscmaryamali22294@gmail.com

Abstract

In this paper, experimental has been executed to investigate thermal performance of modified design of mini-channel plate solar collector. For the application of mini-channel heat exchangers, it is necessary to have perfect design tools for prophesy pressure drop and heat transfer. Experimental setup were carried out in Baghdad city from (July) with a tilt angle of (30º) to the south under sunny weather condition. The working fluid is propylene glycol in the laminar regime is used for experimental investigation at constant fluid inlet temperature (15 ºC - 20 ºC) and at different flow rates (4.6L/h, 5.77L/h, 7.96L/h, 11.2L/h, and 18.35L/h). The mini- channel solar collector performance is evaluated in terms of heat transfer coefficient, pressure drop, friction factor pumping power, and working fluid temperature difference between the outlet and the inlet .In this paper study the test rig with selective coating and with cover glass The experimental results show that an increase in mass flow rate the heat transfer coefficient is also increased while the friction factor is decreased. Also, increase in mass flow rate lead to the temperature difference between the outlet and the inlet working fluid decreases.

Keywords: Flat plate, Mini-channel, Solar collector, Heat transfer coefficient.

Nomenclature

Symbol	Title	Unit
A_c	Cross sectional area of mini-channel	(m^2)
A_{ch}	Channel heating surface area	(m^2)
b	Time increment	(s)
D_h	Hydraulic diameter	(mm)
cp	Specific heat capacity	(KJ/Kg K)
H	Channel height or thickness	(mm)
h	Heat transfer coefficient	($w/m^2.k$)
G_T	Measuring hourly solar radiation	(J)
I_T	Total Hourly solar radiation	(J)
k	Thermal conductivity	(w/m.k)

L	Channel length	(mm)
$\dot{m}$	Mass flow rate	(kg/s)
Nu	Nusselt number	
P	Pitch	(mm)
Q_U	Useful energy	(watt)
Q_{Ud}	Daily useful energy	(J)
Q_R	Daily solar radiation	(J)
Re	Reynolds number	
T	Temperature	(c°)
Ta	Ambient temperature	(c°)
$\dot{V}$	volume flow rate	(l/h)
W	Channel width	
Greek symbols		
ρ	Density	(Kg/m^3)
η	Collector efficiency	
$_i\eta$	Instantaneous efficiency	
Δp	Differential pressure	Pa
f	Fraction factor	
Subscripts		
f	Fluid	
in	Inlet fluid	
out	Outlet fluid	

1. Introduction

The study of renewable energies (the near-term resurgence and source of natural resources) has become a target for many scientists and researchers because they are better than fossil fuels. Particularly, different technologies that use solar energy have been checked by different industries and universities so to evolve many ways that are cost competitive and environmentally friendly to generate power, cooling and heating, for residential and commercial uses. The thermal system of solar (such as air heaters, solar water heaters and dryers) is one of the systems in which the solar energy could be utilized. Solar water heating, specifically, flat solar heater, is widely used in most of the countries in all over the world especially in The Middle East region. Since 1891, the solar energy has been utilized to heat the water [1], and the patented Climax solar water heater was the primary commercial model. After that, a number of collector designs have been suggested, like flat plate [2], evacuated tube collectors [3], and units that need compound parabolic concentrators [4]. The small scale channels (micro or mini) have been a famous field of investigation for the previous three decals owing to their high rate of heat transfer, especially for heat exchangers. Many reviews were performed by different investigators about characteristics of flow and heat transfer in mini-channels under heat flux conditions, such as [5] and [6]. Tubes having mini-channels are categorized according to their hydraulic diameter over the range between 200 μm and 3 mm [7]. Investigated the thermal performance of a new design of mini-channel-based solar flat-plate collector. The solar collector consists of an array of mini-channels located in the absorber plate which is covered by a single glass cover[8], studied flat plate absorbers that may pass the fluid through a tube bonded to a thermally conducting plate or achieve lower thermal resistance and pressure drop by using a flooded panel or micro-channel design. The optimum diameters were in the range (6–16) mm depending on the pumping power and (diameter/pitch) ratio [9]. Presented novel solar-thermal arrays for facades integration, based on a trapeze-shaped solar-thermal collector [10]. Solar collectors differ in performance relying on their design. Effectively, one important topic that stays a matter of intensive research is transferring the heat sun to the operating fluid. The present paper analyzes the performance of modified solar collector based on mini-channel to raise the heat-transferred quantity to the operating fluid. The characteristics of the solar collector having mini-channels are based on the absorber plate design, selective coatings, thermal insulation, tilt angle of the collector and working fluids. The present work is used adequately model the heat transfer in a new design of mini-channel collector based on solar radiation with possibility of increasing the energy efficiency of thermal process.

2. **Experimental Work:**

Solar collector based on mini-channel has been manufactured from two absorbing metal plates made of (Aluminum, alloy 6061 T6). The dimensions of each plate are (700 mm×400 mm) with thickness of (20 mm). Computer Numerical Control (CNC) is used to drill (46 mini-channel) with square cross section area (3 mm×3 mm), considering that the distance between the channels is (11 mm) in the top plat as shown in fig. (1). Grooves are made on the top surface of the plate to fix seven thermocouples; the distance between them is 100 mm, as shown in fig. (2). A hole is made in the top plate to show the outlet and inlet of the working fluid and two thermocouples have been used to measure the outlet and inlet temperatures of the working fluid, then the two plates are joined with screws. Now, the mini-channel is ready for any scientific tests. The diagram of the test facility is schematically depicted in fig. (3). While the mini-channel absorbing plate is shown in fig. (4) Finally, the sample is smoothly cleaned by soft silky fabric until one should almost see himself on it. The test section (i.e. solar collector based on mini-channel) composed of a temperature controlled storage tank, circulation pump, connecting pipes and fittings, measuring devices which consist of: solar radiation measurement, two flow meters; the first one used at range (1-10 L/h) and the other one used at range (1.6-16 L/h), two pressure gages to measure the pressure difference across the test section, temperature controller and thermocouples type (K).

Figure (1): Test Mini-Channels Solar Collector.

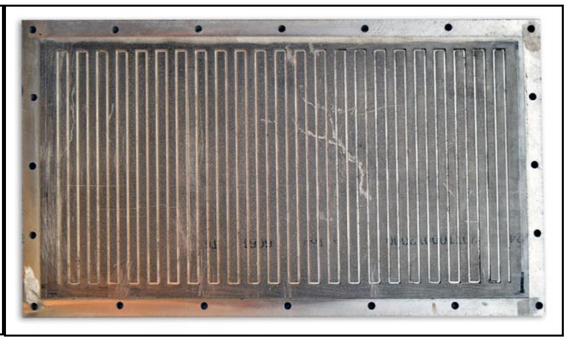


Figure (2): Thermocouples Location at The Top Plate.

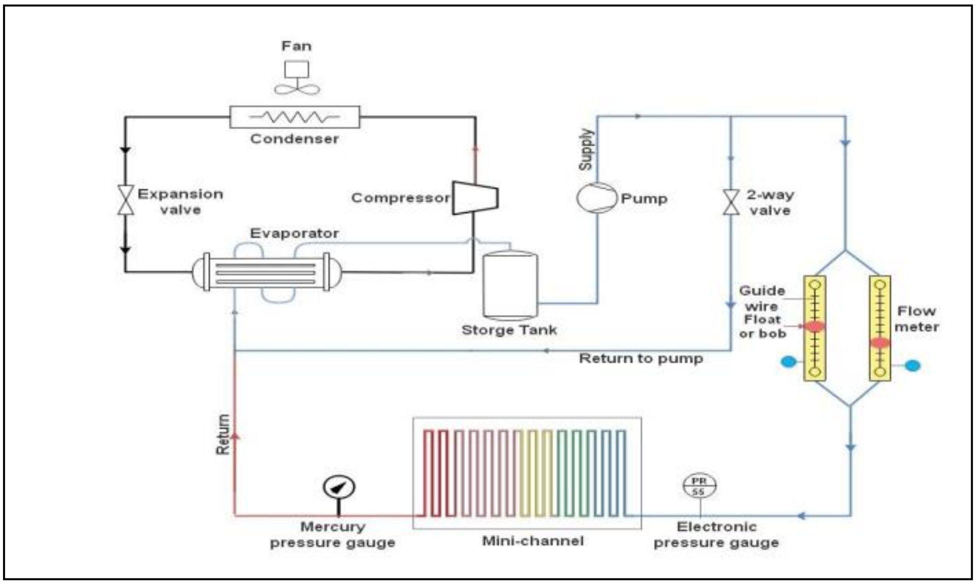


Figure (3) Schematic Representation of Test Facility

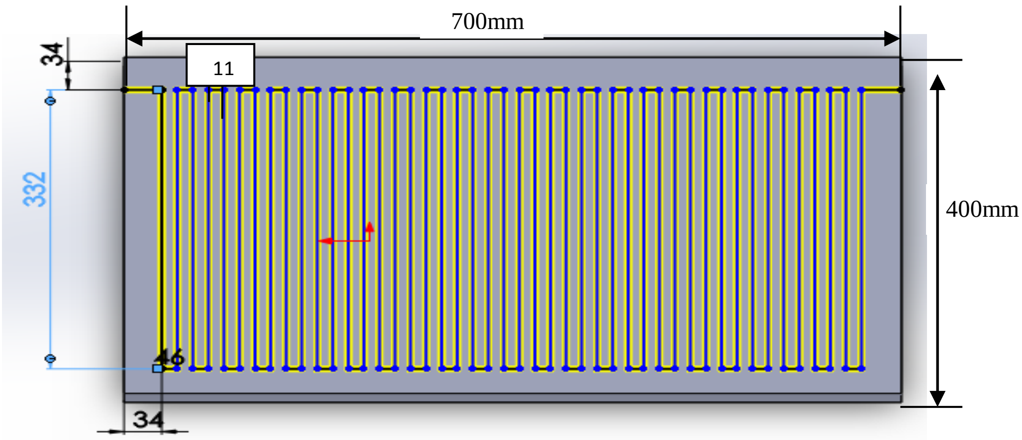


Figure (4) Mini-Channel Absorbing

A. Experimental Procedure

In this paper study the test rig with selective coating and with glass cover, the tests were conducted in Baghdad with southeast orientation at latitude (33.3 °) during July. The data was recorded from (8:00 Am to 6:00 Pm). Working fluids is propylene glycol was chosen in the tests with five different mass flow rates as follows: (4.6, 5.77, 7.96, 11.2 and 18.35) L/h. The mini-channel solar collector was tested under a steady-state condition. The following test procedures were considered:

1. Recording the date and time of experiment.
2. Measuring the ambient temperature.
3. Turning on cooling system which controlled the constant temperature storage tank to a chive the desired fluid inlet temperature. In these tests, two inlet temperatures were considered (15ºC and 20°C).
4. Operating the circulating pump to adjust the flow rate to the exact desired value by gradually controlling the flow rate by using control valve and flow meter, which are constantly checked in order to get the accurate value of flow rate.

5. Measuring the solar radiation intensity, which initiates the heating at the test section.
6. Recording the inlet and outlet temperature of the working fluid and the temperatures distributed along the plate.
7. Recording the pressures across the test section.
8. Repeating the experiments every 60 minutes for 10 hours.

B. Experimental Data Analysis

The calculations were done by conventional equations [11]. The mass flow rate is computed by measuring the volume flow rate and density of propylene glycol.

$$\mathbf{M^{\bullet}} = \boldsymbol{\rho} \,.\, \mathrm{v}^{\bullet} \qquad \textbf{... (1)}$$

Hydraulic diameter was calculated by using the formula

$$\mathbf{D_h} = \frac{\mathbf{4A_c}}{\mathbf{P}} \qquad \textbf{... (2)}$$

Where, Ac: channel cross-sectional area, P: perimeter of channel.

For Reynolds number

$$\mathbf{Re} = \left(\frac{\boldsymbol{\rho}\mathbf{uD_h}}{\boldsymbol{\mu}}\right) \qquad \textbf{... (3)}$$

Where, ρ is the density of fluid, μ is the fluid dynamic viscosity, u is the velocity of fluid, and D_H is hydraulic diameter of fluid.

Friction factor was calculated including entrance and exit loses

$$\boldsymbol{f} = \frac{\mathbf{1}}{\mathbf{2}} \frac{\mathbf{D_h}}{\mathbf{L}} \frac{\mathbf{\Delta P}}{\boldsymbol{\rho}.\mathbf{u_m^2}} \qquad \textbf{... (4)}$$

Where ΔP: pressure difference that measured by a pressure transducer; $\Delta p = p_{out} - p_{in}$

The total heat that transferred to the fluid across the test section and represented as hour useful energy for mini-channel solar collector, is given by:

$$\mathbf{Q_u = \dot{m} \,.\, C_P \,.\, (T_{f(out)} - T_{f(in)})} \qquad \textbf{... (5)}$$

Where; CP = Specific heat capacity of propylene glycol (kJ/kg.ºC) and ($T_{f(out)}$, $T_{f(in)}$) =Inlet and outlet propylene glycol temperatures (°C).

The heat flux is compute by dividing **Q_u** by the channel heating area A_{ch}

$$\mathbf{q_U} = \frac{\mathbf{Q_u}}{\mathbf{A_{Ch}}} \qquad \textbf{... (6)}$$

It is assumed that the longitudinal fluid temperature in the test section is linearly varying, it is calculated as follows:

$$\mathbf{T_f(x) = T_{f,i} + \left(T_{f,o} - T_{f,i}\right).\frac{x}{L}} \qquad \textbf{... (7)}$$

The coefficient of local heat transfer can be defined as:

$$\mathbf{h(x)} = \frac{\mathbf{q}}{[\mathbf{T_p(x)} - \mathbf{T_f(x)}} \qquad \textbf{... (8)}$$

Where, Tp(x) are the measurements of temperature along the plate by thermocouples.

The local Nusselt number can be defined as:

$$\mathbf{Nu(x)} = \frac{\mathbf{h(x).D_h}}{\mathbf{k_f\ (x)}} \qquad \textbf{... (9)}$$

The average Nusselt number can be computed by using the average value of seven readings of local Nusselt number for each experiment.

$$\mathbf{Nu_m} = \frac{1}{7}\sum \mathbf{Nu(x)} \qquad \textbf{... (10)}$$

Trapezoidal rule has been used to calculate the daily useful energy **(Qu)** for solar collector [12].

$$\mathbf{Q_{Ud}} = \sum_{ti}^{tf} \mathbf{qt} = \mathbf{b}[\frac{\mathbf{QU1}}{2} + \mathbf{Q_{U2}} + \mathbf{Q_{U3}} + -- + \frac{\mathbf{Q_{Un}}}{2}] \qquad \textbf{... (11)}$$

Where, b is time increments=1800 second, and qt is useful energy at that time.

The daily solar radiation for mini-channel solar collector as:

$$\mathbf{Q_R} = \mathbf{A_C} * \mathbf{b} * \left[\frac{\mathbf{It_1}}{2} + \mathbf{It_2} + \mathbf{It_3} + - - + \frac{\mathbf{It_N}}{2}\right] \qquad \text{... } \textbf{(12)}$$

Where, **AC:** Collector area (m^2).

The instantaneous collector efficiency can be calculated using the following equation:-

$$\boldsymbol{\eta_i} = \mathbf{Q_U / (A_C .\ I_T)} \qquad \textbf{... (13)}$$

To calculate the daily efficiency for mini-channel solar collector:

$$\boldsymbol{\eta} = \mathbf{Q_{Ud} / Q_R} \qquad \textbf{... (14)}$$

3. Results and Discussion

1. Temperature Distribution

Figures (5a and 5b) show the relation between the temperature distribution of mini-channel solar collector where(x_1 - x_7) represents the thermocouples location [shown in fig. (2)], on the absorber plate, with time for different flow rates (4.6L/h) for test . In This paper presented, the temperature distributions of the absorber plate increase gradually in the direction of flow along the mini-channel until (12:00PM) where maximum solar radiation are recorded, after that hour the temperature distribution become to decrease. Figures (6) shows the temperature distribution along the absorber plate at (12:00PM) for two inlet fluid temperature ($T_{f(in)}$ =15°C) as shown in figure(6a) and ($T_{f(in)}$ =20°C) as shown in figure(6b)It can be noticed from this figure that the values of plate temperature when ($T_{f(in)}$ =20°C) is higher than that when ($T_{f(in)}$ =15°C) for different flow rate. When using glass cover, with selective coating when working fluid is propylene glycol, the selective coating leads to increase temperature distribution of absorber plate. This is because the advantages of matted coatings are the high absorption (α) of short wavelengths and low emissivity (ε). And the glass cover leads to increase temperature distribution of absorber plate The reason for this is conveniently foreseeable because of the cover thermal resistance, which causes a decrease in energy loss to the ambient, thus the heat capacity is larger. Also the temperature distributions decrease when the mass flow rate increased in all test.

In figures (7a and 7b) shows the fluid outlet temperature with time. The result show that the outlet temperature decreased when increasing the flow rate. Also, the outlet temperature decreasing after mid-day because decreasing the solar radiation that is lead to decrease the absorber heat to the working fluid. The outlet temperature when the ($T_{f\,(in)}$ =20°C) is higher than that when ($T_{f\,(in)}$ =15°C) for different flow rate.

2. Useful Energy

The total heat that transferred to the fluid across the test section and represented as hour useful energy for mini-channel solar collector is given in eq.(5) .

Figures (8a and8b) shows the relation between useful energy and solar radiation with time at different flow rate for test cases when working fluid is propylene glycol. In general, the behavior of useful energy is the same of solar radiation. Also the useful energy increasing with increase mass flow rate .The result show that the useful energy when ($T_{f\,(in)}$ =20°C) is higher than that when ($T_{f\,(in)}$ =15°C) for different flow rate because the outlet temperature when the ($T_{f\,(in)}$ =20°C) is higher than that when ($T_{f\,(in)}$ =15°C) for different flow rate

3. Hydraulic Thermal Performance of Mini-Channel Solar Collector

Hydraulic performance is one characteristic that influences mini-channel design. If the energy output is to be maximized, the power expended on pumping fluid should be minimized. Figure (9) shows the relation between the pressure difference across the plate and Reynolds number and figure (10) shows the relation between pressure differences and mass flow rate when the working fluid is propylene glycol, the pressure difference is increasing with increase Reynolds number and mass flow rate the percentage is (56%). Figures (11) show the relation between the friction factor and Reynolds number for propylene glycol. The result shows that the friction factor is inversely proportional with Reynolds number when increasing in Reynolds number decrease friction factor in the percentage (86%). Fluid temperature rise can have significant effects on the frictional characteristics; when the temperature of propylene glycol rises, the kinematic viscosity decreases which results in a corresponding increase in Reynolds number this also explains at a given pumping power, smaller channels will have lower flow rates which will yield higher fluid temperature rise. Pumping power is important parameter in the mini-channel operation. It is propos pressure drop arcos the mini-channel which relates to the working fluid pumping power required. It is the product of the pressure drop across the test section, ΔP and volume flow rate, $V^{\bullet}$. Pumping power = $V^{\bullet}\Delta P$. Figure (12) shows the plot of pumping power with fluid velocity the pumping power increasing when fluid velocity increase the percentage is (89%). Lower pumping power yields higher overall fluid temperatures due to lower fluid velocities.

4. Heat Transfer Characteristics

Figure (13) show the relation between Nusselt number versus Reynolds number for different solar time (8: AM - 6:00PM) with propylene glycol as working fluid. It can be seen from this figure that the maximum value of Nusselt number occurs at (12:00PM) where the solar radiation recorded maximum value. Nusselt number is given increasing with increase Reynolds number at ($T_{f(in)}$=20C°) increasing is (20%) and at ($T_{f(in)}$=15C°) increasing is (16%) this percentage between the maximum and minimum Nusselt number when the absorber plate with cover glass and selective coating and working fluid is propylene glycol .

4. Conclusions

This section presents the conclusions about the work of this thesis which focused on investigating the effect of heat transfer and flow field on the performance of serpentine mini-channel solar collector. The main conclusions can be listed as follows:

1. The temperature distributions of the absorber plate solar collector based on mini-channel increase gradually to the direction of flow along the mini-channel, and the working fluid outlet temperature was increased in the direction of flow inside the mini-channel for test case when increasing the solar radiation.
2. The temperature of absorber plate and working fluid increase when the solar radiation increases and mass flow rate decrease for the different, two inlet temperatures were considered (15ºC and 20°C) .
3. Hydraulic performance is one characteristic that influences the mini-channel design the pressure drop increases when increasing Reynolds number and fluid velocity. The increase in Reynolds number will result in lower average friction factors. Also pumping power is an important parameter in the mini-channel operation. Lower pumping power yields higher overall fluid temperatures.
4. Heat transfer coefficient can be improved by reducing the hydraulic diameter.

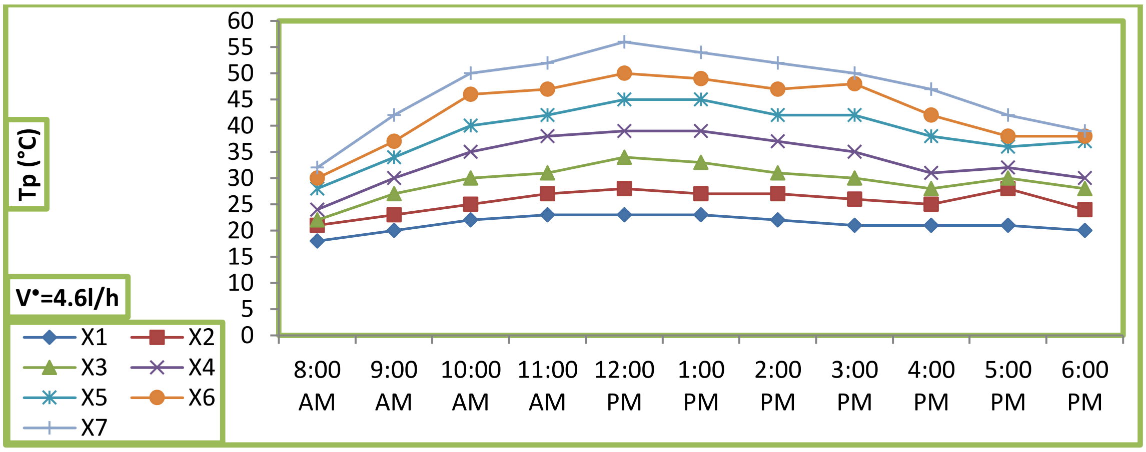


Figure (5a) Temperatures Distribution of Absorber Plate with Time ($T_{f\,(in)}$ =15°C)

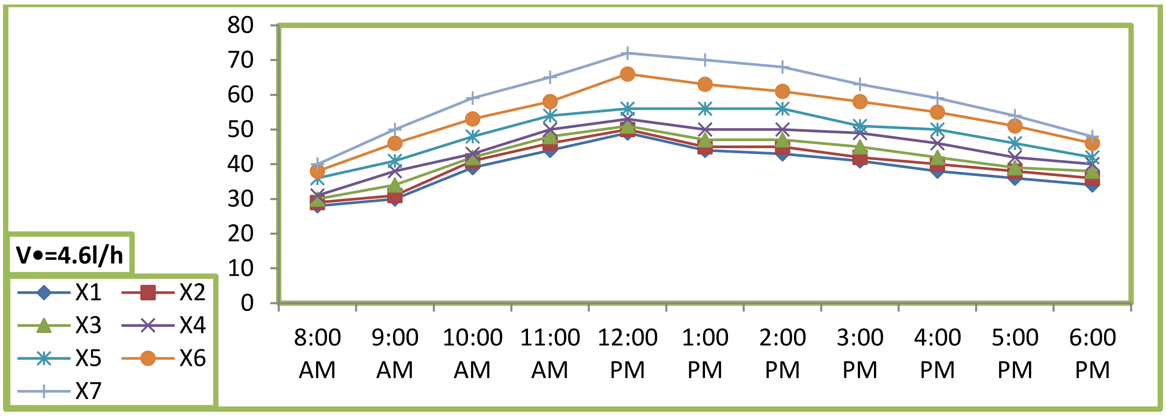
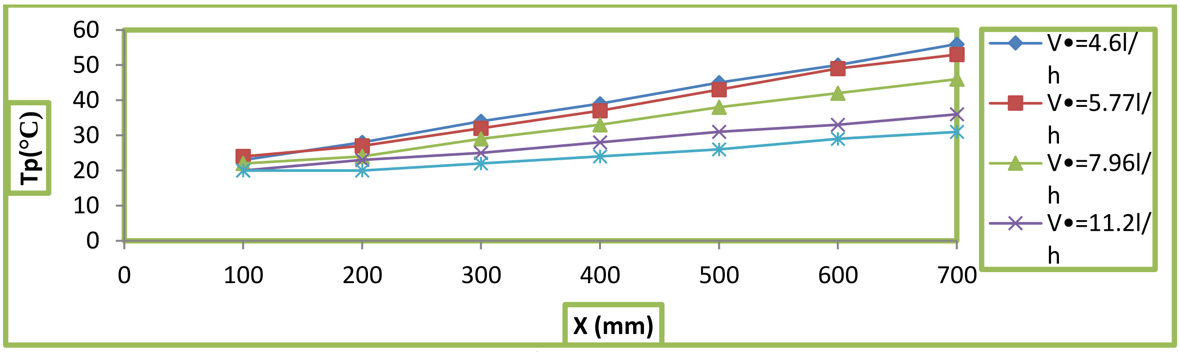
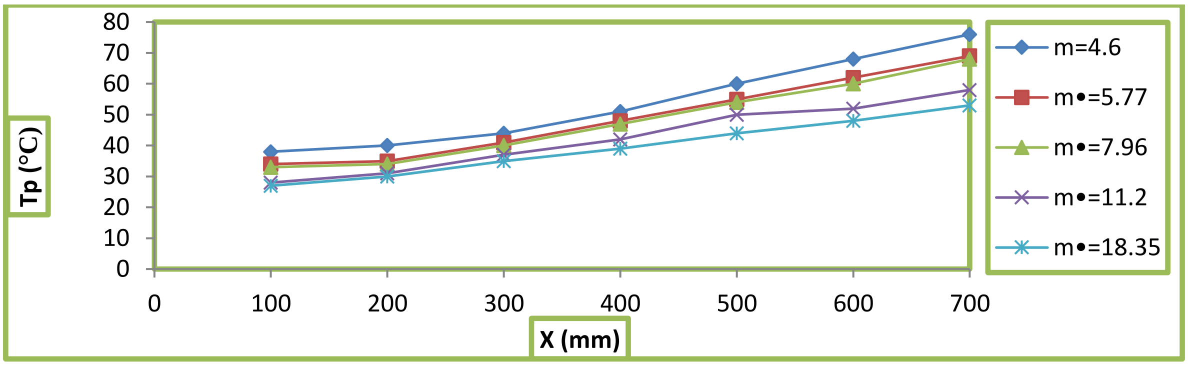


Figure (5b) Temperatures Distribution of Absorber Plate with Time ($T_{f\,(in)}$ = 20°C).

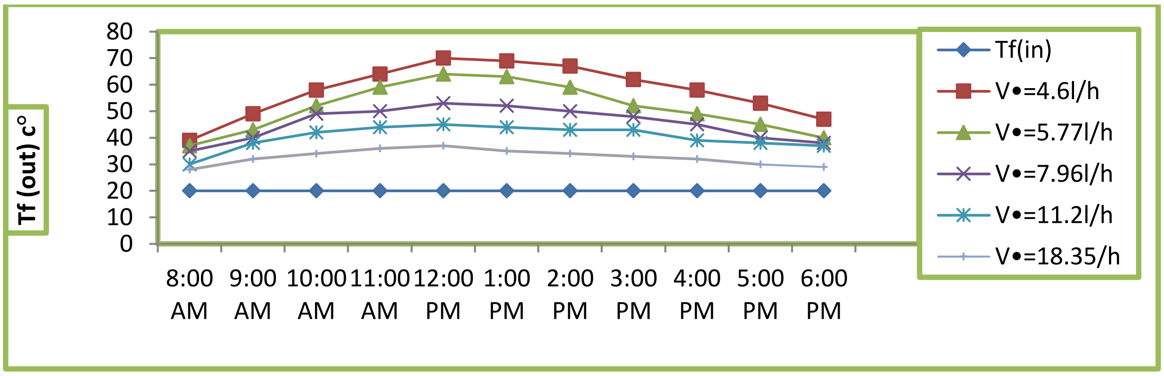


a. (at $Tf_{(in)}$ = 15°C)

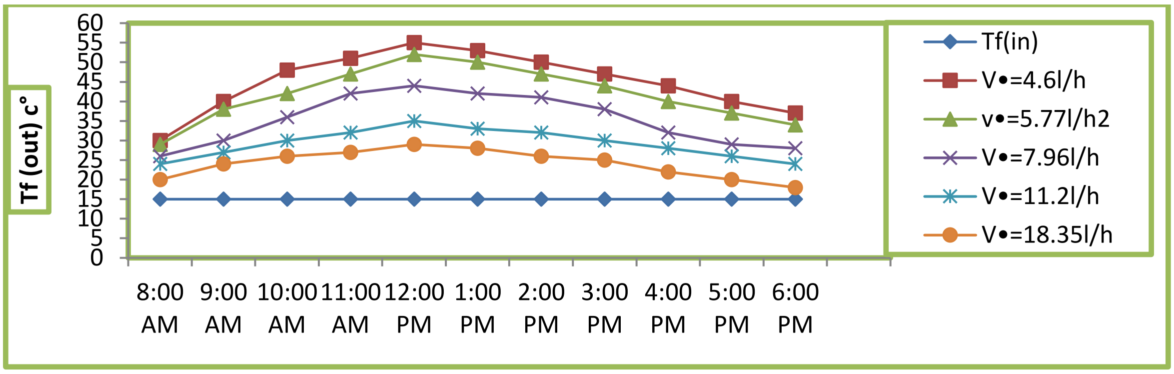


b. (at $T_{f(in)}$= 20°C)

Figure (6). Temperatures Distribution of Absorber Plate with Plate Length at (12:00 pm) (a,b).



a (at $T_{f(in)}$= 20°C)



b (at $T_{f(in)}$= 15ºC)

Figure (7). Outlet Temperatures of Fluid with Time (a,b).

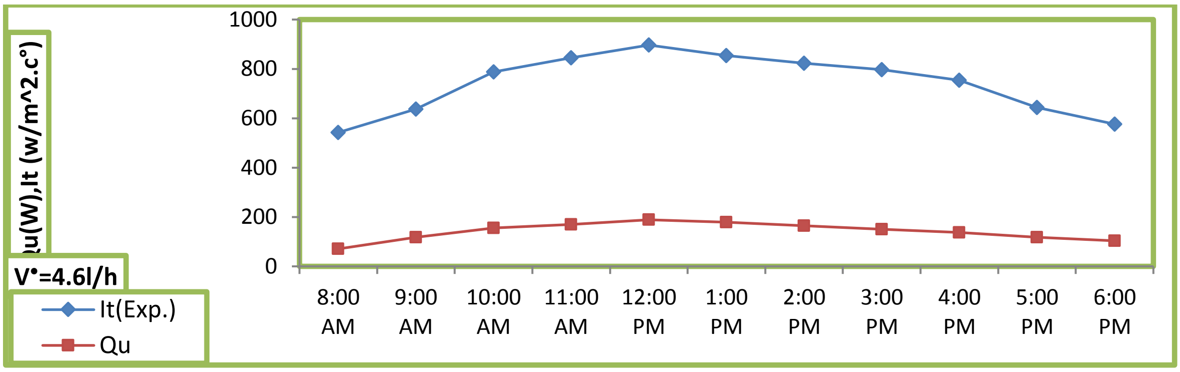


Figure (8). Useful Energy and Solar Radiation with Time at ($T_{f(in)}$=15ºc) .

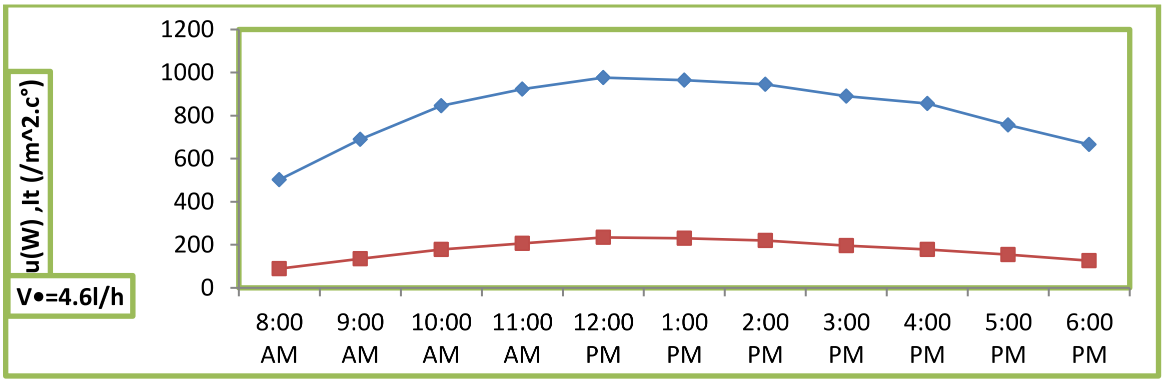


Figure (8b). Useful Energy and Solar Radiation with Time at ($T_{f(in)}$=20ºc) .

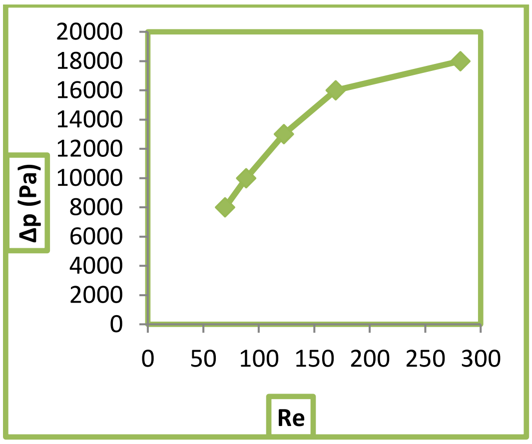


Figure (9). Deferential Pressure versus Reynolds Number (propylene glycol)

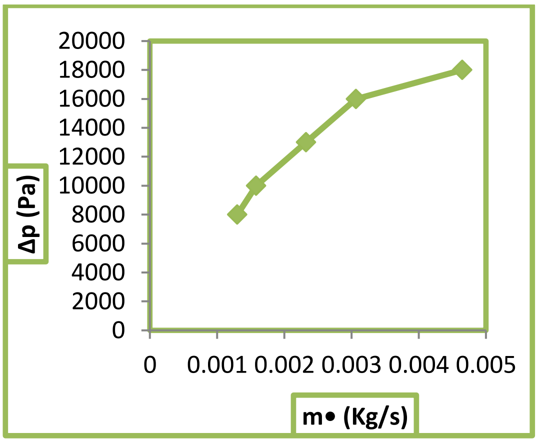


Figure (10). Deferential Pressure versus Mass Flow Rate (propylene glycol)

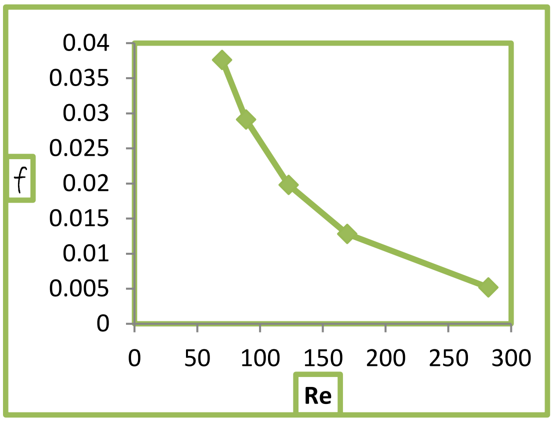


Figure (11). Friction Factor versus Reynolds Number (propylene glycol)

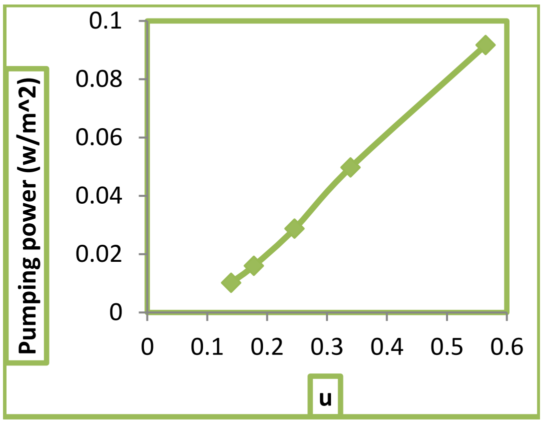


Figure (12).Pumping Power versus Fluid Velocity

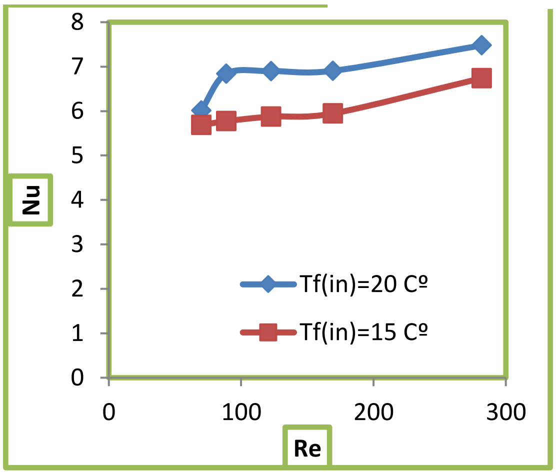


Figure (13). Nusselet Number versus Reynolds Number

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زينب حسون حسن   محمد فوزي محمد   مريم علي عبد الامير

قسم الهندسة الميكانيكية، الجامعة التكنولوجية، بغداد، العراق

dr_alnaji_z@yahoo.com

الخلاصة

الهدف من هذه الدراسة تنفيذ التجريبية للتحقيق في الأداء الحراري للوح مجمع طاقة شمسية يعمل ع اساس قناة مصغرة. لتطبيق المبادلات الحرارية قناة صغيرة، فمن الضروري أن يكون أدوات تصميم مثالية لتنبأ انخفاض الضغط ونقل الحرارة. جميع التجارب العملية اجريت في مدينة بغداد خلال (تموز) عند زاوية ميلان (30°) درجة باتجاه الجنوب تحت ظروف الطقس المشمس. تم استخدام مائع عمل هو بروبلين كلايكول في جريان طباقي خلال تحقق التجارب العملية عند درجة حرارة دخول ثابتة (C^o (20−15)) ولمعدلات تدفق مختلفة (4.6 لتر/ساعة،5.77لتر/ساعة ،7.96لتر/ساعة ،11.2لتر/ساعة و18.35لتر/ساعة). تم تقييم اداء المجمع الشمسي من حيث معامل انتقال الحرارة، انخفاض الضغط، عامل الاحتكاك، طاقة الضخ، وفرق درجات حرارة الدخول والخروج. في هذه الدراسة تم اختبار الجهاز جود طلاء انتقائي وجود غطاء زجاجي بينت النتائج العملية ان زيادة معدل التدفق تؤدي الى زيادة معامل انتقال الحرارة بينما معامل الاحتكاك يقل. ايظا زيادة معدل التدفق تؤدي الى نقصان الفرق درجات الحرارة لمائع العمل بين الدخول والخروج.

الكلمات المفتاحية: لوحة مسطحة، مصغرة– قناة، جامع الشمسية، معامل نقل الحرارة.