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THEORATICAL ANALYSIS OF FLAT PLATE SOLAR COLLECTOR PLACED IN MOSUL CITY BY USING DIFFERENT ABSORBING MATERIALS AND FLUIDS

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ABSTRACT

In this paper, a mathematical model and simulation of flat plate solar collector are developed. The weather data, which used in the calculations of the performance of the collector, is for Mosul city. Detailed energy analyses were carried out for evaluating the efficiency and useful heat gain of a typical flat plate solar collector under certain operation and design conditions. In this analysis, different fluids and different absorbing materials were used to indicate their effect on the performance of flat plate solar collector. Operating parameters, which considered as variables, are the mass flow rate, the inlet and the outlet temperature difference and the total solar radiation flux. The simulation program had written by using EES (Engineering Equation Solver) software program. The results of this analysis show that the copper and aluminum gives a good efficiency up to (0.6) with value (0.02) of collector performance coefficient when water as a working fluid, while the plain carbon steel gives efficiency (0.46) that stated previously because of low heat conductance . The results show also that the copper and the aluminum give the largest useful heat gain extracted from the collector as compared with plain carbon steel. It has been also show that the solar collector efficiency is higher in case of using water as working fluid than that of propylene glycol solution.

KEY WORDS

Simulation, Flat Plate, Solar collectors, heat gain, absorbing plate materials, propylene glycol solution.

دراسة نظرية لمجمعات شمسية ذات صفائح مستوية موضوعة في مدينة الموصل باستخدام معادن وموائع مختلفة

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المستخلص

يتضمن البحث الحالي إنشاء نموذج رياضي لمجمعات شمسيه ذات صفائح مستوية بغرض محاكاة النموذج الواقع تحت تأثير أجواء مدينة الموصل من درجات الحرارة العظمى والصغرى بغرض تحديد كفاءة تلك المجمعات الشمسية. حيث تم اجراء تحليل مفصل للطاقة الشمسية بغرض تقييم كفاءة هذه المجمعات الشمسية و الحرارة النافعة المكتسبة تحت ظروف تشغيلية وتصميمية معينة. تم أستخدام الماء ومحلول البروبلين كلايكول كموائع تشغيل في المنظومة قيد الدراسة بينما أستخدم النحاس و الالمنيوم و الصلب الكاربوني كمعادن للصفائح الماصة للحرارة في المجمع الشمسي. تم أختبار معدل الجريان الكتلي للمائع والتغير في درجة حرارة المائع الداخل والخارج من المجمع الشمسي بالإضافة الى التغير في مقدار فيض الاشعاع الشمسي كظروف تشغيلية للمنظومة. تم بناء برنامج حسابي لمحاكاة المجمع الشمسي وذلك باستخدام الوسط البرمجي لحل المعادلات الهندسية (EES) ولقد أظهرت النتائج المستحصل عليها من خلال البرنامج أن أستخدام النحاس والالمنيوم كصفائح ماصة للحرارة تعطي أعلى كفاءة يصل مقدارها إلى (0.6) عندما تكون قيمة معامل اداء الشمسي(0.02) باستخدام الماء كمائع تشغيل في المنظومة بينما الصلب الكاربوني أعطى كفاءة مقدارها (0.46)، كما أظهرت النتائج أيضاً أن النحاس والالمنيوم يعطون أعلى كمية من الطاقة النافعة بالمقارنة مع الصلب الكاربوني بالاضافة الى أستنتاج أن استخدام الماء كمائع للتثليج اعطى كفاءة اعلى مقارنة مع البروبلين كلايكول.

الكلمات المرشدة

محاكاة ، صفائح مستوية ، مجمعات الشمسية، الحرارة المكتسبة، مواد الصفائح الماصة، محلول البروبلين كلايكول.

1. INTRODUCTION

Flat-plate solar collectors have potential applications A/C systems, industrial process heat and also for heating domestic water [1]. These collectors use both beam and diffuse radiation. A well-designed collector can produce hot water at temperature up to the boiling point of water [2]. They are usually fixed in position permanently, have fairly simple construction, and require little maintenance to keep costs at a level low enough to make solar heating more attractive than other sources of heat, the materials, dimensions, and method of fabrication must be chosen with care. A flat-plate solar collector consists of a radiation - tubes attached to the plate to absorbing flat plate beneath one or more transparent covers transport the circulating fluid and back and edge insulation to reduce heat loss, water or an anti-freeze fluid circulates through the collector by a pump or by natural convection to remove the absorbed heat [2].

A solar collector is a very special kind of heat exchanger that uses solar radiation to heat the working fluid. While conventional heat exchangers accomplish a fluid-to fluid heat exchange with radiation as a negligible factor, the solar collector transfers the energy from an incoming solar radiation to a fluid. The wavelength range of importance for flat-plate solar collectors is from the visible to the infrared [3]. A review of literature sources were listed here, Abdul Hai Alami [4], experimentally investigate the selecting of absorber materials for solar collectors, copper and aluminum alloys were cast at four different percentages of each, then their grain structure was examined and comprehensive solar tests were conducted to measure the heat capacity of each alloy. E. I. Igweonu et al [5], analyzes the efficiency of different solar collectors and the determining factors affecting the efficiency of collectors. A. Alvarez et al [6], they present an experimental analysis and a thermal and hydrodynamic modeling of a newly designed flat - plate solar collector characterized by its corrugated channel and by the high surface area directly in contact with the heat transport fluid. R. Herrero Martin et al [7], study of heat transfer enhancement in a tube-on-sheet solar panel with wire-coil inserts, using TRNSYS as the simulating tool. The numerical simulation methodology predicts the thermo hydraulic flow behavior of enhanced and standard tube-on-sheet solar collectors, evaluating the local losses, friction coefficients and Nusselt numbers as functions of the operating parameters. Tooraj Yousefi [8] the effect of Al_2O_3-water Nano fluid, as working fluid, on the efficiency of a flat-plate solar collector was experimentally investigated in comparison with water as absorption medium. Balaram Kundu [9], his paper presents a comparative study on the performance and optimization of several profile shapes namely, rectangular, trapezoidal and rectangular profile with a step change in local thickness. Francis O. Wayua et al [10], Thermal performance tests were carried out on four water heating flat plate solar collectors with the aim to select a suitable one to be used to provide process heat for milk pasteurisation.

In literature through the vision of a modern research, we can note that these researches did not focused on the effect of material and fluid type on the efficiency of flate plate solar collector placed at Mosul's weather condition extracte from Iraqi metrological office [11].

2. MATHEMATICAL MODEL AND SIMULATION OF SOLAR COLLECTOR

In steady state, the performance of a flat-plate solar collector can be described by the useful gain from the collector Qu, which is defined as the difference between the absorbed solar radiation and the thermal loss or the useful energy output of a collector [2]:

$$Q_u = A_{sc} F_R [S - U_L (T_{in} - T_a)] \qquad (1)$$

The solar radiation absorbed by a collector per unit area of absorber S can be calculated using the optical properties of covers and a plate. In this study the absorbed radiation on the absorber plate is calculated by isotropic sky model [12]:

$$S= I_bR_b(\tau\alpha)_b+I_d(\tau\alpha)_d\left(\frac{1+\cos\beta}{2}\right)+(I_b+I_d).\rho_{gr}.(\tau\alpha)_{gr}(\frac{1-\cos\beta}{2}) \tag{2}$$

Where the subscripts *b*, *d*, and *g* represent beam, diffuse, and ground reflected radiation respectively, *I* is intensity of radiation on a horizontal surface,($\tau\alpha$) the transmittance absorptance product that represents the effective absorptance of the cover-plate system, and β the collector slope. g_r *is* the diffuse reflectance of ground and the geometric factor R_b is the ratio of beam radiation on the tilted surface to that on a horizontal surface. This section treats the way to calculate the transmittance absorptance product of beam, diffuse, ground-reflected radiation for a given collector configuration and specified test conditions, for accurate the prediction of collector performance coefficient, it is necessary to evaluate properties of the working fluid to calculate the forced convection heat transfer coefficients inside of tubes and the overall loss coefficient, the mean fluid temperature T_{fm} at which the fluid properties are evaluated can be obtained by [3]:

$$T_{fm}=T_i+\frac{Q_u/A_{sc}}{F_RU_L}(1-F'') \tag{3}$$

where the collector flow factor *F''*, defined as the ratio of *FR* to *F'*, are given by [3]:

$$F''=\frac{\dot{m}\,C_p}{A_{sc}\,U_L\,F'}\left[1-\exp\frac{A_{sc}\,U_L\,F'}{\dot{m}\,C_P}\right] \tag{4}$$

$$F'=\frac{\frac{1}{U_L}}{w\left(\frac{1}{U_L(d+(w-D))F}+\frac{1}{C_b}+\frac{1}{\pi d h_f}\right)} \tag{5}$$

where *F* is the fin efficiency for straight fins with rectangular cross section and defined as:

$$F=\frac{\tanh(\frac{m(w-D)}{2})}{m(w-D)/2} \tag{6}$$

Where *m* is a parameter of the fin-air arrangement defined as

$$m=\sqrt{\frac{U_L}{k\,\delta}} \tag{7}$$

The mean plate temperature, T_{pm}, is always greater than the mean fluid temperature due to the heat transfer resistance between the absorbing surface and the fluid.

$$T_{pm}=T_i+\frac{Q_u/A_{sc}}{F_RU_L}(1-F_R) \tag{8}$$

The collector heat removal factor, F_R, is the ratio of the actual useful energy gain of a collector to the maximum possible useful gain if the whole collector surface were at the fluid inlet temperature. It is defined as:

$$F_R=\frac{\dot{m}_w Cp_w(T_o-T_i)}{A_{sc}[S-U_L(T_i-T_a)]} \tag{9}$$

Physically the collector heat removal factor is equivalent to the effectiveness of a conventional heat exchanger [2]. The solar collector efficiency is defined as the ratio of the useful heat gain over any time period to the incident solar radiation over the same period. The instantaneous energy efficiency of the solar collector can also be expressed in the form of the average Bliss coefficient ($F_R(\tau\alpha)$) and the heat loss coefficient (F_RU_L), as shown below [3]:

$$\eta_{sc}=\frac{Q_u}{A_{sc}\,G_T} \tag{10}$$

$$\eta_{sc} = FR\ (\tau\alpha) - \frac{F_R U_L (T_i - T_o)}{G_T} \quad (11)$$

3. DESCRIPTION THE MODEL OF FLAT PLATE SOLAR COLLECTOR

The important parts of a typical liquid heating flat-plate solar collector, as shown in Fig. 1 are the black solar energy –absorbing surface with means for transferring the absorbed energy to a fluid, envelopes transport to solar radiation over the solar absorber surface that reduce convection and radiation losses to the atmosphere, and back insulation to reduce conduction losses. Flat plate solar collectors are almost always mounted in a stationary position e.g. as an integral part of wall or roof structure within orientation optimized for the particular location in question for the time of year in which the solar device is intended to operate. The dimensions of flat plate solar collector model with thermal conductivity for different absorber plate materials that simulate in this paper [13] as shown in Tables 1 and 2.

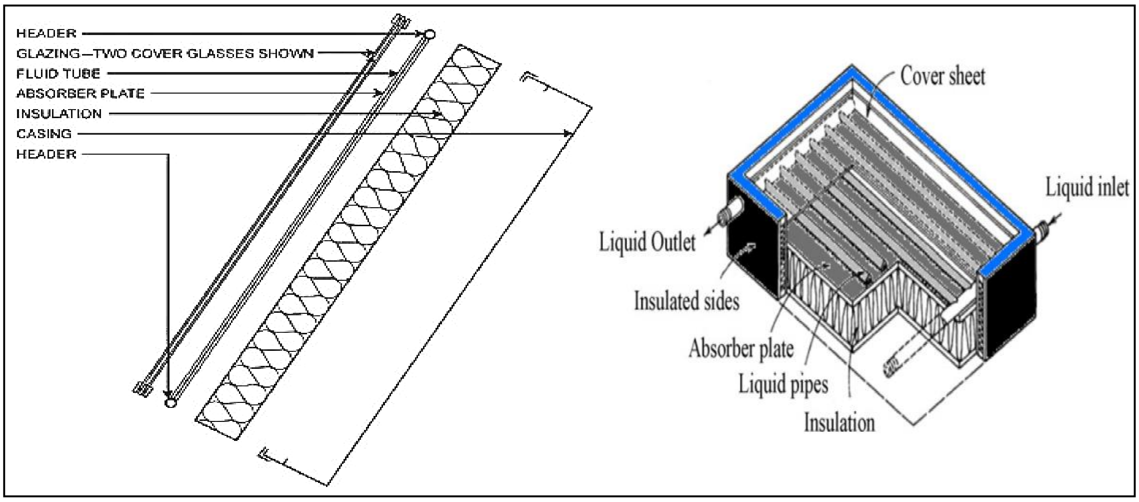

Fig. 1. Pictorial View of a Flat- Plate Solar Collector

Table 1. Dimensions of Flat Plate Solar Collector Model

Parts Description	Dimensions
Inner Tube Diameter	1 (cm)
Thickness of Flat Plate Collector	0.05 (cm)
Width of Flat Plate Collector	100 (cm)
Length of Flat Plate Collector	200 (cm)
Gross Area	23,100(cm^2)
Absorber Area	20,000(cm^2)
Number of Tubes	10

Table 2. Thermal Conductivity of Using Tubing Materials

Materials	W/m.K
Carbon Steel	54
Copper	401
Aluminum Alloy	205

4. MODELING TOOLS

In this research, the EES simulation tool is used to model and analyze the performance of a solar system [14]. Engineering Equation Solver (EES) is a program developed by Professor Sanford A. Klein of the Solar Energy Laboratory, University of Wisconsin – Madison. EES is a powerful tool for solving engineering problems and is relatively easy to learn. It is particularly useful in solving thermodynamic and heat transfer problems since it offers several built-in libraries comprising of thermodynamic and thermo physical properties, hence there is no need to look these values up in tables. Moreover, algebraic mistakes are not a concern and the use of EES is time efficient in solving complicated engineering problems.

One major advantage to EES is that it can solve a system of simultaneous equations, which is not easy to do using Excel. This includes a system with a transcendental equation (i.e. one in which the dependent variable cannot be isolated). It can be solve a system of algebraic, differential, and complex equations and it can also perform optimization, provide linear and nonlinear regression, and generate publication quality plots. Since it automatically identifies and groups equations to be solved simultaneously, the solver always operates at optimum efficiency. Many mathematical functions, thermo physical properties and transport properties are also provided by built-in functions that are helpful in solving engineering problems in thermodynamics, fluid mechanics, and heat transfer. With these features, the user is able to concentrate more on his / her own's problem.

EES program is particularly useful for design problems in which the impacts of one or more parameters need to be investigated .The mathematical model of the whole collector was written in the Engineering Equation Solver (EES), Properties for the material and fluid are taken from the library of EES.

4.1. Verification the Results of Program:

We have been comparing the program, which built upon the results of this research with theoretical and experimental result:

Theoretical comparison accomplished with the results of the (CoDePro) program [2, 15] as shown in Fig. 2. at same weather and thermal conditions. The flat-plate collector design program (CoDePro) is a program that can help solar engineers design flat-plate solar collectors. It has been developed so that most details of the collector configuration can be specified. The program has been developed with the professional version of EES and beta-tested from its development level by solar engineers. The test methodology is based on the standard test methods provided by ASHRAE Standard 93-86 [1]. The curves of the collector efficiency versus collector performance coefficient that depend upon theoretical comparison based on CoDePro and our program results as shown in Figs. 2 and 4, respectively, show that there is a clear convergence and fit in the results between the two programs, especially at collector performance coefficient range 0.02 until 0.04 for copper and aluminum alloy.

Experimental comparison accomplished with the results of experimental tests were performed by the testing and laboratories division, Florida solar energy center according to the solar rating and certification corporation (SRCC) testing method [16].Comparison of the program calculated results with the experiments indicate that the design program developed in this study has an ability to predict the thermal performance of the collector. The predicted instantaneous efficiency of the collector is almost the same as the experimental results especially at collector performance coefficient range 0.021 until 0.038 for copper, while there is a little discrepancy between the calculated and experimental values due to angle modifier may come from the lack of information about the SRCC.

5. RESULTS

The program calculates the collector efficiency for different values of ($\Delta T/G_T$), the coefficients of these equations are determined by linear regression as specified in ASHRAE Standard 93-86 [1].

As can be seen from Figs. 2 and 3, that the copper and aluminum gives the best efficiency up to 0.6 with value of 0.03 for ($\Delta T/G_T$) by using water as a working fluid , while the efficiency has been shown to be 0.5 with propylene glycol solution as a working fluid. The figures also reveals that the plain carbon steel gives solar collector give a lowest efficiency as compared with both copper and aluminum because of low heat conductance. The variation in the instantaneous efficiency with the term ($\Delta T/G_T$) as shown in equation (11) will decrease solar collector efficiency due to the increase in temperature difference between inlet fluid and the ambient temperature which affect on the solar collector performance and intern reduced the efficiency.

Figs. 4 and 5 show that the effect of the fluid mass flow rate with different plate and fluid types on the useful heat gain of the solar collector. The results show that the largest useful heat gain extracted from the collector was found with aluminum as the flow rate increase the useful heat gain increase too, as a result, the instantaneous efficiency improves with the increase of mass flow rate. The transferred heat to the fluid was decreased with an increase in mass flow rate of the fluid, this is because an increase in the mass flow rate which reduced the hydraulic diameter of fluid inside the tube as a result heat transfer by convection will increase the heat transfer rate.

Figs. 6 and 7 show that the effect of the fluid mass flow rate on the plate temperature. The figures reveal that the temperature of copper plate with propylene glycol solution as a working fluid is 130 °C which is much higher than the temperature produced by using water (117 °C), this is because the specific heat of propylene glycol solution is much lower than that of water.

Figs. 8 to 10 show that the relationship between useful heat gain as a function of fluid mass flow rate for solar collectors made from copper, aluminum and plain carbon steel with water and propylene glycol solution as a working fluids. The figures indicate that the best useful heat gain was archived with copper solar collector and water as shown in Fig. 8 , while copper solar collector with propylene glycol solution gives a less useful heat gain as compared with water. It is clear also that plain carbon steel collector in Fig. 10 gives a less useful heat gain as compared with copper and aluminum collector. That is due to the variation of both thermal conductivity and absorbance coefficient the heat gain quantity was varied too and that variation was directly proportional with heat gain quantity of solar collector.

The program calculates the collector efficiency for different values of collector performance coefficient ($\Delta T/G_T$).The coefficients of these equations are determined by linear regression as specified in ASHRAE Standard 93-86 [1].

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Figs. 6 and 7 show the mass flow rate with different plate and fluid types on the useful heat gain of the solar collector. The results show that the largest useful heat gain extracted from the collector was found with aluminum as the flow rate increase the useful heat gain increase too, as a result, the instantaneous efficiency improves with the increase of mass flow rate. The transferred heat to the fluid was decreased with an increase in mass flow rate of the fluid, this is because an increase in the mass flow rate which reduced the hydraulic diameter of fluid inside the tube as a result heat transfer by convection will increase the heat transfer rate.

Figs. 8 and 9 show that the effect of mass flow rate on the plate temperature. The figures reveal that the temperature of copper plate with propylene glycol solution as a working fluid is 130 °C which is much higher than the temperature produced by using water (117 °C), this is because the specific heat of propylene glycol solution is much lower than that of water.

Figs. 10 to 11 show that the relationship between useful heat gain as a function of fluid mass flow rate for solar collectors made from copper, aluminum and plain carbon steel with water and propylene glycol solution as a working fluids. The figures indicate that the best useful heat gain was archived with copper solar collector and water as shown in Fig. 10, while copper solar collector with propylene glycol solution gives a less useful heat gain as compared with water. It is clear also that plain carbon steel collector in Fig. 12 gives a less useful heat gain as compared with copper and aluminum collector. That is due to the variation of both thermal conductivity and absorbance coefficient the heat gain quantity was varied too and that variation was directly proportional with heat gain quantity of solar collector.

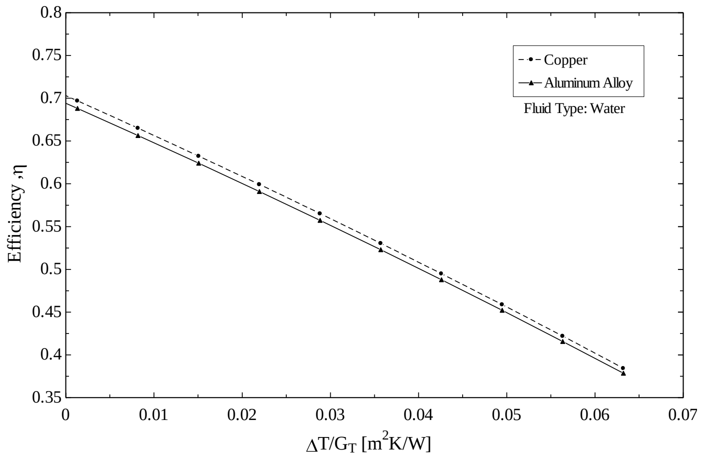

Fig. 2. Effect of (ΔT/GT) on the Collector Efficiency with Water as a Working Fluid Based on CoDePro

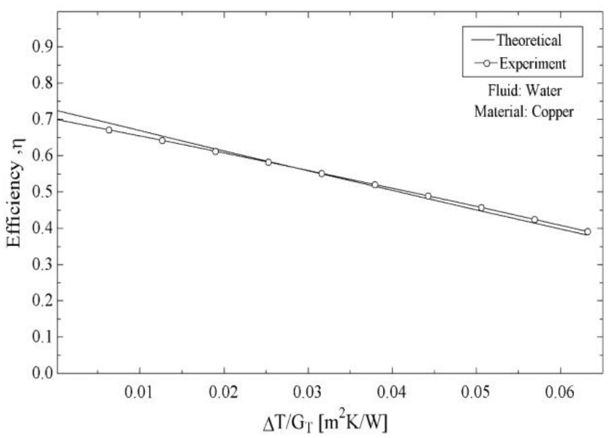

Fig. 3. Comparison between Theoretical and Experimental Results for Water Fluid and Copper Material

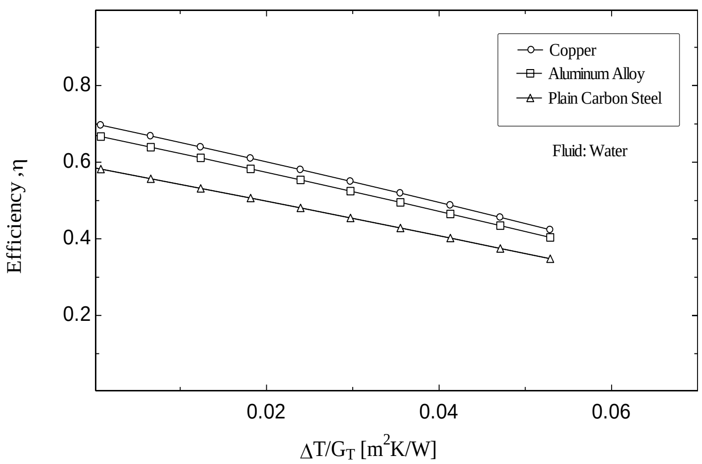

Fig. 4. Effect of (ΔT/GT) on the Collector Efficiency with Water as a Working Fluid

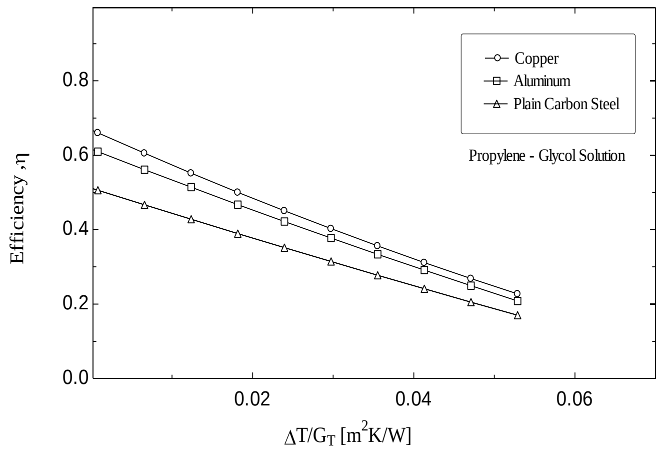

Fig. 5. Effect of (ΔT/GT) on the Collector Efficiency with Propylene as a Working Fluid

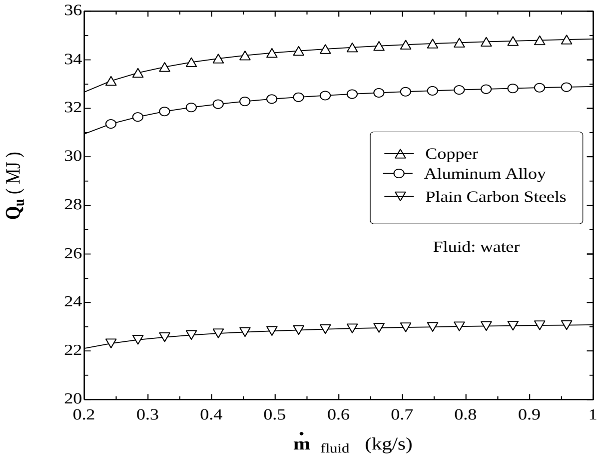

Fig. 6. Effect of water Mass Flow rate on the Useful Heat Gain

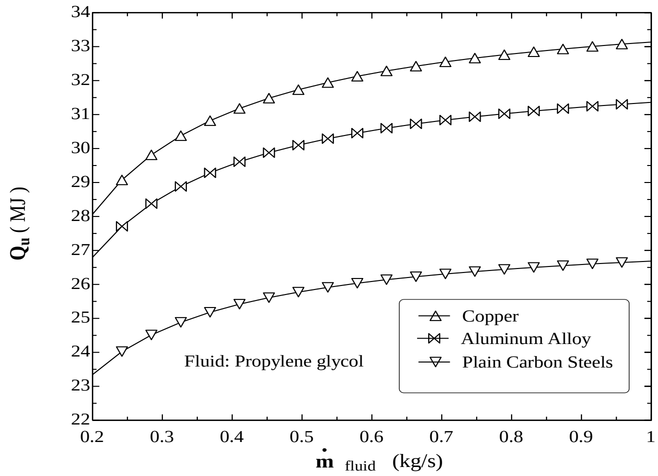

Fig. 7. The Effect of Propylene Solution Mass Flow Rate on the Useful Heat Gain

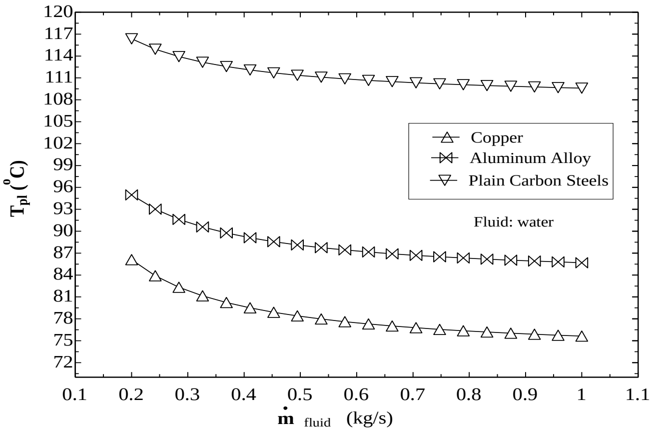

Fig. 8. Effect of Water Mass Flow Rate on the Absorber Plate Temperature

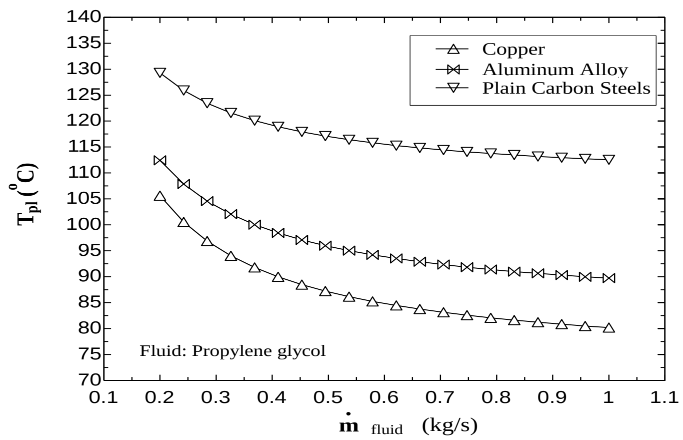

Fig. 9. Effect of Propylene Solution Mass Flow Rate on the Absorber Plate Temperature

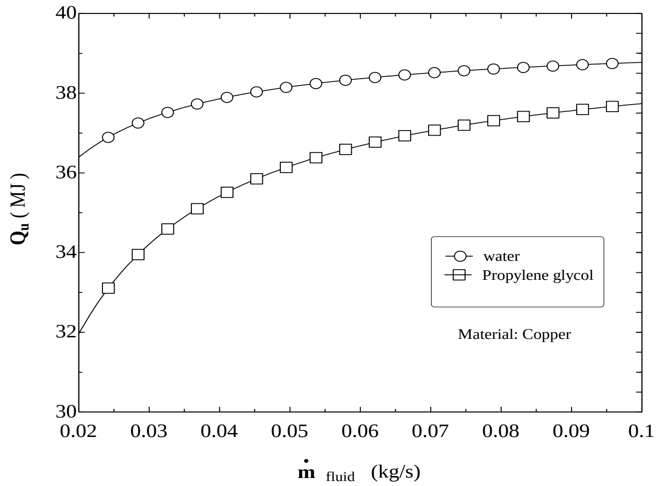

Fig. 10. The Effect of Fluid Mass Flow Rate on the Useful Heat Gain with Copper as an Absorbed Plate

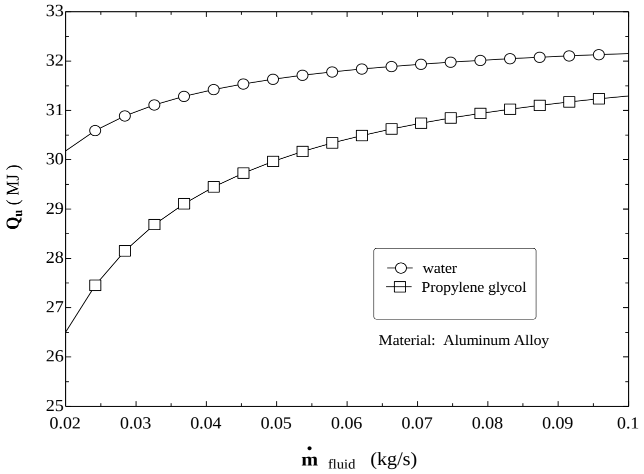

Fig. 11. The Effect of Fluid Mass Flow Rate on the Useful Heat Gain with Aluminium as an Absorbed Plate

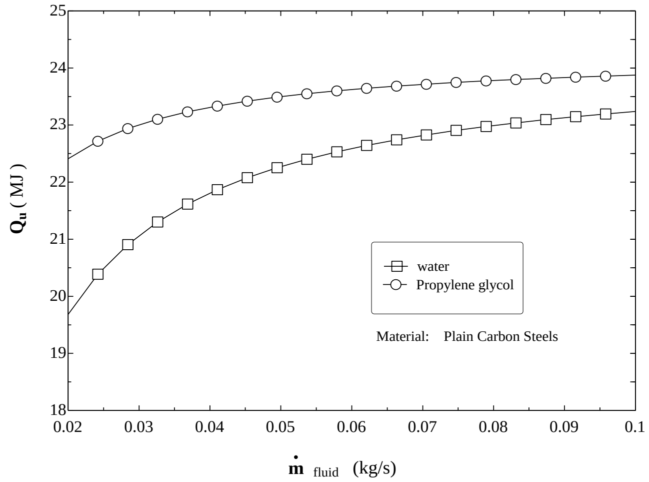

Fig. 12. The Effect of Fluid Mass Flow Rate on the Useful Heat Gain with Plain Carbon Steels as an Absorbed Plate

6. CONCLUTIONS

Mathematical model applied for solar collectors manufactured from copper, aluminum and plain carbon steel materials using both water and glycol solution fluids led to the following conclusions:

1. For both water and propylene glycol solution fluids, efficiency of solar collector have been decreased with an increase in the ($\Delta T/GT$) fraction for copper, aluminium and plain carbon steel materials.
2. For both water and glycol solution fluids, copper plate collector showed a higher efficiency than both aluminium and plain carbon steel material.
3. Plain carbon steel collector showed a lowest efficiency, while aluminium flat plate showed an intermediate efficiency.
4. Copper, aluminium and plain carbon steel plates, the useful heat gain (Q_u) was increased with an increase in mass flow rate of fluid.
5. Copper flat plate solar collector showed a higher useful heat gain (Qu) while plain carbon steel showed a lower values of (Qu) and aluminium alloy have an intermediate (Qu) value.
6. Both water and propylene glycol solution fluids, solar collector plate temperature have been decreased with an increase in mass flow rate for all materials.
7. A higher value of plate temperature (Tp) was showed for copper solar collector flat plate, while plain carbon steel showed a lower (Tp) value, and an intermediate value of Tp was shown for aluminium collector plate.

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NOMENCLATURE

A_{sc} Solar collector area (m^2)
C_b Tube-plate bond conductance, $(W/m.^{\circ}C)$
Cp Specific heat (J/ kg.K)
F_R Collector heat removal factor
F' Collect or efficiency factor
F'' Collector flow factor
G_T Total incident solar radiation, W/m^2
h_f Forced convection heat transfer coefficient, $(W/^{\circ}C.m^2)$
D Outer diameter of tube, m
I Intensity of incident radiation, (W/m^2)
k Thermal conductivity, $(W/m.^{\circ}C)$
m Parameter of the fin-air arrangement
m° Total collector mass flow rate, (kg/s)
Qu Useful heat gain from collector. (W)
Rb Geometric factor
S Absorbed radiation per unit area, (kJ/m^2)
T_a Ambient temperature, C
T_b Fin base temperature, C
T_f Local fluid temperature, C
T_{fm} Mean fluid temperature, C
Ti Fluid temperature at inlet, C
To Fluid temperature at exit, C
T_{pm} Mean plate temperature, C
U_L Overall loss coefficient of the collector, $(W/^{\circ}C.m^2)$
W Distance between the centers of adjacent tubes, m
ΔT Temperature *difference* between fluid inlet and ambient, C
$\Delta T/G_T$ collector performance coefficient, $(^{\circ}C.m^2/W)$

Subscripts:

A/C Air Conditioning
EES Engineering Equation Solver
SRCC solar rating and certification corporation

GREEK:

α Absorptance
β Collector slope
η Instantaneous efficiency of solar collector
θ Angle of incidence of solar radiation