

Numerical modeling of a flat air solar collector fitted with obstacles

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Abstract. The weakness of the solution of flat-air solar collectors in the absence of a turbulence promoter has led researchers to seek other means to improve the performance of the collector. To improve the heat exchange in the air stream from the flat solar collector to the air is the creation of baffles or obstacles to give the longest possible flow path and create a large possible turbulence network. In this article, we studied an air flow around an obstacle field in a flat air solar collector, using the Ansys CFX calculator software, we make a digital 3 D similarity and we give results on the heat exchange in the flat air solar collector and the aim of this study is to show the effect of the obstacles for the fluid flow and the heat transfer in the fluid flow of the flat air solar collector.

1 Introduction

The improvement of the performances of the flat air solar collector is the interest of several researchers for that there are several works on the increase of the efficiency of the solar collector, I noted some work on this field of research.

The author MA Bernier and al [1] studied the air flow in a solar air collector, they made an experimental study to test two air flow rates with different gauge pressure for three possible cases of air passage in the solar sensor, the efficiency was made by three inlet and outlet mass flow and the enthalpy equilibrium method, they concluded that it is necessary to standardize the inlet gauge when testing them.

In the study by Sari Hassoun Zakaria and al [2], is interested in improving the performance of a flat-air solar collector equipped with mini concentrators at the absorber level. A bibliographic study on previous work relating to flat air solar collectors enabled us to orient their research towards specific aspects still addressed in the literature. The aim of this work is to make a digital simulation of the flow of the air studied, the evolution of the outlet temperature of the sensor. The evolution of the temperature of the absorber is also determined.

The article of Ole Arborg [3] presents on the use of the solar plane collector with air, he gave several study which presents the importance of the solar collector to produce the heat, the author gave several results like the graph which shows the relation between the energy consumption of the fan and the flow of air flowing into the flat air solar collector, Power consumption of the fan for a particular air flow and Power consumption in relation to the solar radiation used.

Andrei-Stelian Bejan and al [4] presents a study on flat air solar collectors for home heating, they gave several studies in this field, they gave several models of flat air solar collectors with glass and without glass, the authors have given a graph presenting Energy and temperature supplied by an opaque perforated collector in real conditions.

The work of T. Letz and al [5] concerns the study of the behavior of a flat air solar collector operating in a dynamic regime. A model based on solving heat balance equations by a nodal method has been established. The behavior of solar air collectors has been studied in natural sunlight and in artificial sunlight in order to better control the parameters on which the yield depends. It should be noted that this type of sensor, mounted on the roof, has a relatively high inertia which results in a low value of the efficiency of the sensor at the start of the day, and a higher value at the end of the day. While the air flow in the sensor and the inlet temperature have a great influence on the efficiency, on the other hand the inclination of the sensor and the illumination have little influence.

The authors Ioan Luminosu and al [6] have a study on air solar collector in Romania, they studied the influence of flow on the efficiency of the solar collector, they concluded that the optimal flow is minimum and the use of photovoltaic systems Hybrid heaters good for the economic cost of energy where the electrical energy used to power the fans in addition to that this system can be used for any type of solar drying.

In the work of Zedairia Merouane and al [7] were interested in improving the thermal performance of a range of flat air solar collectors (single pass). A digital investigation was carried out to highlight the impact of

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geometric parameters such as, the height of the channel, the distance between the glass and the absorber, the length and width of the sensor, and the thickness of the insulation on the thermal performance of flat air solar collectors. To do this, they developed a computer calculation program under the MATLAB environment, which allowed them to have several information on the evolution of all the parameters studied. Finally, representative curves were established to visualize these impacts which help to identify optimal values of the geometric parameters.

The air sensor studied in the article by S. Oudjedi and al [8] is a single-pass insulator between the absorber and the glass. An analysis of unsteady heat exchanges in such a sensor is presented. It is shown that in a quasi-stationary regime the heat balance equations of the sensor components cascade into a first-order ordinary differential equation, which alone governs the thermal behavior of the sensor. The solution of this differential equation is written as an explicit expression of the local temperature of the heat transfer fluid as a function of the time-varying solar flux. The influence of various parameters such as the inlet temperature of the fluid, its velocity and the height of the air flow channel on the thermal performance of the solar air collector is also studied.

In our model we made a numerical study on a flat air solare sensor equipped with square obstacles, we gave the diagram of our model after we made the mesh of this model and then we gave results on the temperature distribution, the speed and the turbulence field and finally we presented graphs on the average Nuselt number, the average friction coefficient as a function of Reynolds number.

2 Analysis and modelling

2.1 Problematic

have made a flat air solar collector with square obstacles, the length of this collector is 900 mm, the width is 500 mm and the height of the obstacles and the air stream is 25 mm.

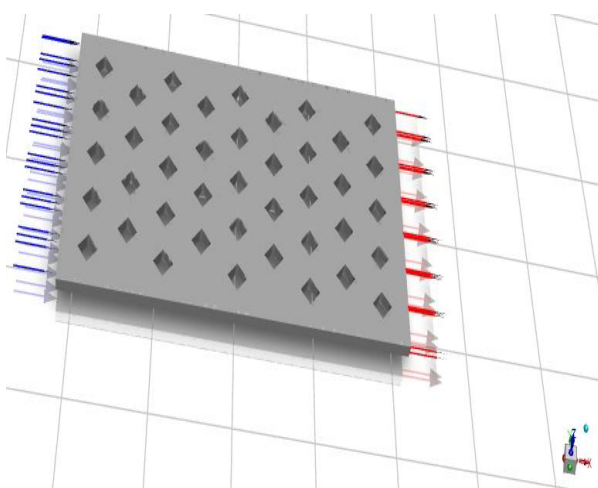


Fig. 1. Sketch for the solar collector

2.1.1 The boundary conditions

We used the k-ε model for our air flow the flat air solar collector, to do this simulation we used the value of the input speed ($u_0 = 0.02216$ m/s), the air temperature at the inlet $T_e = 300$ K, the turbulent kinetic energy at inlet $k = 0.005 \cdot U_0^2 = 2.456 \cdot 10^{-6} \text{m}^2/\text{s}^2$, the energy dissipation at inlet $\epsilon = 0.1 \cdot k^2 = 6.03 \cdot 10^{-13} \text{m}^2/\text{s}^3$, the temperature of the absorber: $T_{abs} = 380$ K, the temperature of the insulation and the obstacles: $T_{iso} = 340$ K and the outlet pressure: $P_s = P_{atm}$.

we have validated our numerical results by the experimental results of abdelhafid [9], one notices that the results almost equal.

Table 1. Validation of results between experimental and CFD results [10].

Flow m^3/hm^2	CFD T (°C)	Experimental T (°C)
Q1=79.79	53	50
Q2=76.32	53	50
Q3=74.01	54	51
Q4=69.96	54	52.3
Q5=64.76	59	56
Q6=58.97	62	58
Q7=42.79	65	63
Q8=37.58	65	63
Q9=23.71	69	68

2.1.2 Governing equations

- The Mass Conservation Equation:

The equation for conservation of mass, or continuity equation, can be written as follows:

$$\nabla \cdot (\rho \vec{v}) = 0 \tag{1}$$

- Momentum Conservation Equations:

$$\nabla \cdot (\rho \vec{v} \vec{v}) = -\nabla p + \nabla(\vec{\tau}) + \rho \vec{g} \tag{2}$$

$\rho \vec{g}$ The gravitational body force.

\vec{g} : gravitational acceleration (m/s²)

ρ : density (kg/m³).

p : the static pressure (pa).

\vec{v} : overall velocity vector (m/s).

$\vec{\tau}$: the stress tensor (described below) (pa)

The stress tensor $\vec{\tau}$ is given by

$$\bar{\tau} = \mu \left[(\nabla \vec{v} + \nabla \vec{v}^T) - \frac{2}{3} \nabla \cdot \vec{v} I \right] \quad (3)$$

The second term on the right hand side is the effect of volume dilation

The Energy Equation:

$$\nabla \cdot (\vec{v}(\rho E + p)) = \nabla \cdot (k_{\text{eff}} \nabla T - \sum_j h_j \cdot \vec{j}_j + (\bar{\tau}_{\text{eff}} \cdot \vec{v})) \quad (4)$$

The first three terms on the right-hand side of equation (4) represent energy transfer due to conduction, species diffusion, and viscous dissipation, respectively.

$$k_{\text{eff}} = k + \frac{c_p \mu_t}{Pr_t} \quad (5)$$

The default value of the turbulent Prandtl number is 0.85.

$$E = h - \frac{p}{\rho} + \frac{v^2}{2} \quad (6)$$

$$h = \sum_j Y_j h_j + \frac{p}{\rho} \quad (7)$$

$$h_j = \int_{T_{ref}}^T c_{p,j} dT \quad (8)$$

E : the total energy (J).

h : Sensible enthalpy (energy/mass).

I : the unit tensor.

\vec{j}_j : n the diffusion flux of species j .

Pr_t : the turbulent Prandtl numbers.

Where T_{ref} 298.15 K.

Transport Equations for the Standard k-ε Model:

The turbulent kinetic energy, k , and its turbulent eddy dissipation, ε , are obtained from the following transport equations:

$$\frac{\partial}{\partial x_i} (\rho k u_i) = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + G_k - \rho \varepsilon \quad (9)$$

And

$$\frac{\partial}{\partial x_i} (\rho \varepsilon u_i) = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_j} \right] + C_{1\varepsilon} \frac{\varepsilon}{k} G_k - C_{2\varepsilon} \rho \frac{\varepsilon^2}{k} \quad (10)$$

G_k : the generation of turbulence kinetic energy due to the mean velocity gradients.

Modeling the Turbulent Viscosity:

The turbulent (or eddy) viscosity, μ_t , is computed by combining k and ε as follows:

$$\mu_t = \rho \cdot C_\mu \frac{k^2}{\varepsilon} \quad (11)$$

Where C_μ is a constant.

Model Constants:

The model constants $C_{1\varepsilon}$, $C_{2\varepsilon}$, C_μ , σ_k and σ_ε have the following default values:

$$C_{1\varepsilon} = 1.44, C_{2\varepsilon} = 1.92, C_\mu = 0.09, \sigma_k = 1.0, \sigma_\varepsilon = 1.3$$

2.1.3 Collector study

A flat air solar collector transforms the solar radiation energy by a thermal energy absorbed by the heat transfer fluid "air"; therefore, a flow of air enters the flat air solar collector by a temperature T_1 and follows an x axis up to at the output of the solar collector by a temperature T_2 .

$$\varphi_0 \cdot \ell \cdot L = \rho \cdot c_p \cdot q_v (T_2 - T_1) \quad (12)$$

ρ : average density of air $\rho = 1.25 \text{ kg/m}^3$

c_p : average mass heat of air $c_p = 1000 \text{ J/(kg}^\circ\text{C)}$

L : the length (along x) (m).

φ_0 : the solar flow is perpendicular to the collector (W/m²).

An air flow by abscissa x with an average temperature T , we take an element of air dx we have:

Power received by the collector:

$$\varphi_0 \cdot \ell \cdot dx \quad (13)$$

ℓ : the width of the flow (m).

Power carried by the fluid:

$$\rho \cdot c_p \cdot q_v \cdot dT = h \cdot \ell \cdot dx (T_p - T) \quad (14)$$

h : the transfer coefficient between the absorbent wall and the fluid (W/m²).

T_p : the temperature of the absorbent

q_v : the air flow

We present h by the following equation:

$$\frac{h \cdot dH}{\lambda} = Nu \quad (15)$$

$$e \ll \ell \text{ so } dH = 2e$$

dH : hydraulic diameter of the section.

The power lost by conduction to the insulating part:

$$\frac{\lambda_i}{E_i} \cdot \ell \cdot dx (T_p - T_e) \quad (16)$$

T_e : outside temperature (equal to T_1).

We will have a steady state:

$$\rho \cdot c_p \cdot q_v \cdot dT = \frac{\lambda \cdot Nu}{2e} \cdot \ell \cdot dx (T_p - T) = \varphi_0 \cdot \ell \cdot dx - \frac{\lambda_i}{E_i} \cdot \ell \cdot dx (T_p - T_e) \quad (17)$$

we solve these equations so we eliminate T_p ; at the end we conclude the differential equation:

$$\frac{dT}{\varphi_0 + \frac{\lambda_i}{E_i} (T_e - T)} = \frac{\ell \cdot dx}{\rho \cdot c_p \cdot q_v \left(1 + \frac{\lambda_i \cdot 2e}{E_i \cdot \lambda \cdot Nu} \right)} \quad (18)$$

Let's integrate this relationship between entry and exit:

$$\int_{T_e}^{T_2} \frac{dT}{\varphi_0 + \frac{\lambda_i}{E_i} (T_e - T)} = \int_0^L \frac{\ell \cdot dx}{\rho \cdot c_p \cdot q_v \left(1 + \frac{\lambda_i \cdot 2e}{E_i \cdot \lambda \cdot Nu} \right)} \quad (19)$$

$$-\frac{E_i}{\lambda_i} \left[\ln \left(\varphi_0 + \frac{\lambda_i}{E_i} \cdot (T_e - T) \right) \right]_{T_e}^{T_2} = \frac{\ell \cdot L}{\rho \cdot c_p \cdot q_v \left(1 + \frac{\lambda_i \cdot 2e}{E_i \cdot \lambda \cdot Nu} \right)} \quad (20)$$

From where the value of the temperature at the exit of the collector:

$$T_2 = T_e + \varphi_0 \frac{E_i}{\lambda_i} \left[1 - \exp \left(- \frac{\lambda_i}{E_i} \cdot \frac{\ell.L}{\rho.c_p.q_v} \left(1 + \frac{\lambda_i.2e}{E_i.\lambda.Nu} \right) \right) \right] \quad (21)$$

$$\Delta T = \varphi_0 \frac{E_i}{\lambda_i} \left[1 - \exp \left(- \frac{A}{1+B} \right) \right] \quad (22)$$

λ_i : conductivity of the insulation (w/ (m)).
 With

$$A = \frac{\lambda_i.\ell.L}{E_i.\rho.c_p.q_v}, B = \frac{\lambda_i}{E_i} \cdot \frac{2e}{\lambda.Nu}$$

When the insulation is perfect $\frac{\lambda_i}{E_i} \rightarrow 0$, and we fall back on the equation (12).

Finally, we obtain the performance of the flat air solar collector by the formula which equals the ratio between the two real powers and which supplied by the sun radiation:

$$\eta = \frac{\rho.c_p.q_v(T_2-T_1)}{\varphi_0.\ell.L} \quad (23)$$

$$\eta = \frac{\rho.c_p.q_v.E_i}{\lambda_i.\ell.L} \left[1 - \exp \left(- \frac{\lambda_i}{E_i} \cdot \frac{\ell.L}{\rho.c_p.q_v} \left(1 + \frac{\lambda_i.2e}{E_i.\lambda.Nu} \right) \right) \right] \quad (24)$$

Ask

$$1/A = \frac{\rho.c_p.q_v.E_i}{\lambda_i.\ell.L}$$

E_i : thickness of the insulation (m).
 e : the thickness (m).

$$\eta = \frac{1}{A} \left[1 - \exp \left(- \frac{A}{1+B} \right) \right] \quad (25)$$

3 Results and discussion

3.1 Mesh

A mesh is a partition of space or a domain into elementary cells. To be usable for numerical simulation, the meshes must represent the geometry well enough, comprise enough elements to calculate precisely, in our model we used an unstructured mesh because of the complexity of the geometry of the flat air solar collector. The number of elements is 22,596 and the number of nodes is 122,606.

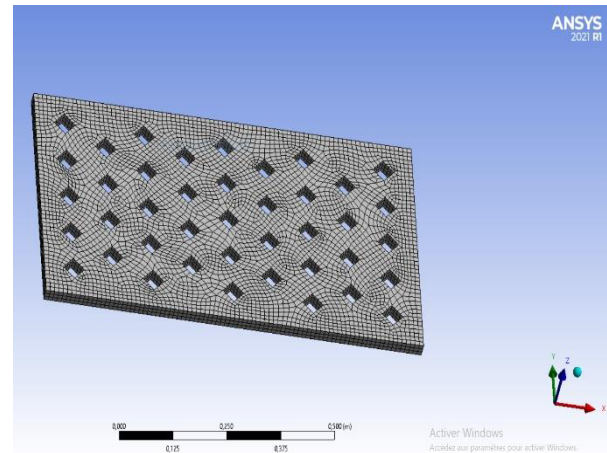


Fig. 2. 3D mesh of Solar Flat Plate Collector.

3.2 Temperatures field

The heat transfer mode between the absorber and the air is convection. The first layer of air near the absorber begins to warm up and goes mixed with the layer of secondary air due to obstacles and heat transfer due to conduction and convection, to improve heat transfer between the absorber and the air we have placed square obstacles to increase the flow path and create large areas of significant turbulence.

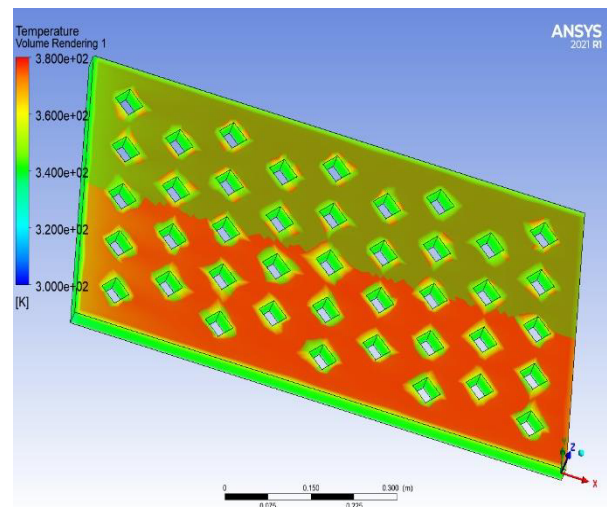


Fig. 3. Temperatures Field for the collector.

3.3 The velocity vector V

Figures 4 and 5 show the movement of air in the fluid stream of the flat air solar collector, the speed at the entry is similar until the arrival at the first row of obstacles or the speed increases more than 100% between the obstacles which means an increase in turbulence is the heat transfer between the absorber and the air.

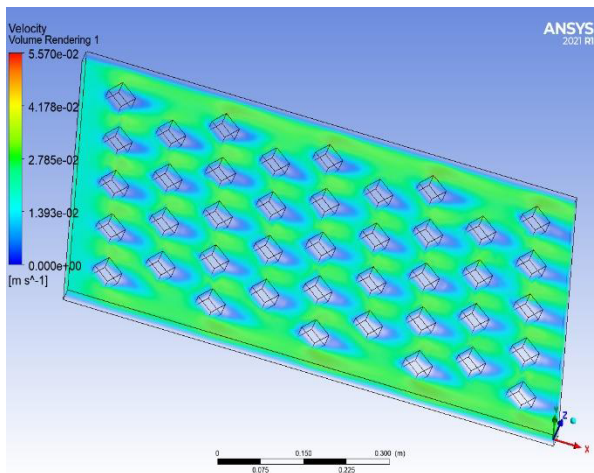


Fig. 4. Velocity distribution.

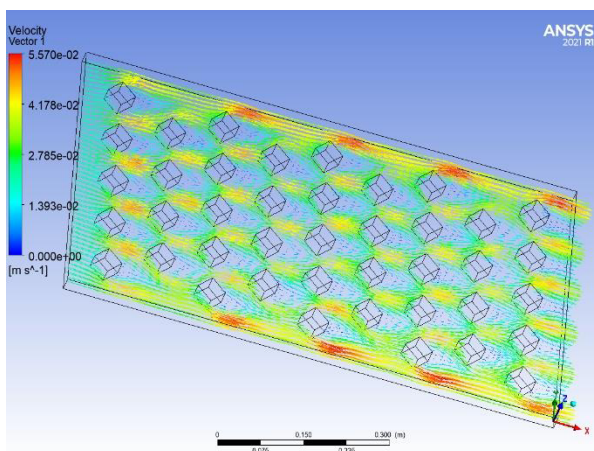


Fig. 5. Velocity vector.

3.4 Turbulence field

Figures 6 and 7 show the distribution of the turbulent kinetic energy (k) and the turbulent vortex dissipation (ϵ) on the fluid stream of the flat air solar collector, the field of these energies appears in all the surface of the solar collector, we notice that there is a great increase in this energy close to the obstacles, but the turbulence diminishes when one moves away from the obstacles.

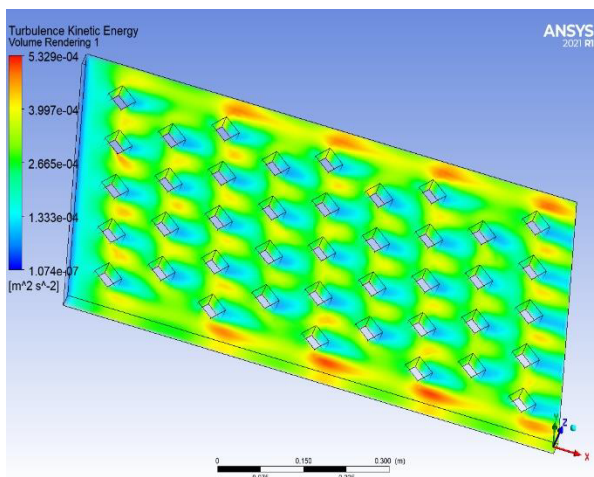


Fig. 6. Turbulent kinetic energy (k).

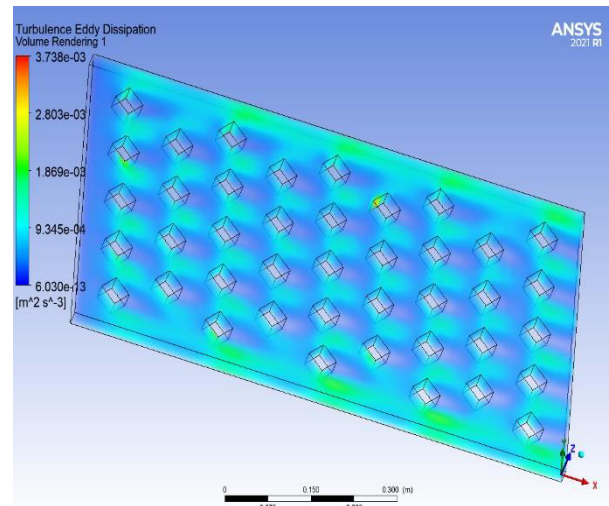


Fig. 7. Turbulent eddy dissipation (ϵ).

3.5 The Nusselt number and friction factor versus Reynolds number

The study of a turbulent flow being much more difficult and complex, we seek more to determine the empirical correlations. For a fully developed turbulent flow in a smooth channel, the local Nusselt number can be obtained from the Dittus - Boelter equation [11].

$$Nu = 0,023 Re^{4/5} Pr^{0.4} \quad (26)$$

$$Re \geq 10000$$

Petukhov [12] has developed a correlation for smooth surface finish that encompasses a wide range of Reynolds numbers and is presented as the friction factor as follows:

$$f = (0,790 \ln Re - 1,64)^{-2} \quad (27)$$

$$3000 \leq Re \leq 5 \times 10^6$$

The flow Reynolds number, Re is calculated as

$$Re = \rho \bar{U} D_h / \mu \quad (28)$$

The hydraulic diameter of the channel, D_h is calculated as

$$D_h = 2HW / (H + W) \quad (29)$$

we made a study of local Nusselt number and friction factor as a function of different Reynolds number between (10500 up to 16500), we notice that the local nusselt number increases with the increase in reynolds number, for the friction factor decreases with increasing reynolds number.

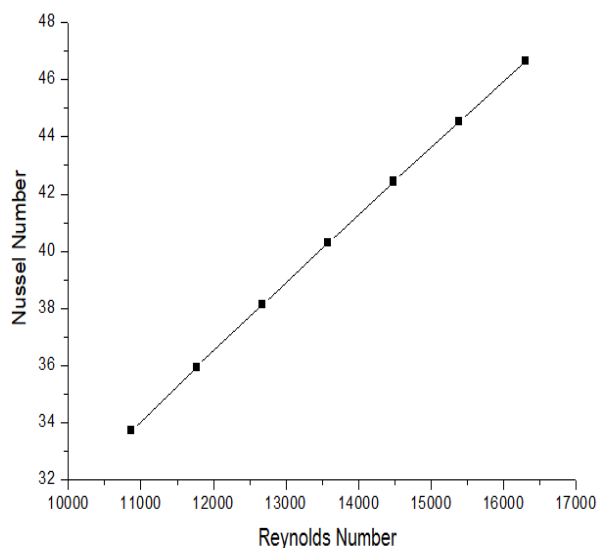


Fig. 8. The local Nusselt number versus Reynolds number.

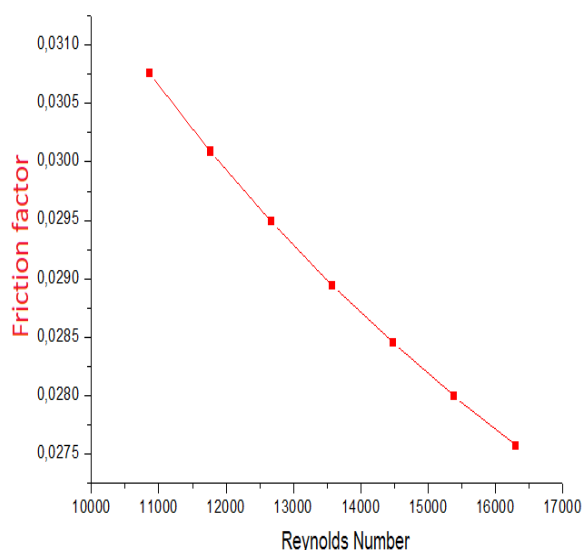


Fig. 9. The friction factor versus Reynolds number.

4 Conclusions

To increase the efficiency of the flat air solar collector we have added square obstacles to increase the efficiency, so we have a very important path of the air flow in the fluid vein of the flat air solar collector and important ones zone of turbulence close to obstacles square. We also notice an increase in the speed between the obstacles due to the section narrowing. we made this placement of obstacles square to reduce the dead zones downstream of the obstacles. we also notice an increase in the local Nusselt number and decrease in the friction factor if the Reynolds number increases.

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