Investigation on Choosing the Suitable Geometry of the Solar Air Heater to Certain Conditions

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Abstract—This study focuses on how to control the outlet temperature of a solar air heater in a way simpler than the existing methods. In this work, five cases have been studied by using ANSYS Fluent based on a CFD numerical method. All the cases have been simulated by utilizing the same criteria and conditions like the temperature, materials, areas except the geometry. The case studies are conducted in Little Rock (LR), AR, USA during the winter time supposedly on 15th of December. A fresh air that is flowing with a velocity of 0.5 m/s and a flow rate of 0.009 m^3/s. The results prove the possibility of achieving a controlled temperature just by changing the geometric shape of the heater. This geometry guarantees that the absorber plate always has a normal component of the solar radiation at any time during the day. The heater has a sectarian shape with a radius of 150 mm where the outlet temperature remains almost constant for six hours.

Keywords—Solar energy, air heater, control of temperature, CFD.

I. INTRODUCTION

TODAY, energy has a great importance in our life. The world technology developments are threatening the use of conventional energy resource in the future. Solar energy is the most considerable energy source in the world. Nowadays, solar energy involves in many fields, especially in modern equipment as well as in the remote areas. In general, there are two ways for using solar energy. The first one is using solar energy to produce electricity that can be stored (solar panels). The second way is using converting solar energy into heat energy. Solar air heater is an application of the second way of use (heat transfer by radiation and convection). Some applications demand a constant temperature in the spaces for poultry. Solar radiation varies during the day since it starts at low value and reaches its maximum at noon and then goes down again at the end of the day. Atmosphere temperature directly depends on solar radiation with positive relation. In this case, there will be big difference in the space's temperature that changes with time, which is undesired for many applications. This study treats this problem by designing a new geometry for the solar air heaters. In order to control the temperature and because the orientation of the system is very important, the geography of the place must be studied. Our goal in this paper is get a constant outlet temperature and not high temperature. There are many studies about the temperature control issue. Harrison et al. [3] studied stagnation temperature control for solar collector. This study

described the analysis, design, and operation of solar collector equipped with temperature control. Here, the collector still gets the solar radiation till reaching to stagnation point. In this point, heat transfer and thermal analysis were conducted to arrive a suitable design.

Azzouzi [4] conducted a study about the controlling of solar water heater design. In this study, he used an ISIS simulation. He used PROTEUS software to design a water solar heater with control system by implementing the PIC 16F877 microcontroller based on the PROTON programming language. With this technique, the temperature was between 20 °C and 70 °C.

In [5], Costa and Lemos made a new central algorithm in order to control the temperature of the fluid in solar parabolic trough system. To do this process, they solved the partial differential equation in terms of material derivative and formulated the temperature of one particle of fluid mathematically. The controller process in this work satisfied that the fluid does not exceed the reference and the absence of any optimization methods. Silva et al. [6] used a time-varying state space model of the control process. In [7], Camacho et al. made a survey about the different advance automatic control methods that related temperature of solar planets with distributed collectors during the last 25 years. They classified the model first and then explained the main features of each strategy.

The novelty of this study is the use of geometry shape to control the temperature, while all the previous studies used control systems to get constant temperature.

II. THE GEOMETRY SHAPES

The traditional geometry of the solar air heaters is rectangular shape flat plate absorber with rectangular cross sectional area. This shape gives the maximum temperature outlet when the solar radiation is normal on it. When the solar rays deviate, the heat gain will go down as well as the outlet temperature. So, this shape does not solve the problem because it gives different outlet temperatures and matches the atmosphere temperature during the day. The geometric shapes have longitudinal section as a curve with radius (948 mm), but the cross-sectional areas are different. The difference in cross-sectional by radii are shown in Figs. 1-5. These designs were chosen in order to catch solar rays at any time during the day. All of them have the same volume and the same absorber plate area with the absorber area equal to 600 mm x 860 mm and with a gap equal to (30 mm) as shown in Figs. 1-5.

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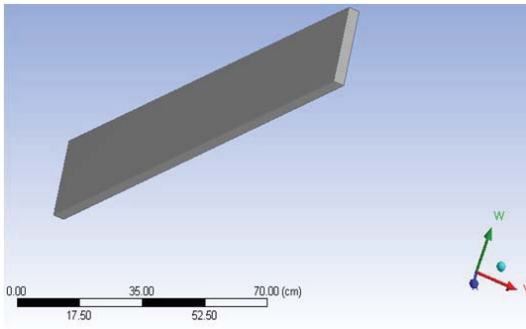
A. Case One
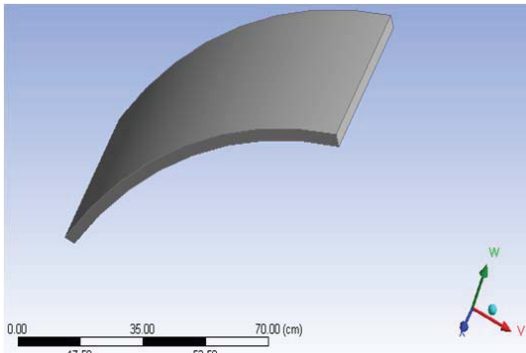

Fig. 1 Geometric shape for case 45°

B. Case Two
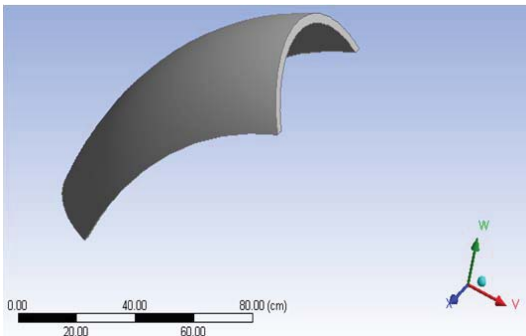

Fig. 2 Geometric shape for case R=∞

C. Case Three

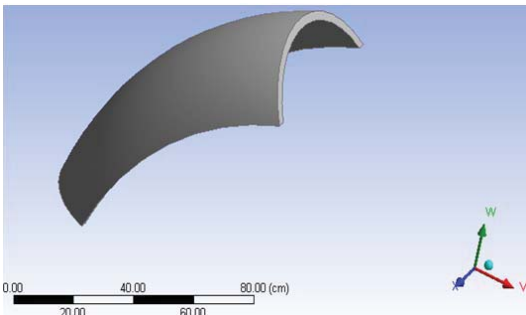Fig. 3 Geometric shape for case R=300 mm
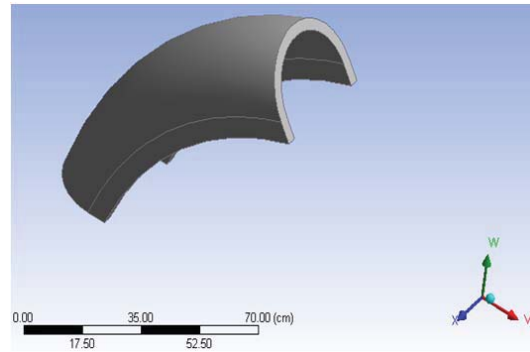
D. Case Four

Fig. 4 Geometric shape for case R=200 mm

E. Case Five

Fig. 5 Geometric shape for case R=150 mm

III. THE THEORY

There is no surface that can emit energy more than a blackbody. A blackbody surface can absorb most of the incident radiations. The absorbed energy emitted by unit area and unit energy is expressed by Stefan-Boltzmann law by [1]:

$$Eb(T) = \sigma T^4 \tag{1}$$

Since Eb is the blackbody emissive power (Wm^{-2}), and σ is the Stefan-Boltzmann constant (Wm^{-2} k^{-4}), while T is the absolute temperature of surface (K). The flow of air under absorber plate is subject to the continuity equation and momentum equation in three dimensions as expressed [2]

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \tag{2}$$

$$\rho \frac{Du}{Dt} = \frac{\partial \sigma xx}{\partial x} + \frac{\partial \tau yx}{\partial y} + \frac{\partial \tau zx}{\partial z} + \sum Fx \ body \ force \tag{3}$$

$$\rho \frac{Dv}{Dt} = \frac{\partial \tau xy}{\partial x} + \frac{\partial \sigma yy}{\partial y} + \frac{\partial \tau zy}{\partial z} + \sum Fy \ body \ force \tag{4}$$

$$\rho \frac{Dw}{Dt} = \frac{\partial \tau xz}{\partial x} + \frac{\partial \tau yz}{\partial y} + \frac{\partial \sigma zz}{\partial z} + \sum Fz \ body \ force \tag{5}$$

The heat transfer converts from absorber plate to the fluid work (air) by forced convection according to (6) [1]:

$$q^. = h * A \ (Ts - Tm) \tag{6}$$

$q^.$ the is heat transfer (W), h is the heat transfer coefficient by convection (W m^{-2} K^{-1}), A is the absorber plate area (m^2), Ts is the absorber plate temperature (K), and Tm is the mean temperature of fluid (K). The energy transfers to the fluid (air), and the temperature increase depends on the mass flow rate and specific heat according to (7) [1]

$$Q = m^. CP \ \Delta T \tag{7}$$

Since Q is the heat gain (W), $m^.$ is the mass flow rate (kg s^{-1}), CP is the specific heat (kJ.kg^{-1}.K^{-1}), and ΔT is different temperature (K).

IV. AMBIENT CONDITIONS

Temperatures have not changed much for sunny days during the winter for most areas. After observing many nearby days of Dec. 15 in Little Rock AR, the majority of them were as shown in Fig. 6. These are considered as a fresh air temperature inlet. Fig. 7 shows the solar radiation with time for Little Rock AR, Day Dec. 15.
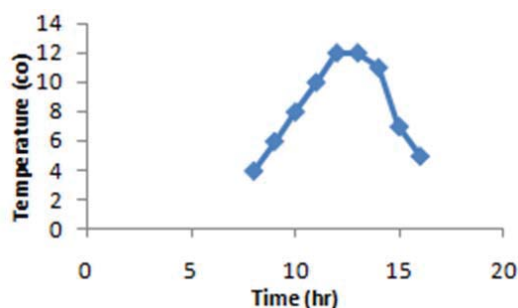

Fig. 6 The relation between temperature and time

V. CFD MODELING

Five cases according to different geometry shapes have been studied. In this paper, CFD code Fluent 13 is used to simulate the cases. The air was used as a fluid, and steel was used for the absorber plate. The models were K-epsilon with fully buoyancy effects and energy equations, continuum equations as government equations. In radiation field, the solar ray tracking was used as a model and the solar calculator option was chosen. The geographical conditions were for Little Rock Arkansas state USA with longitude 92° west and latitude 34° north. The test was for winter season, and Dec. 15 is the chosen day for all cases. The test was conducted every hour.
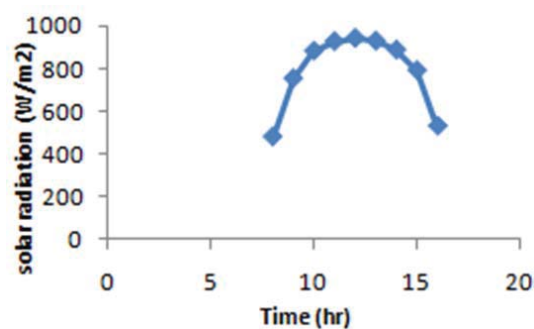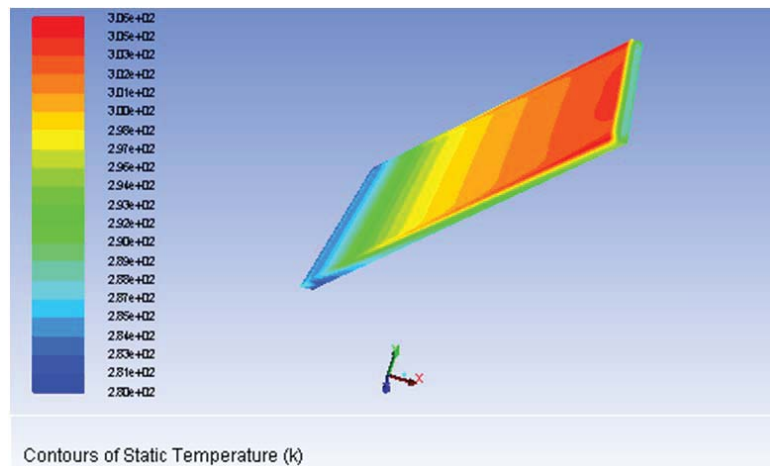

Fig. 7 Solar radiation with time for Little Rock Dec.15

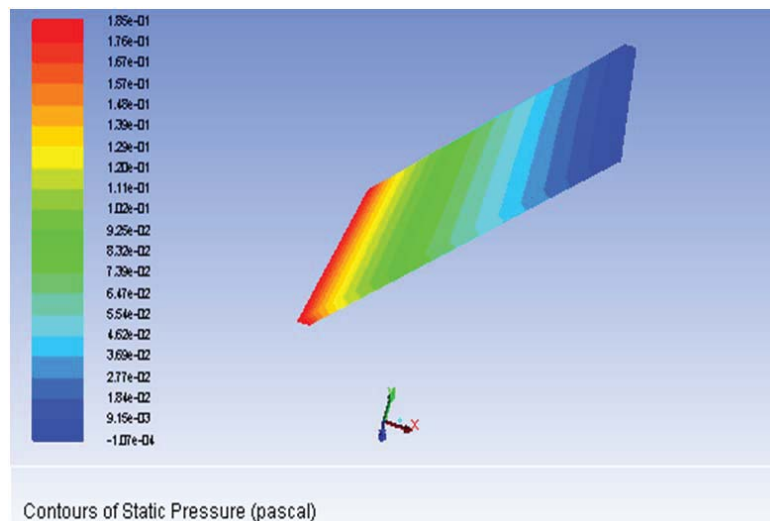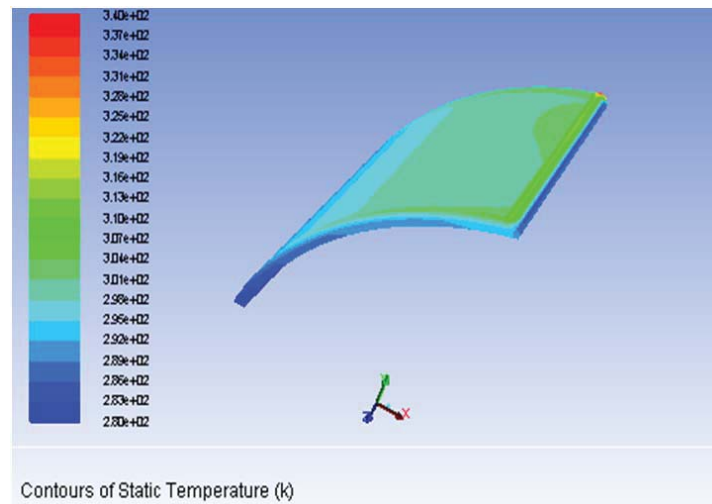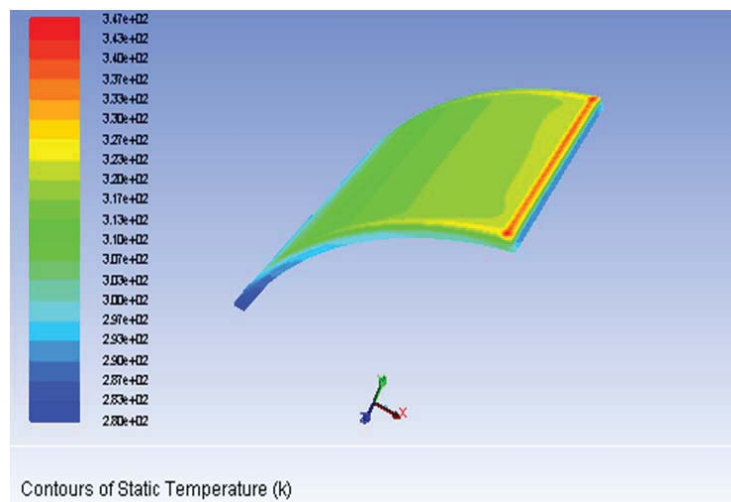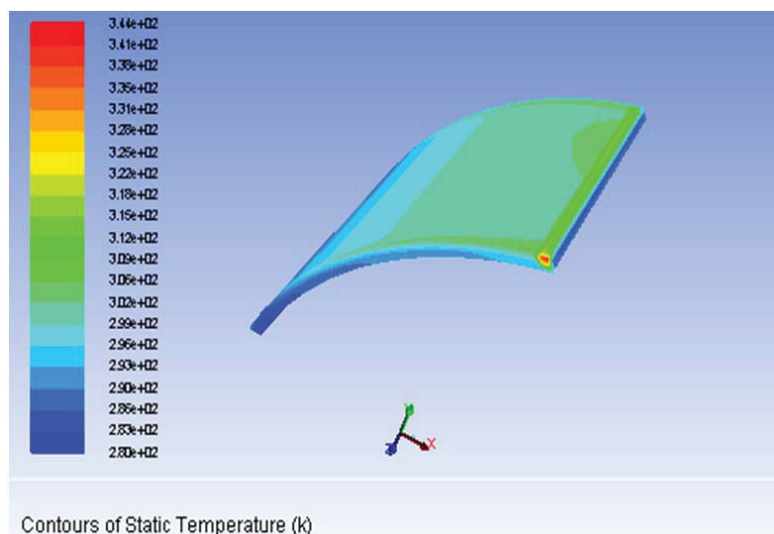Contours of Static Temperature (k)
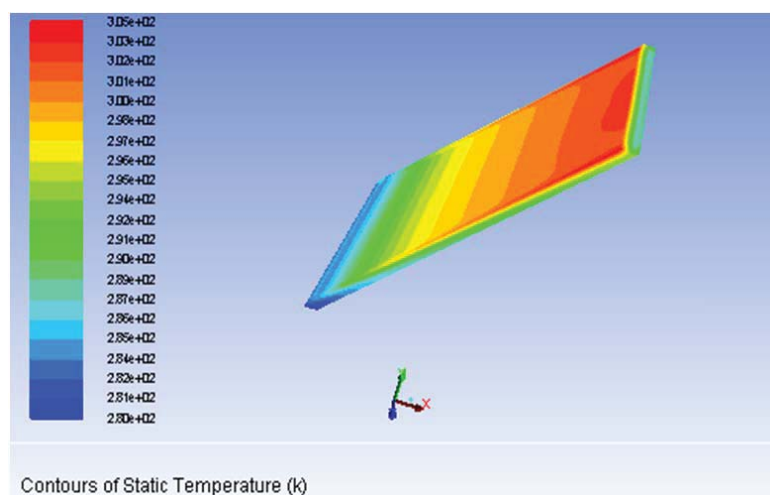
(a)
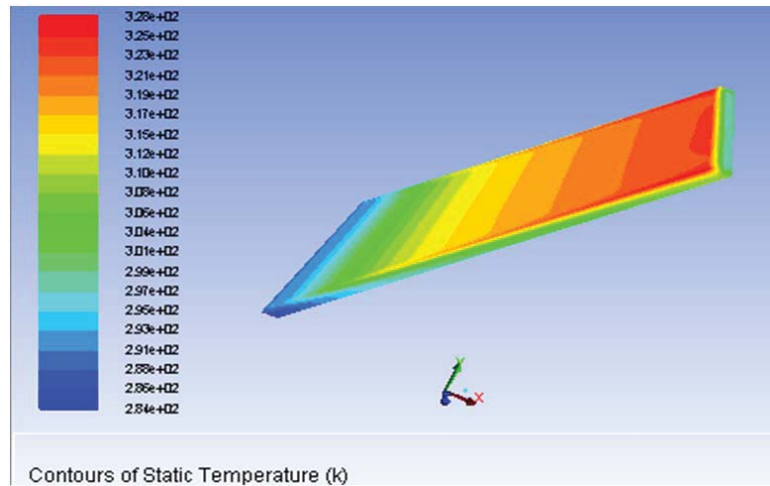
(b)

(c)

(d)

Fig. 8 Contours of static temperature in different times and contours of static pressure for case 1 (a) static temperature at 9:00 a.m. (b) static temperature at 12:00 p.m. (c) static temperature at 15: 00 p.m. and (d) static pressure
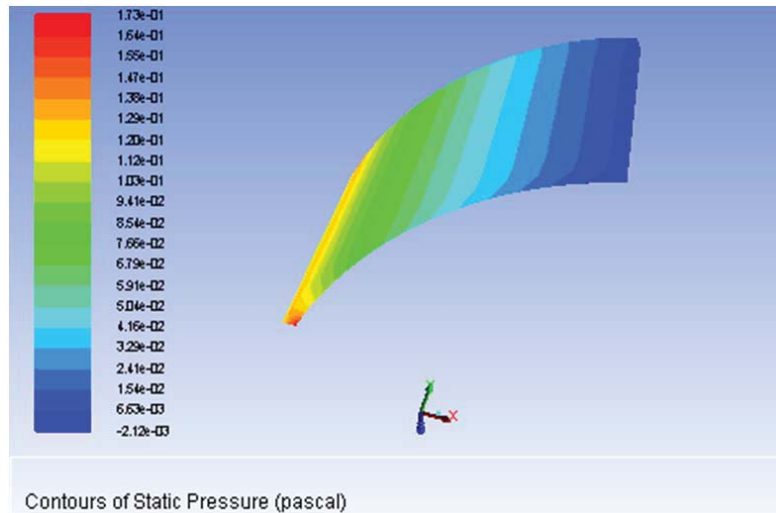
(a)

(b)

(c)

(d)

Fig. 9 Contours of static temperature in different times and contours of static pressure for case 2 (a) static temperature at 9:00 a.m. (b) static temperature at 12:00 p.m. (c) static temperature at 15:00 p.m. and (d) static pressure

VI. RESULTS AND DISCUSSION

This paper focuses on outlet temperature and the suitable geometry shape that gives constant temperature as long as possible. The first one (slope 45°) is considered as a reference for changing the geometries of the other four. The temperature and pressure contours as illustrated in Fig. 8 show distribution of static temperature and static pressure along the duct. From Fig. 8, there is a big deference in outlet temperature for different times during the day because of the change related to the solar ray positions, and the other reason is the change in the radiation value. For these reasons, other geometric shapes (curved geometric shapes) were tested. These curves are based on the essential angles since it changes from 60° to 45° and finally to 30° in order to catch the solar rays as long as possible with different times. The cross section areas are different depending on the radius of the curve. In the second case, the results are not satisfied because the solar radiation does not match as well at the end of the day. Fig. 9 shows the static temperature and pressure contours.

To avoid the shortage in the radiation falling on the collector at the end of the day, case 3 was simulated (cross-sectional area with R=300 mm) in order to get normal radiation at all times. The value of solar radiation is low at the end of the day compared to the noon time. The results are better than the first two, but enhancements are still needed as shown in Fig. 10.

In order to reach our target (get close outlet temperature as long as possible), the projection area is extended in the direction of the solar radiation at the end of the day. In case 4, the radius is decreased to R=200 mm. That will lead the projection area of the absorber plate to increase the direction of solar radiation in the end of the day and decrease in the noon time. The results in this case do not remain perfect as shown in Fig. 11.

In case 5, the radius is decreased to R=150 mm, and the best results were obtained. The average outlet temperature is very close from 9:00 to 15:00 as shown in Fig. 12. The distribution of static temperature and static pressure contours are shown in Fig. 12.

Fig. 13 summarizes all cases and shows the relation between the average outlet temperature and the time. This curve is for Dec. 15 but should be convenient during all the days of season. Case 5 was tested in the other days like Nov. 1st and Feb. 1st. The result is shown in Fig. 14. From this figure, the difference in outlet temperature for the duration (from 9:00 to 15:00) became little bit larger but it still acceptable for many applications.

From the results, static pressures contours are fined. For case 5 (R=150 mm), the pressure drop is (0.2 Pa) which is acceptable according to other cases. Fig. 15 shows the pressure drop for the five cases.

VII. CONCLUSIONS

This study does not focus on how much heat energy is converted from solar energy, but it focuses on the stability of outlet temperature as long as possible. To achieve this, the first condition is the location such because the direction of solar rays is different from one place to another. The second thing is how to design the geometrical shape according to that area. The key is to find the optimum design so that the projection area of collector in the sunlight direction (normal direction) multiplied by the radiation should be equal in that period.
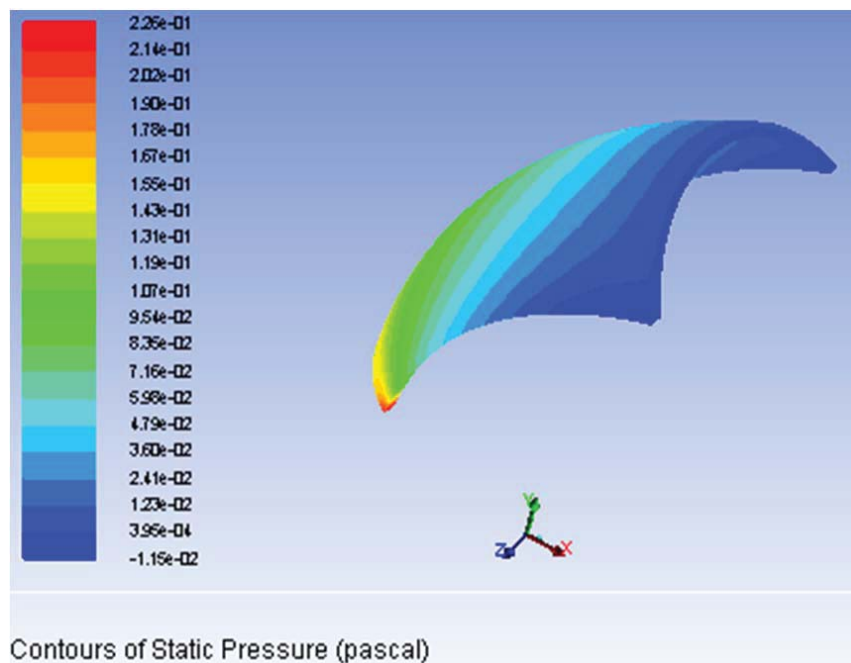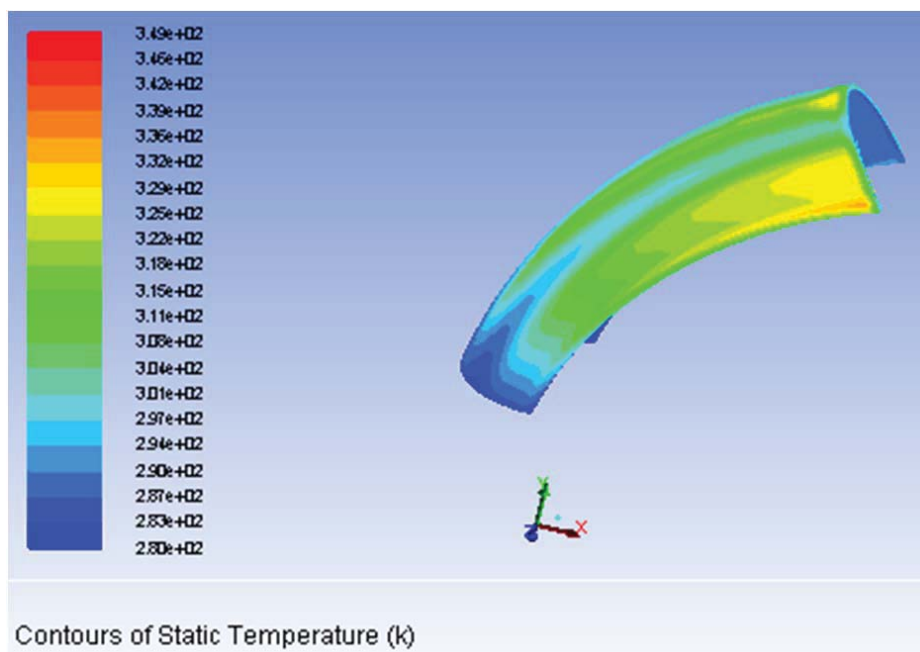
(a)

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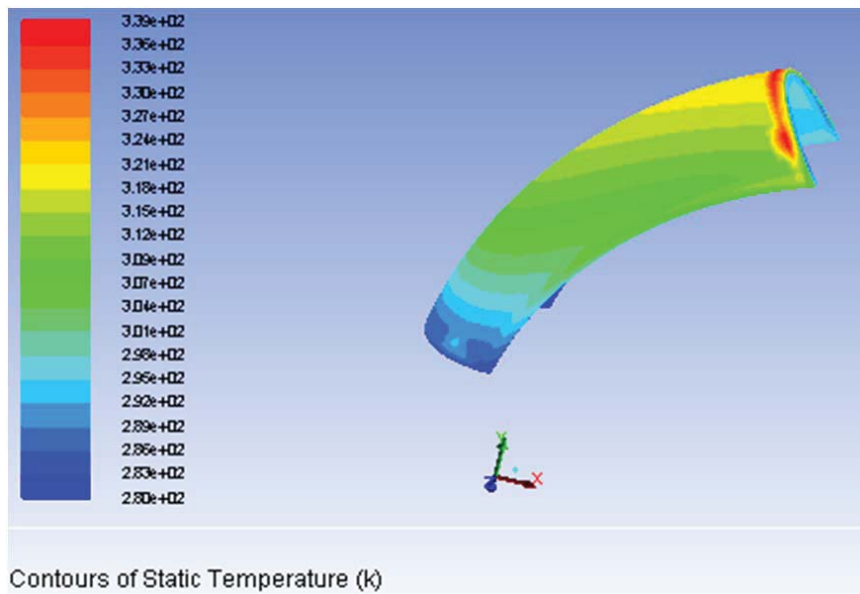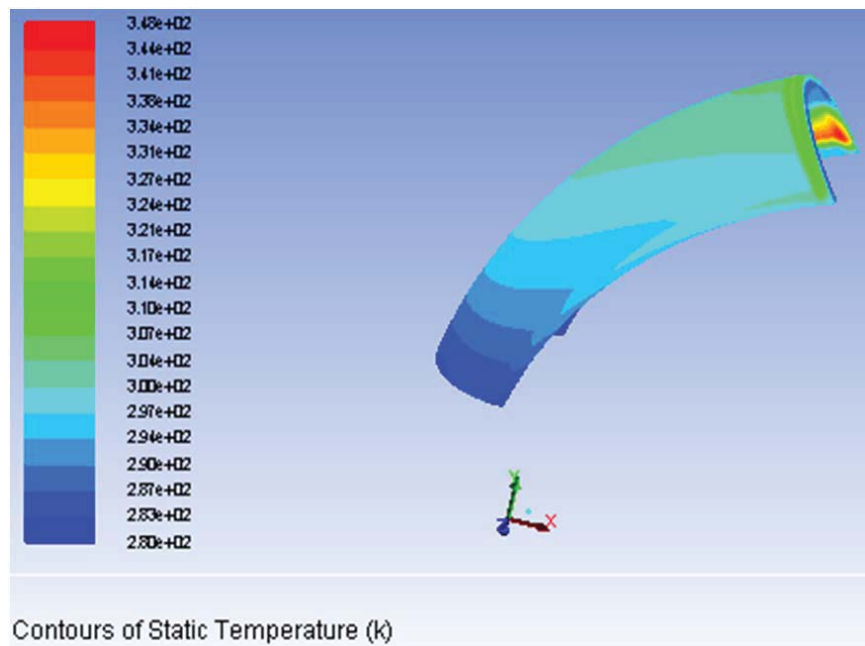Contours of Static Pressure (pascal)
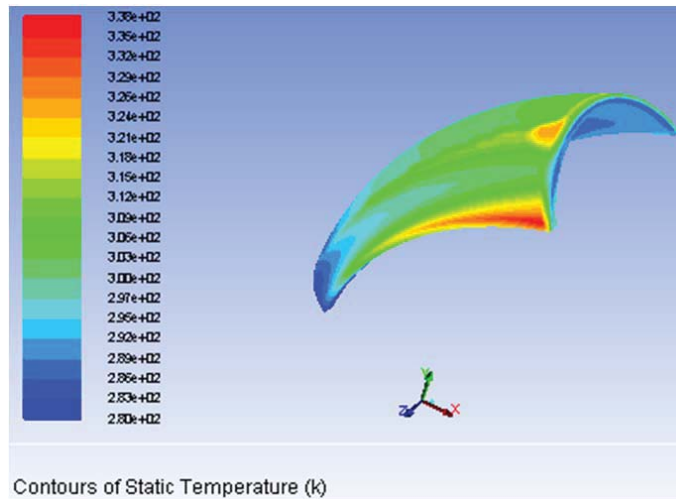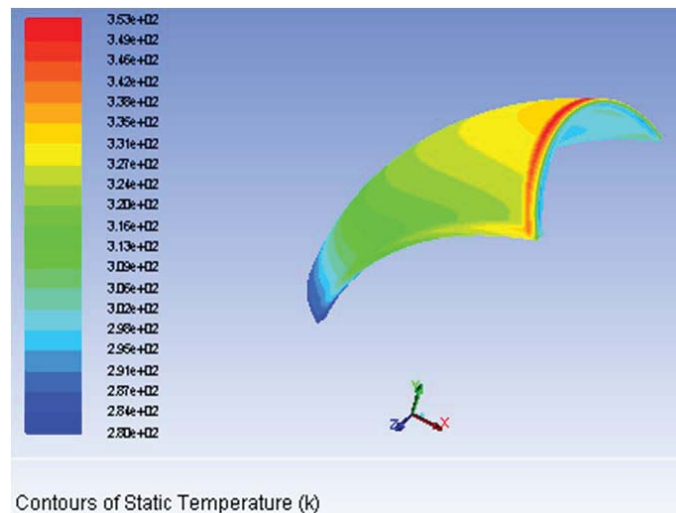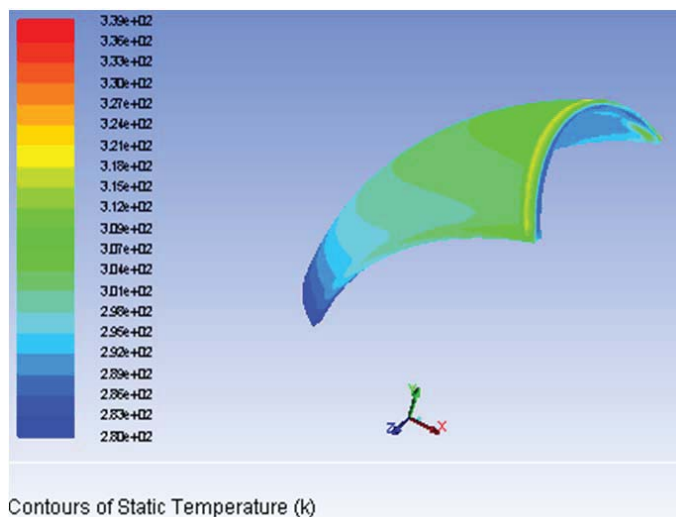
(d)

Fig. 10 Contours of static temperature in different times and contours of static pressure for case 3 (a) static temperature at 9:00 a.m. (b) static temperature at 12:00 p.m. (c) static temperature at 15: 00 p.m. and (d) static pressure
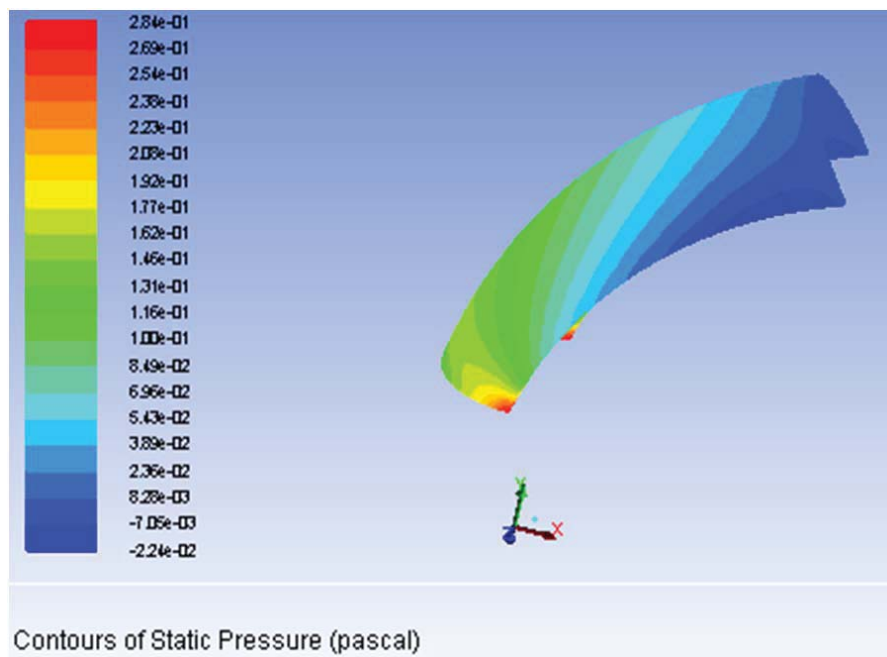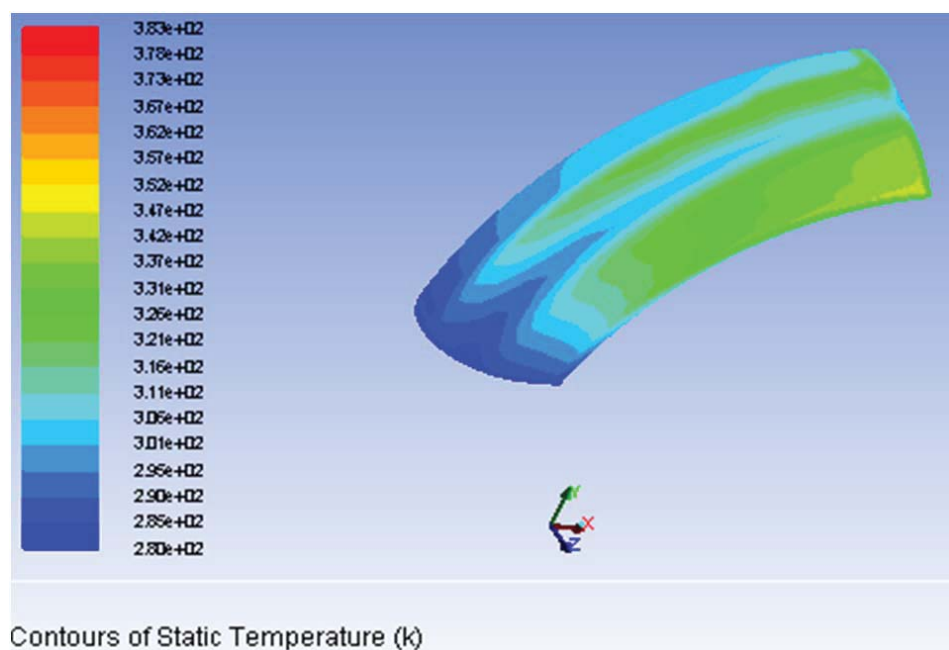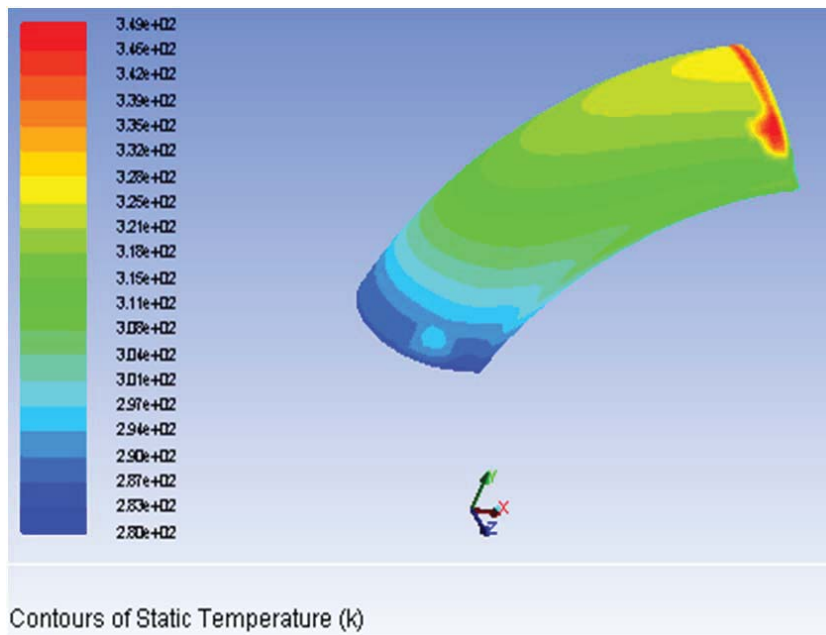

Contours of Static Temperature (k)

(a)

Contours of Static Temperature (k)

(b)

Contours of Static Temperature (k)

(c)

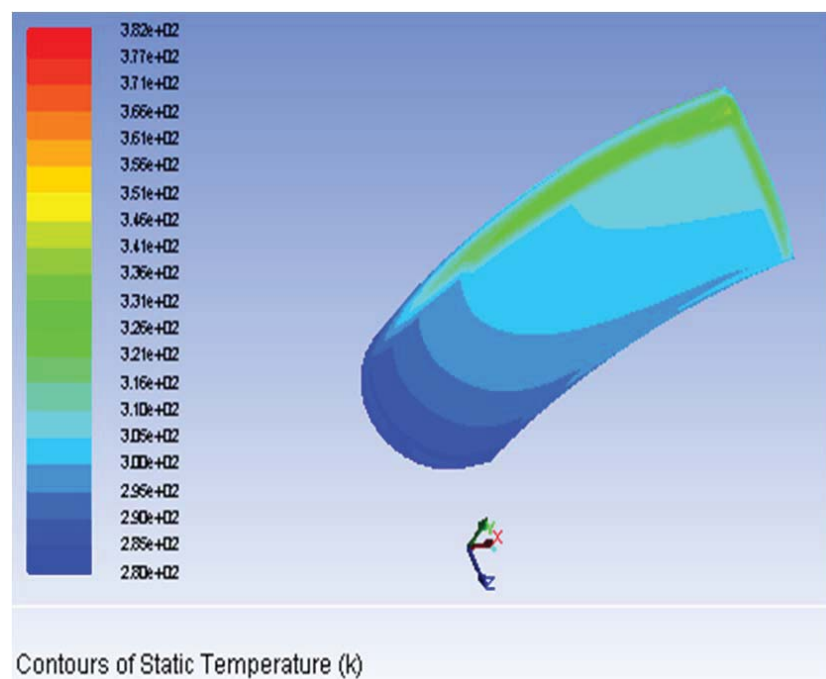Contours of Static Pressure (pascal)

(d)

Fig. 11 Contours of static temperature in different times and contours of static pressure for case 4 (a) static temperature at 9:00 a.m. (b) static temperature at 12:00 p.m. (c) static temperature at 15: 00 p.m. and (d) static pressure
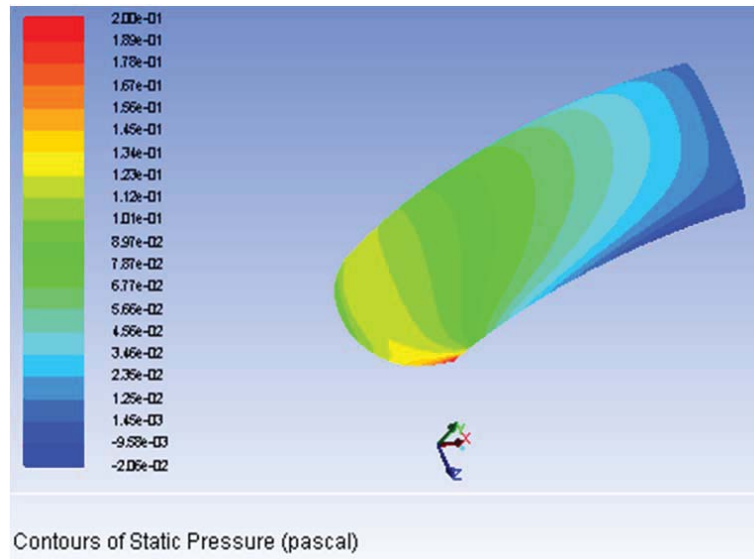

Contours of Static Temperature (k)

(a)

Contours of Static Temperature (k)

(b)

Contours of Static Temperature (k)

(c)

(d)

Fig. 12 Contours of static temperature in different times and contours of static pressure for case 5 (a) static temperature at 9:00 a.m. (b) static temperature at 12:00 p.m. (c) static temperature at 15: 00 p.m. and (d) static pressure
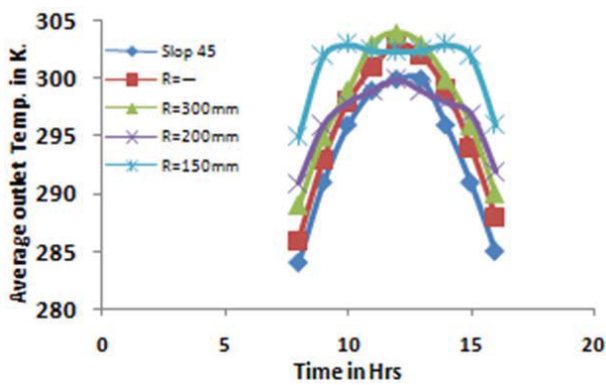

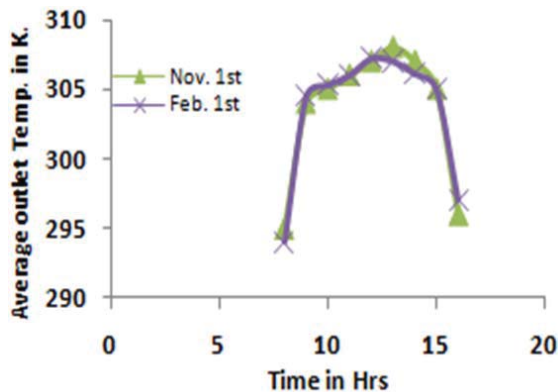Fig. 13 Average outlet temperature with time for all cases on Dec. 15

Fig. 15 Pressure drop along the solar air heater for all cases

Fig. 14 Average outlet temperature with time for case (R=150 mm) on Nov. 1st and on Feb. 1st

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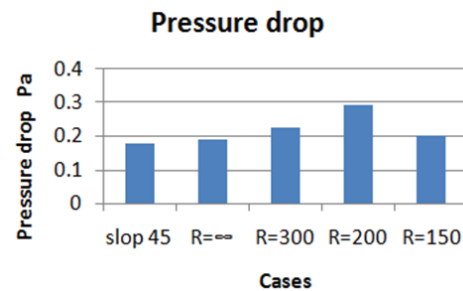[1] Heat and Mass transfer Fundamental and Application Fifth Edition in SI Units yunus A. Cengel-Afshin J. Ghajar.
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