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Flow and Temperature Analysis inside Flat Plate Air Heating Solar Collectors

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***Abstract*— Solar energy is considerably cheap, safe and sustainable source of energy. One of the simplest applications of solar energy is domestic heating and crop drying using air solar collectors. In this paper, an explicit finite difference scheme is implemented in order to study the flow of air inside flat-plate air solar collectors. That is performed by solving the continuity, momentum and energy equations governing the problem with the choice of the appropriate boundary conditions. The application of the explicit finite difference scheme in this case proved to be reliable and convergent in the range of the studied parameters. The velocity field and the temperature distribution are calculated and showed good agreement with other published experimental results.**

***Keywords*— solar air heating, flat-plate collector, velocity field, temperature distribution, explicit FDM**

I. INTRODUCTION

Solar energy is becoming a cheap and safe alternative for the limited fossil fuel resources and nuclear energy. It is also an environmental friendly source of energy.

One of the simplest and most direct applications of solar energy is the conversion of solar radiation into heat, which can be used directly for heating domestic houses. A commonly used solar collector is the flat-plate air solar collector. A tremendous amount of research has been conducted in order to analyze the flat-plate air collector operation and to improve its efficiency, for instance references [1-6].

Flat plate solar collectors are simple and cheap way to convert solar radiation into heat energy that can be used in many applications. For example, it can be used in heating, drying and many other applications. Solar energy is one of the energy sources associated with time where they vary from hour to hour, day to day and from season to season. It is also associated with locations on the earth. This made researchers interested in studying this kind of energy all over the world [1, 3, 7].

In this paper, the flow between two parallel flat plates is investigated with boundary conditions to simulate a simple flat plate solar collector.

Special attention is given to the analysis of the fluid motion as well as the heat transfer inside flat plate solar collectors using the explicit finite difference method. The finite difference method is used due to the difficulties of solving a complete set of the governing equations mathematically and due to its speed and reliability in similar situations.

II. PROBLEM DESCRIPTION AND FORMULATION

In this paper, the solar collector has been simplified by the model shown in Figure 1.The collector consists of two parallel plates. The upper plate is a sheet of glass with high transmissivity in the range of the solar spectrum to allow access of the solar rays. The solar rays eventually fall on the bottom plate. The bottom plate is a black painted metal flat plate with high absorptivity of solar radiation. The thermal energy is extracted from the collector by receiving the solar radiation from the sun fallen across the glass cover and the air gap to be received by the absorber plate. The board absorbs these rays leading to a rise in the temperature of the metal. When the air passes over this board the heat transfers from the metal to the air. The amount of heat transferred to the air depends on several factors including the intensity of solar radiation, the ambient temperature and the air velocity.

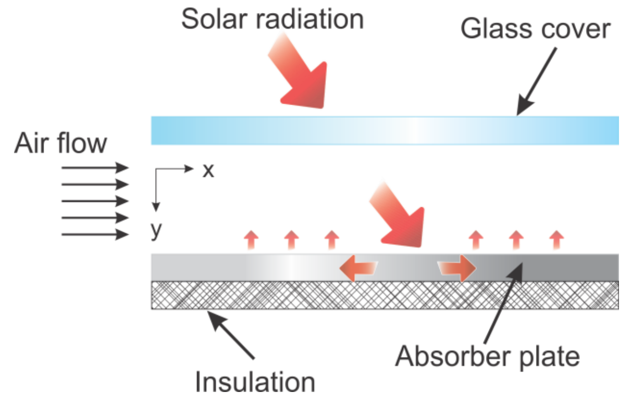

Figure 1 : Flat plate solar collector without storage bed.

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To investigate this problem and solve it for both the velocity field and the temperature distribution, suitable governing equations and boundary conditions has to be set. Moreover, an applicable numerical scheme should be used to solve those equations.

A. The governing equation

In order to obtain the velocity field, pressure gradient and the temperature distribution of the air inside the air collector three types of equations should be used. These equations are the continuity equation, Navir-Stokes equations and the energy equation. Some assumptions should be considered to simplify and allow solving the problem with the explicit finite difference method. These assumptions include; the flow of air is laminar, two dimensional flow, the properties of the air along the period of operation are fixed and the flow is incompressible flow [8]. After applying the governing equations with the above assumptions the following set of equations can be derived.

The continuity equation

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \quad (1)$$

The momentum equation

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=-\frac{1}{\rho}.\frac{\partial p}{\partial x}+v\frac{\partial^2 u}{\partial y^2} \quad (2)$$

The energy equation

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\frac{v}{Pr}.\frac{\partial^2 T}{\partial y^2} \quad (3)$$

The energy equation for incompressible, constant property flow shown above is uncoupled from the momentum equation. Once the velocity distribution is known, the temperature distribution can be obtained directly by using the appropriate formulation of finite difference scheme from the energy equation.

B. The dimensionless governing equations

In order to simplify the solution of equations 1 to 3 the following dimensionless variables are introduced [5].

$$\left.\begin{aligned} U &= \frac{u}{u_m} \\ V &= v.\frac{Re_H}{u_m} \\ X &= \frac{x}{H.Re_H} \\ Y &= \frac{y}{H} \\ P &= \frac{p-p_o}{\rho.u_m^2} \\ \theta &= \frac{(T-T_o).K_a}{q_{avr}.H} \\ Lc &= \frac{L}{HRe_H} \end{aligned}\right\} \quad (4)$$

The definitions of all variables are shown in the list of symbols and abbreviation at the end of the paper. By substituting these dimensionless variables in equations 1 to 3, non-dimensional governing equations are obtained in the following forms.

The continuity equation:

$$\frac{\partial U}{\partial X}+\frac{\partial V}{\partial Y}=0 \quad (5)$$

The momentum equation:

$$U\frac{\partial U}{\partial X}+V\frac{\partial U}{\partial Y}=-\frac{\partial P}{\partial X}+\frac{\partial^2 U}{\partial Y^2} \quad (6)$$

The energy equation:

$$U\frac{\partial \theta}{\partial X}+V\frac{\partial \theta}{\partial Y}=\frac{1}{Pr}.\frac{\partial^2 \theta}{\partial Y^2} \quad (7)$$

C. The boundary conditions

In order for the system of equations (5 to 7) to be solved, the boundary conditions for the velocity and temperature need to be defined as follows:

At the glass, the flow velocity is equal to zero in both vertical and horizontal directions.

$$U = V = 0 \; @ \; Y = 0 \qquad 8$$

Energy wise, the energy absorbed by the glass = energy lost by convection to ambient air

$$K_a \frac{\partial T}{\partial y} = h_o\left(T_g - T_a\right) \;\; @y = 0 \qquad 9$$

By substituting the non-dimensional variables in the above equation we get

$$\frac{\partial \theta}{\partial Y} = Nu_o\left(\theta_g - \theta_a\right) \;\; @Y = 0 \qquad 10$$

At the absorber plate, the flow velocity is also equal to zero in both directions

$$U = V = 0 \; @ \; Y = 1 \qquad 11$$

The absorbed energy by radiation is equal to the energy transferred by conduction to the air.

$$\alpha q_i = K_a \frac{\partial T}{\partial y} \;\; @ \, y = 1 \qquad 12$$

Which can be written in non-dimensional form as follows.

III. Results And Discussions

The results shown in this section are obtained by solving the flow and energy governing equations shown in previous section using the explicit finite difference method. Generally, the figures are presented in two forms; non-dimensional and dimensional forms. The capital letters refer to the dimensionless parameters while the small letters refer to the dimensional parameters (refer to the list of symbols for exact definitions of various parameters). The above results has been validated using the experimental results published in [9].

The horizontal component of the airflow velocity is shown as contours in Figure 2 in dimensionless form (on the left) and in meters per second (on the right). As it is expected, the maximum velocity occur at the mid-plane while the velocity is equal to zero at the walls (no slip condition). The flow becomes fully developed flow at *X* equal to about 0.035 from the entrance. In the fully developed region, the vertical velocity component (*V*) is zero and the gradient of the axial velocity component $\partial U / \partial X$ is zero everywhere.

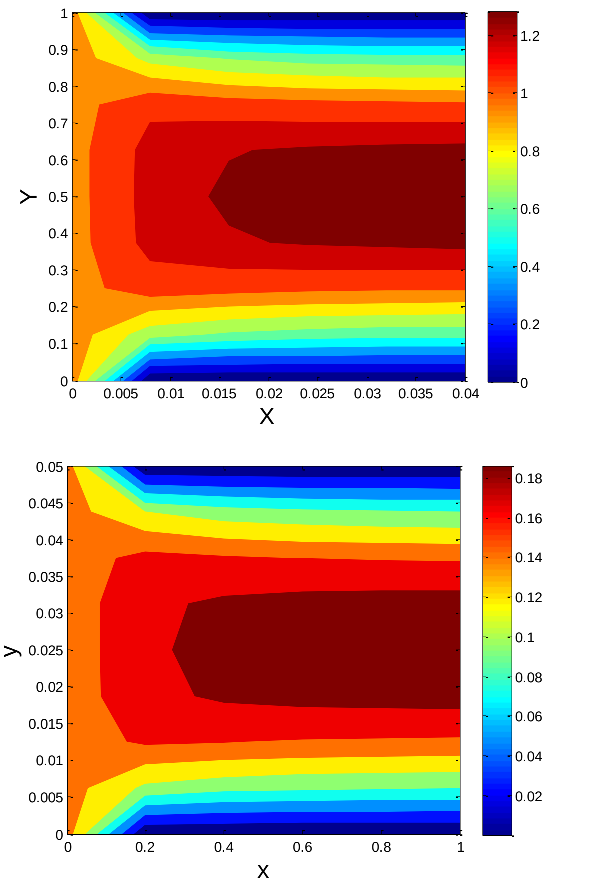

Figure 2: Horizontal component of the air velocity inside the collector (top graph is dimensionless and bottom graph is in m/s).

The vertical component is shown in Figure 3 also in both dimensionless and dimensional contours. The vertical component of the airflow takes place at the start of the channel and disappears as the flow changes to fully developed flow. The figure on the left shows that the effect of the vertical component is very small, in this case of study, and can be neglected when compared to the horizontal component

The resulting velocity profile consist of two boundary layer profiles on the two walls joined in the mid-plane by a line of constant velocity.

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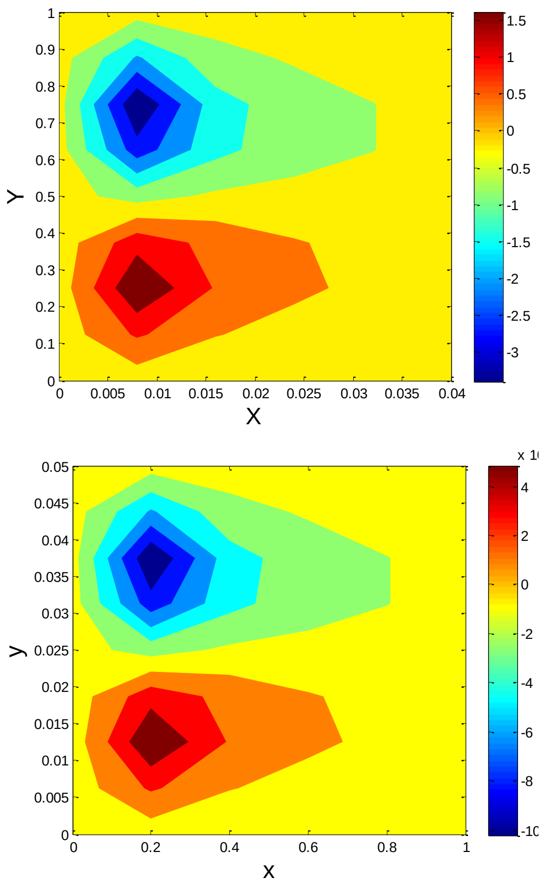

Figure 3: Vertical component of the air velocity inside the collector (top graph is dimensionless and bottom graph is in m/s).

Figure 4 shows the magnitude of velocity of airflow inside the flat plate solar collector. The velocity in the inlet section is uniformly distributed over its width and that its magnitude is (U=1). The velocity at wall equals zero but with an increase distance in y-direction from the surface, the x-direction velocity component of fluid (U), must then increasing until it approaches maximum in mid-plane of the air channel passage. Since the volume of the flow is the same for every section, the decrease in the rate of flow near the walls because of the friction must be compensated by a corresponding increase near the axis. The dominant component of the velocity is the horizontal component. The vertical component is very small in this case, which may allow the researchers to ignore it in modelling such problem of air solar collector.

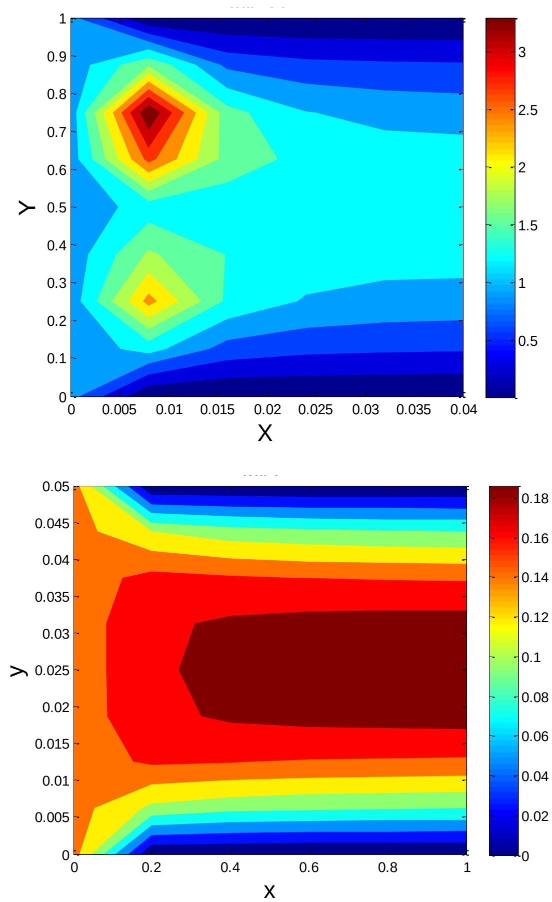

Figure 4: Velocity contours of the air inside the collector.

An important conclusion can be drawn from Figure 4 is that; the vertical component of velocity does not have a considerable effect on the total velocity in this case of study. In similar situations of air flow between parallel flat plats where Reynolds number has greater values than those used in this case, the vertical velocity component is expected to have an important effect on both the velocity fields and the temperature distributions.

The pressure difference is assumed to change in x-direction only and it is calculated based on the assumption of steady state flow. As shown in Figure 5 the pressure gradient increases in the x direction.

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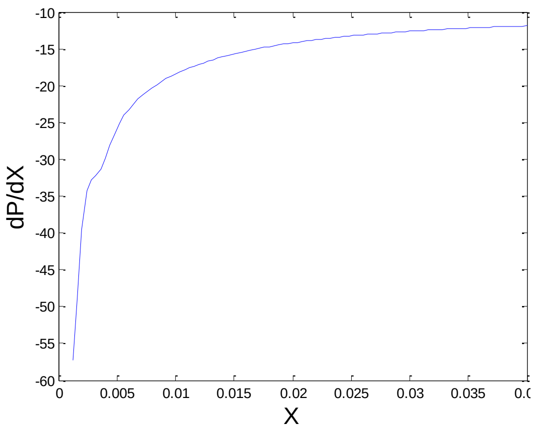

Figure 5: Dimensionless pressure gradient along the horizontal distance of the collector

Solar irradiance is required in order to include the boundary conditions of the energy equation and consequently to find the temperature distribution in the flowing air inside the collector. The dimensionless hourly solar radiation used in this work is calculated for ten hours day length and shown in the following figure. The maximum solar irradiance is found to occur 5 hours after the start of the daylight.

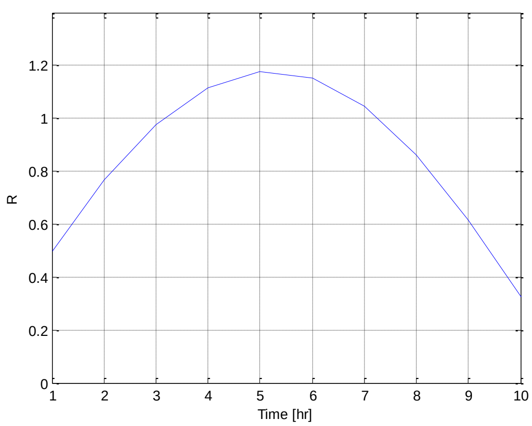

Figure 6: The ratio of hourly solar radiation during 10 hours day.

Figure 7 presents the temperature distribution at the collector outlet after five hours of the sunrise. As it is expected from the solar irradiance profile, the maximum temperature occurs after 5-hours.

The temperature distribution at the collector outlet shows that, the upper layers of air temperature were not affected by the plate temperature, i.e. the temperature is equal to the ambient temperature in the upper layers of the air, which may affects the efficiency of the solar collector during the day. Finally, Figure 8 represents the contours of the temperature of the air inside the collector.

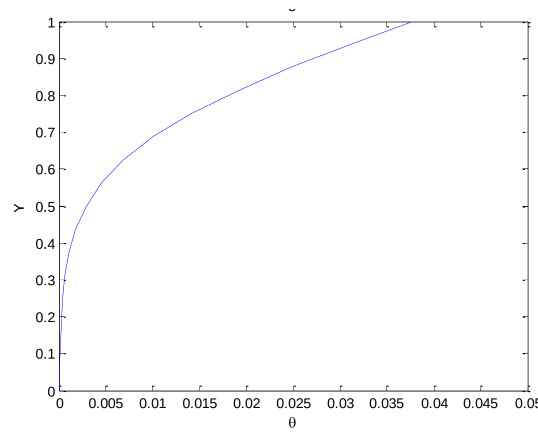

Figure 7: Temperature at the collector exit after five hours of the solar radiation.

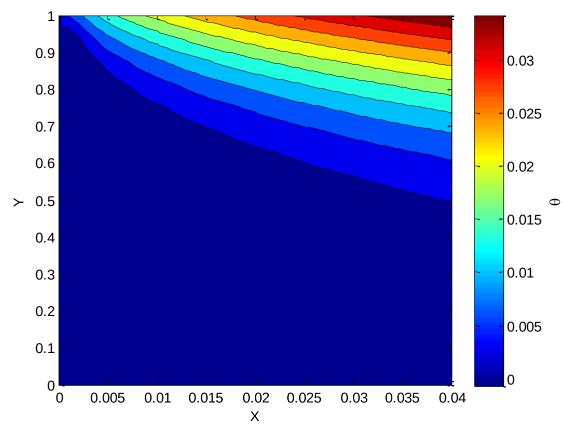

Figure 8: Temperature distribution inside the solar collector after five hours of the solar radiation.

IV. Summary And Conclusions

In this paper, partial differential equations governing the airflow inside flat-plate solar collectors is derived and converted by using appropriate parameters to non-dimensional equations.

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Then explicit finite difference scheme is implemented in order to solve those equations. The explicit finite difference method showed good results in the range of the studied parameters.

The computational algorithm is used to calculate some important parameters such as velocity components in both directions, pressure and the temperature distribution. In addition, the algorithm is able to predict all the thermal properties such as the bulk temperature, thermal efficiency, air enthalpy and local Nusselt number. The work shows that there is a good agreement between the results of the present numerical solution and the related experimental results.

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