Optimization Performance of Solar Collector Based on the Fractional Factorial Design

الأمثلية في أداء المجمع الشمسي بالاعتماد على تصميم المضروب المصغر

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Abstract

The research focuses on investigation of multi factors which influenced on the Performance of flat plate solar collector and selects the optimum conditions. The model of solar collector is treated with number of glass covers, Cover- Plate air spacing and flow rate of water. The stagnet temperature of absorber plate was calculated. The calculations were carried out by using *EES* program in connection with Taguchi method and regression model. The outcome of fractional factorial design of experiments by Taguchi method was accomplished by Minitab 17 software.
Key words: *EES* program, Taguchi method, Stagnet temperature, Solar Collector

الخلاصة:

يركز البحث الحالي على استقصاء العوامل المؤثرة على اداء المجمع الشمسي ذو اللوح المستوي ومن ثم اختيار افضل ظروف العمل. يتعامل موديل المجمع الشمسي مع مجموعة عوامل تتألف من عدد الاغطية الزجاجية، الفسحة الهوائية بين الغطاء الزجاجي واللوح الماص ومعدل تدفق الماء. تم احتساب درجة حرارة الركود عند اللوح الماص. كذلك تم اجراء الحسابات اعتمادا على برنامج المحاكاة *EES* . تم اجراء خطة تجارب تصميم المضروب المصغر وفقا لطريقة تاكوشي وذلك باستخدام برنامج Minitab 17 .

Nomenclatures

Symbols	Definition	Units
A_c	Area of the gatherer	m^2
b	Length of bond	cm
C_b	Bond conductance	Kcal/m/h °*C*
C_w	Tube wall conductance	W/m K
D	Diameter of tube	cm
h_{fi}	Coefficient of local film heat transfer	W/ m^2 K
H	The rate of entrant or spread rays on a surface.	KJ/ kg/ h
HR	Solar power got on the top surface of the gatherer.	W. m^{-2}
K	Thermal conductivity of metal	W/m K
K_b	Conductivity of bond	W/m K
k^n :	Full factorial design 2^3 = 8 experiments where: k is tow levels and n is three factors.	unitless
L = (W-D)/2	Fin length	cm
L_4	Fractional factorial design 2^{3-1} = 4 experiments	unitless
Q_l	The heat spread into the environment.	KJ/h
Q_e	The energy rate of stockpiling in the gatherer.	KJ/h
Q_u	Beneficial energy conveyed by gatherer.	KJ/h
Q_u	The valuable rate of heat shifts into operating liquid.	KJ/h

R	A factor to switch entrant or spread rays on the gatherer surface.	KJ/ kg/ h
S	Absorbed solar energy	Watts
t_a	Environmental temperature	°C
t_p	Absorber temperature.	°C
T_b	Temperature at $x = L$	°C
U_L	The general coefficient of scattered heat.	kJ/h-m²-K
W	Distance between center of tubes	cm
Y	Thickness of bond	cm
α	Absorptivity, is the portion of sun rays that approaching the absorbing surface that is ingested.	unitless
τ	Transmissivity, is the portion of entrant sun rays that approaching the absorbing surface.	unitless
$(\tau . \alpha)_e$	Effective transmittance absorptance output for entrant or spread rays.	unitless
Δx	Thickness of sheet	cm

1. Introduction

The energy radiation transforms into warm phase with the assistance of solar collector. The solar gatherer is the fundamental component of a warm sun oriented establishment. Flat plate solar gatherer working guideline depends on the ingestion surface warming under the activity of the sun oriented radiation [1]. The flat plate sun oriented gatherers having distinctive sorts are generally connected in the solar based field. Investment of solar gatherers requires at first characterize some fundamental parameters and variables. The common solar power potential is measured, prepared and mapped for building up the present solar collector. Likewise, a climatic condition where the solar collector can be connected should be taken into account while building the flat plat sun gatherer [2]. Flat plate solar collector has found the largest application in this way. Its qualities are known, and contrasted and other gatherer sorts, it is the simplest and slightest costly to create, introduce, and keep up. In addition, it is fit for utilizing both the diffuse and the direct sun radiation. For private and business use, flat plate gatherers can deliver heat at adequately high temperatures to warmth swimming pools, boiling water, and structures. They additionally can work a cooling unit, especially if the entrant of sun ray is expanded by the utilization of a reflector. Flat plate gatherers effortlessly achieve temperatures of 40 to 70ºC. With Utilizing exceptional surfaces, reflectors to expand the entrant of sun ray, and insulation materials, higher working temperatures are plausible [3]. The fundamental part of a flat plate sun gatherer appears in figure 1.

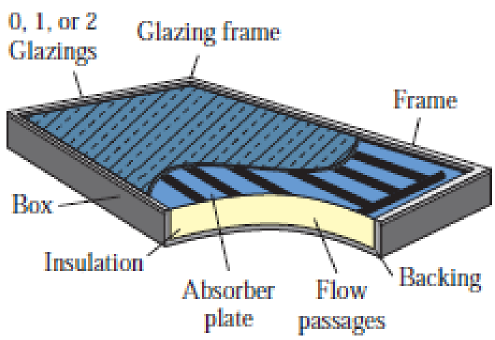


Figure 1: Components of flat plate solar collector [4].

Figure 2 demonstrates a schematic drawing of the warmth absorption, reflection and radiation through a flat plate solar collector [5]. The warm loading has been appeared to quicken the corruption of frightfully particular safeguard coatings utilized as a part of sun gatherers and act as disintegration factor on liquids utilized as a part of the solar collector.

High stagnation temperatures may be brought stresses in the gatherer circle and in the stockpiling of boiling water. So, Solar collector utilize a liquid catalyst for transport heat in the sun gatherer. The most well-known catalyst liquids utilized as a part of sun collector of is solution from water and propylene glycol which disintegrate during high temperature. The warmth liquid may get to be destructive, bringing about quickened fouling and erosion of the group segments of collector [6 & 7].

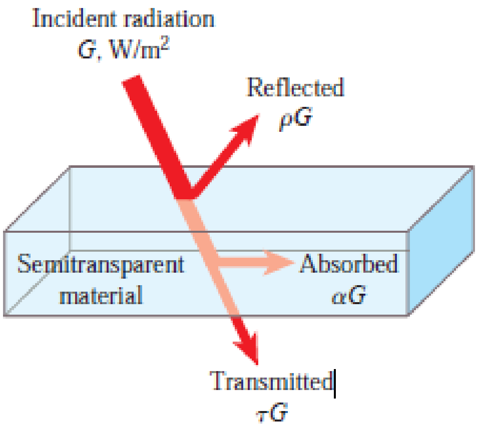


Figure 2: Heat through collector by semitransparent material [5].

The other wellspring of warmth dispersions that occurred on back and edge warmth dispersions. The power dispersions during gatherer back are the conduction result during back protection. The convection and heat radiation transmission during gatherer back into the environment. The warm impedance sizes of the convection and warm radiation transmission are littler than conduction, thusly all the warm impedance during back can be accepted because of the protection [8]. The warranty that the gatherer can endure high warm loads, the maximum temperature in the gatherer ought to be the not exactly same temperature of parts melting that is amassed from. Stagnant temperature is most noteworthy temperature of hoods with ingestion plate which occur when the operating liquid does not flow. For this situation, the valuable profit from the gatherer is zero [9]. The present paper investigated the optimum parameters for operating of falt plate solar collector. The investigation used different ways to insure that the outcome of results are correct and prevent any error. These ways are simulation performance of flat plate solar collector by using *EES* program, factorial design of experiments and regression model. All primary conditions are listed in the modeling below.

2. Theory basis

In the steady state, the beneficial warmth that has been transferred by gatherer of sunlight depend on the power consumed in the surface of metal except the warmth scattered from the surface of metal specifically and in a roundabout way to the environment. This guideline can be expressed in the following relationships, [10].

$$Q_u = A_c \left[HR(\tau.\alpha)_e - U_L\left(t_p - t_a\right)\right] \quad (1)$$

Parameters in Eq. (1) relies on the layout of gatherer, conditions of working, sun energy and environment temperature. The overall energy equilibrium formula for collector can be expressed as, [10]:

$$A_c\,[HR(\tau.\alpha)_e\ + HR(\tau-\alpha)_d] = Q_u\ + Q_l\ + Q_e \qquad (2)$$

Also; $$r_c\ = \frac{\int Q_u\, d_T}{\int HRd_t} \qquad (3)$$

Eq. (3) discrip efficiency of Gatherer (r_c) that is the valuable proportion of beneficial energy transferred by the collector over period of time to the solar power got on the top surface of gatherer over the same period of time, [10].

Tubes arrangement of the flat-plate solar collector appeared in figure 3. Local component of width Δx with length toward flow shown in figure 4, an energy equilibrium formula on this component gives equation (4) [10].

$$S\,\Delta x - U_L\,\Delta x(T-T_a) + \left(-k\delta\frac{dT}{dx}\right)\Big| - \left(-k\delta\frac{dT}{dx}\right)\Big|_{x+\Delta x} = 0 \qquad (4)$$

By dividing through Δx and finding the limit as Δx approaches zero, gives equation (5).

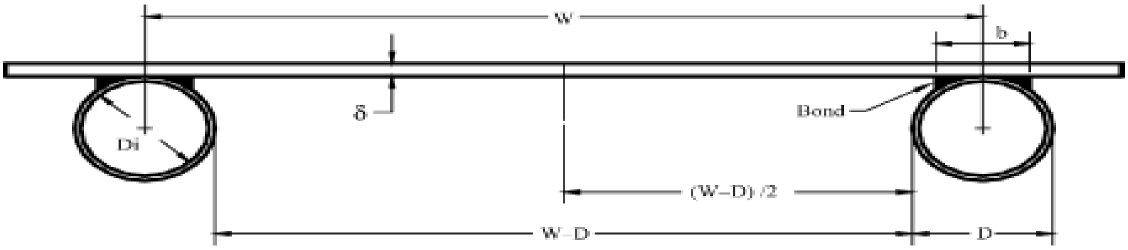


Figure 3: Tubes arrangement of flat-plate solar collector [11]

$$\frac{\mathrm{d}^2T}{dx^2} = \frac{U_L}{K\delta}\left(T - T_a - \frac{S}{U_L}\right) \qquad (5)$$

Figures 4 and 5 are illustrated the two boundary conditions as listed below respectively.

$$(i)\,\frac{dT}{dX}\Big|_{=0} = 0,$$
$$(ii)\;T|_{x-\frac{W-D}{2}} = T_b$$

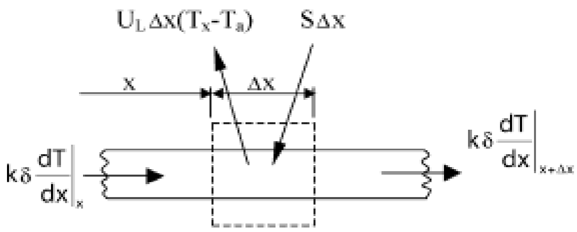


Figure 4: Equilibrium energy for the tube [11]

Let $$m^2 = \frac{U_L}{K_\delta}\ , and\ \Psi = \mathrm{T} - \mathrm{T}_a - \frac{S}{U_L}$$

$$\frac{d^2\Psi}{dx^2} - m^2 = 0 \qquad (6)$$

Eq.(5) is of the second order differential equation. It solved by using these boundary conditions, thus Eq.(5) becomes:

$$\Psi = C_1\,\sinh mx + C_2\,\cosh mx \qquad (7)$$

The boundary conditions is substituting to found the constants C_1 and C_2, so Eq. (7) becomes:

$$\frac{T - T_a - {}^{S}/_{U_L}}{T_b - T_a - {}/_{U_L}} = \frac{\cosh\, m\,x}{\cosh m\left(\frac{W-D}{2}\right)} \qquad (8)$$

This equation gives distribution of temperature toward *x*-axis at any given value of *y* [10].
The energy held within region of tube per unit length toward flow is shown during figure 5:

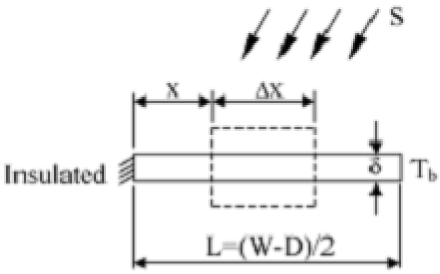


Figure 5: Equilibrium energy for the fin [11]

$$q_{finbase} = \frac{K\delta m}{U_L}\,[S - U_L(T_b - T_a)]\tanh\left(\frac{W-D}{2}\right)\,m \qquad (9)$$

The energy conducted to local component of the tube per unit length toward flow is:

$$q_{finbase} = \frac{K\delta m}{U_L}\,[S - U_L(T_b - T_a)]\tanh\left(\frac{W-D}{2}\right)\,m \qquad (10)$$

Eq.(10) represents the energy received on the one side of a tube. In addition to that, beneficial energy furthermore involves the energy received over region of the tube. The beneficial energy picks up in this area is:

$$q_{tube} = D\,[\,S - U_L\,(\,T_b\, -\, T_a\,)\,] \qquad (11)$$

Eq.(12) expressed the overall beneficial energy yield through tubes toward flow:

$$q_u = q_{finbase} + q_{t\ tube\ section} \qquad (12)$$

Beneficial gain from Eq. (9) should be conveyed into the liquid. Wall thickness of tube resist heat flow in tube, hence

$$q_u = \frac{T_b - T_f}{\frac{1}{C_b} + \frac{1}{\pi D_i\, h_{f\,i}} + \frac{1}{C_w}} \qquad (13)$$

The bond conductance is given as:

$$C_b = \frac{K_b b}{y} \qquad (14)$$

Beneficial energy that was received in the liquid can be expressed by solving Eq. (13) at T_b then substitution it to get q_u from Eq.(12), [10].

$$q_u = WF^1\left[S - U_L\left(T_f - T_a\right)\right] \qquad (15)$$

$$F^1 = \frac{{}^{1}/_{U_L}}{W\left[\frac{1}{U_L\ [D+(W-D)F]} + \frac{1}{C_b} + \frac{1}{C_w} + \frac{1}{\pi D_i\ h_{fi}}\right]} \qquad (16)$$

3. Design of experiments

In this research, the experiments are depends on three factors and its levels for making an investigation of these factors on the performance of flat plate solar collector. Since there are three factors and two levels have been used as mentioned in table 1, so that a full factorial design of experiments 2^3 = 8 experiments. Taguchi method have been used in order to minimize the number of experiments. According to the Taguchi table, this method used fractional of full factorial design L_4 = 2^{3-1} = 4 experiments as described in table 2. The data of factors, levels and response in the table 2 was used in Minitab 7 software for selection optimum conditions which have great effects on performance of flat plate solar collector.

Table. 1: Factors and its levels

Number of level	Factors		
	Number of glass cover	Cover- Plate air spacing (cm)	Flow rate of water (L/min)
1	1	1.5	2.5
2	2	2.5	3.5

Table. 2 : Fractional factorial design

Number of run	Factors			Response
	Number of glass cover	Cover- Plate air spacing (cm)	Flow rate of water (L/min)	Stagnant temperature ($^{\circ}$C)
1	1	1.5	2.5	137.5
2	1	2.5	3.5	140.2
3	2	1.5	3.5	157.5
4	2	2.5	2.5	156.9

4. Modeling

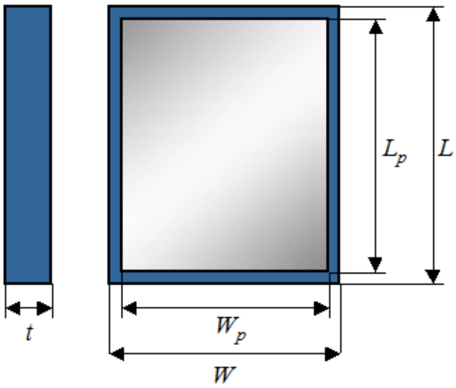
EES program have been used for Simulation process of flat plate solar collector. In this research, modeling of solar collector was based on consider of sets of constants and dimensions as listed below, and on the variables as mentioned in the table 2. The sequence of construction of the model throughout EES software is illustrated as following:

4.1

Test Conditions

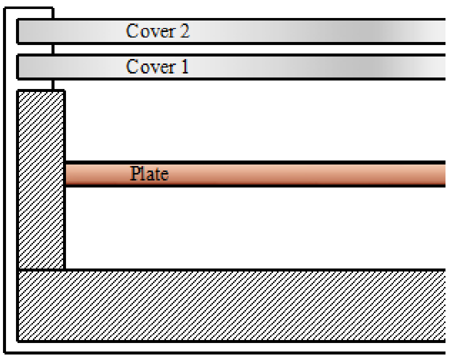
- Incident Solar Radiation : G_T = 830 [W/m^2]
- Diffuse Radiation Proportion : G_d/G_T = 43 [%]
- Incident Angle of Beam Radiation : θ = 57 [deg]
- Collector Slope : β = 37.5 [deg]
- Ambient Temperature : T_{amb} = 23 [C]
- Wind Speed : V_{wind} = 1.5 [m/s]
- Relative Humidity : R = 12 [%]

4.2
Collector Dimensions



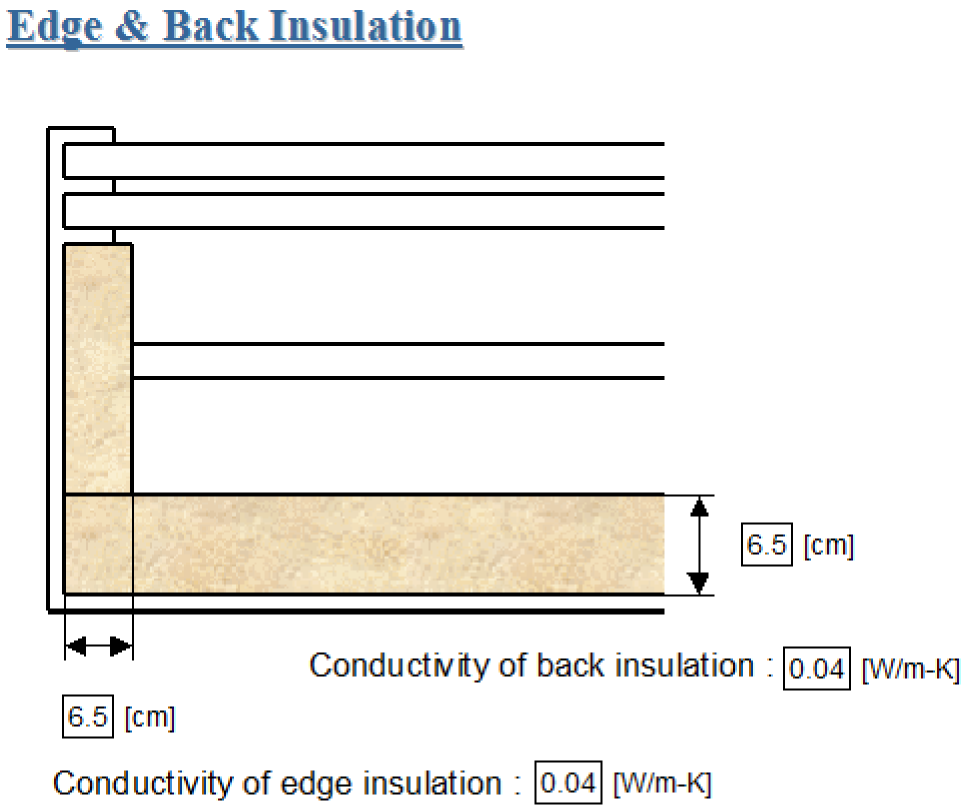
Overall Dimensions	Length	L	2.5 [m]
	Width	W	1.4 [m]
	Thickness	t	0.17 [m]
Absorber Dimensions	Length	L_p	2.45 [m]
	Width	W_p	1.35 [m]
	Gross area	A_c	3.5 [m^2]
	Absorber area	A_p	3.308 [m^2]

4.3
Cover & Plate



Number of covers			N_{cov}	2
Cover 2	Cover Material			Glass
	Properties of cover material			
	Solar spectrum	Refractive index	n	1.526
		Transmittance	$\tau_{c,s}$	0.891
	Long-wave	Absorptance	ε_c	0.88
		Transmittance	$\tau_{c,IR}$	0
Cover 1	Cover Material			Glass
	Properties of cover material			
	Solar spectrum	Refractive index	n	1.526
		Transmittance	$\tau_{c,s}$	0.891
	Long-wave	Absorptance	ε_c	0.88
		Transmittance	$\tau_{c,IR}$	0
Cover-plate air spacing			d_{cp}	2.5 [cm]
Cover 1 - cover 2 air spacing			$d_{c1,c2}$	1.75 [cm]
Plate	Plate Material			Copper
	User-defined Conductivity		k_{pl}	380 [W/m-K]
	Thickness		t_p	0.03 [cm]
	Solar spectrum	Absorptance	α_n	0.88
	Long-wave	Emittance	ε_{pl}	0.15

4.4



5. Results and discussion

The values of main effect are listed in the table 3, have been calculated by using Minitab 17 software.

Table 3: Main Effect of level of factors on stagnant temperature

Number of level	Factors		
	Number of glass cover	Cover- Plate air spacing (cm)	Flow rate of water (L/min)
1	138.8	147.5	147.2
2	157.2	148.6	148.8
Rank	1	3	2

From main effect table it is found that the number of glass cover has the largest effect while Cover- Plate air spacing has the smallest effect on the stagnant temperature of solar collector. The interaction between three factors displayed in figure 6. Main effects of levels factors on collector efficiency was illustrated in figure 7.

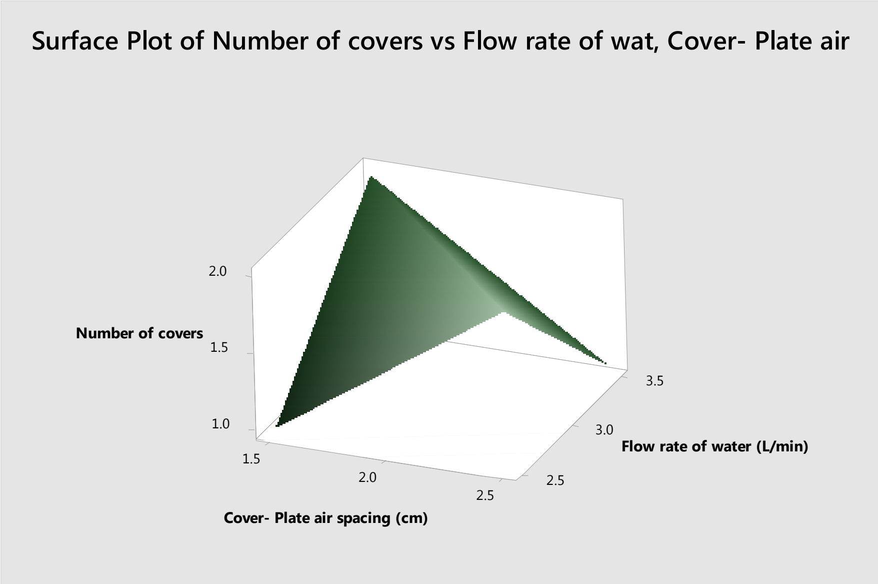


Figure 6: Interaction between three factors

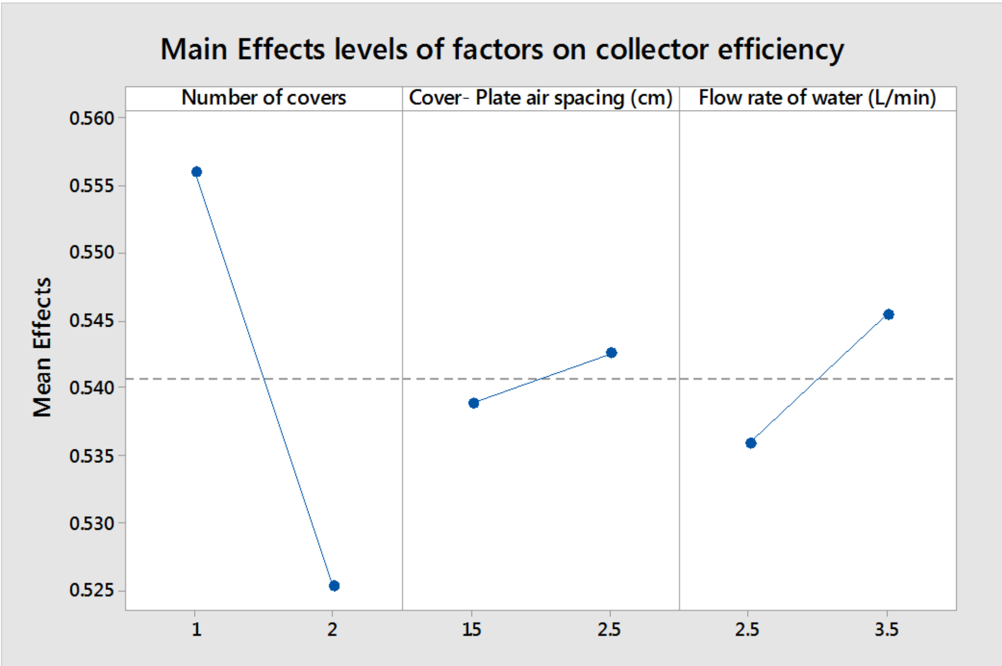


Figure 7: Main effects of levels factors on collector efficiency

The optimum conditions listed in the table 4 below. These conditions was carried out by prediction of best conditions. The prediction based on the rank of the main effects of the stagnant temperature that listed in the table 3. The response of best conditions are listed in the table 5, the results in this table are from simulation by EES program, predicted result from Taguchi method and from the regression model in equation (17). This equation have been determined during static's analysis through Minitab 17 software.

5.1: Regression Equation

T = 113.5 + 18.35 Number of covers + 1.050 Cover- Plate air spacing (cm)
+ 1.650 Flow rate of water (L/min) (17)

Table 4: Best condition

Factors		
Number of glass cover	Cover- Plate air spacing (cm)	Flow rate of water (L/min)
2	2.5	2.5

Table 5: Response

Stagnant temperature ($^{\circ}C$)		
Simulation by *EES* program.	Taguchi method	Regression Eq. 17
156.9 $^{\circ}C$	158.55 $^{\circ}C$	158.9 $^{\circ}C$

6. Conclusions

1- The number of glass cover has the largest effect while Cover- Plate air spacing has the smallest effect on the stagnant temperature of solar collector.

2- Stagnant temperature of collector is approximately 160 °C for collector which has absorber plate from Cu, 2 Number of glass covers, 2.5 cm Cover- Plate air spacing and 2.5 L/min Flow rate of water.

3- Simulation of flat plat solar collector by *EES* software, fractional factorial design of experiments and regression model shows good match of results.

7. References

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