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# Performance Evaluation of Updraft Air Tower Power Plant Integrated with Double Skin Solar Air Heater

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**Abstract:** This paper presents and discusses a novel Computational Fluid Dynamics simulation of a solar air heater as part of the updraft air tower model for an electrical power generation. A solar air heater is built upon double transparent upper skin to capture the solar energy and create the greenhouse effect, which is forming hot air flow into power generator part. The influence of different transparent skin geometrical of the proposed solar air heater on the tower power plant performance at various operational parameters have been simulated and evaluated using ANSYS Fluent software to solved the Navier-Stokes and energy equations integrated with discrete ordinates (DO) radiation model. The evaluation result demonstrates that as the number of skin solar air heater in collector increases, also the area of these air heaters, the system performance enhances.

Keywords: energy recovery; solar air heater; solar chimney power plant; solar air collector

## 1. Introduction

In today's scenario requirement of clean energy is increasing at industrial as well as domestic level. So nowadays, solar heaters collector is being used to utilize renewable sources of energy <sup>1, 2</sup>. Many researchers interested to study the thermal performance of different solar systems; solar distiller to enhance the heat input and yield rate <sup>3</sup>, solar water heaters <sup>2, 4</sup>.

Solar updraft tower power plant SUTPP is a plant to generate electricity from solar irradiation depending on buoyancy force to drive air to ascend <sup>5</sup>. The SUTPP parts are simple and free of complexity in the design, operation, and maintenance. Main parts of the SUTPP are a solar air collector (SAC), tower and turbine, as shown in Fig.1. Conventionally, the solar beams are penetrated through the transparent cover of collector and received by the absorber medium (ground) and the air inside of solar collector. But the ground has some drawbacks, such as limited storage capacity, thermal leakage and enhances thermal storage requirements. However, the energy storage can be used to improve these systems during night or cloudy days; the stored heat in the absorber medium is released to the collector air. The temperature or the difference in density between the ambient and the inner collector warm air generates buoyancy force which considered driving force or pressure potential. Warm airflow towards the tower base and drive the power conversion unit (turbine) and

powering generator <sup>6</sup>. Therefore, enhanced the SAC part was focused by the previous studies to maintain a high-performance level of SUTPP. Three class have been examined by previous studies can be classification, the first class analysis the effect of absorber mediums deposition characterized on the SAC outcomes. In this regard, wide ranges of attempts have been reported, Al-Kayiem et al. <sup>7</sup> summarized the advantage and disadvantage of each thermal storage technique in the SCPP which suggested by many previous researchers. Wahhab and Al-Maliki <sup>8</sup> studied the enhancement of the efficiency of energy conversion of the collector and extending the operation time using a six type of natural ground materials, the study recommended using the black stones as a thermal heat storage media of the collector for its efficiency, low cost, and availability. Fadaei et al. <sup>9</sup> evaluated the effect of utilizing paraffin wax as a phase change material for heat storage in the constructed SAC. The results in this study showed increasing the average mass flow rate of SUTPP model around 8.33%. Liquid heat storage system was proposed by Kreetz <sup>10</sup> and Schlaich et al. <sup>11</sup> by adding closed water-filled systems with different heat storage mechanisms, the researchers showed that the SCPP with closed water-filled systems can generate power at night but with decline in power generation during sunshine. The second class of researchers proposed to join the SAC with external heat source to allow the SUTPP works 24 hours. In line with this, Chikere et al. <sup>12</sup> studied how can

benefit from the thermal energy which came from the flue gases of the thermal power plant to enhance the performance of the SUTPP. Later Al-Kayiem et al.<sup>13)</sup> design hybrid arrangement model by used Flue-gas channels that employed to supplying hot air into SAC passage. The study showed that the model resolves the drawbacks of night hours and enable the SUTPP operation 24 hours' electricity power production. Where, the third class of researchers investigated the geometrical shape of SAC. For example, Different configurations of the collector i.e. converging flow, diverging flow and parallel flow were studied numerically by Semai et al.<sup>14)</sup>. Double passes counter flow was investigated numerically and compared with the conventional SAC design by Larbi et al.<sup>15)</sup>, the study appeared enhanced the SAC efficiency about 28%. Therefore, continuously the studies on various design of SAC is consider necessary to investigate the flow visualization within SAC and it is effect on efficiency<sup>16-21)</sup>. Hence, a new model of SAC consisted from double transparent skin surface (DTSS) to upgrade the SAC efficiency has been devised and proposed in this work<sup>22-26)</sup>. In details, different DTSS geometrical at variable operating parameters has been simulated by using ANSYS FLUENT computational fluid dynamics (CFD) to evaluate the optimum design of the SAC part for the SUTPP future work development.

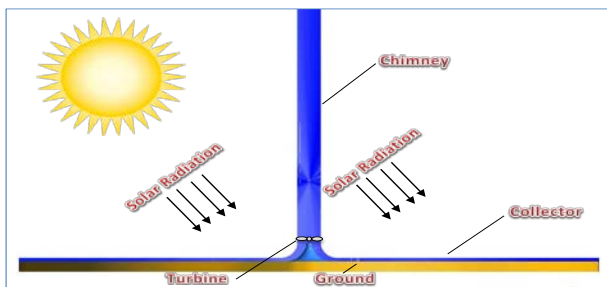


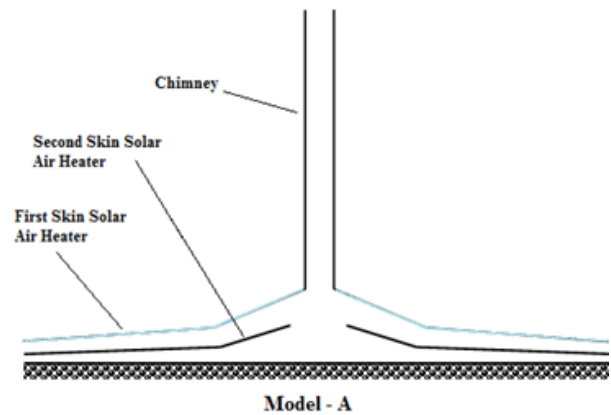
Fig. 1: Schematic diagram of solar power plant updraft tower.

## 2. Guidelines of SUTPP Design

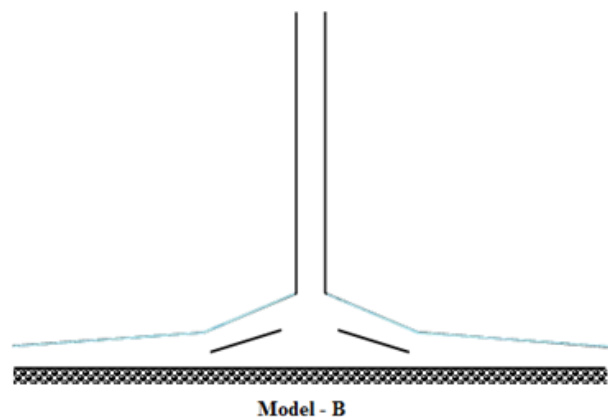
In design of a collector for solar chimney power plant, further considerations in the design of solar chimney plant including diameter and height of the inlet air as well as chimney base height all pertaining collector, ground material, and transforming power system<sup>27-31)</sup>. Generally, single skin solar heaters are the most used to date, especially those operating at low height for the collector, variable speed turbines are often installed in the upper point for solar collector (chimney base), and the air speed is increasing in an effort to improve power capture, reduce loads, obtain better energy quality, and enable more advanced aspects of power control. In this investigation, three simulated models were performed, normal design which is the first model given by<sup>13)</sup> (single solar air heater with diameter 6 m), (Model A) is the second model having double skin solar air heater with diameter 6 m as can be seen in Fig.2 (a), and third

model (Model-B) is double skin solar air heater with diameter 2.8 m as shown in Fig.2 (b). The main inputs were:

- The range of solar intensity ( $50-950\text{W/m}^2$ ) with;
- Ambient air temperature ( $30-34^\circ\text{C}$ );
- Ground, it is supposed to be 10 cm thick.



(a)



(b)

Fig. 2: Schematic of the double skin solar air heater: (a) Model-A, and (b) Model-B.

## 3. Numerical Implementation

ANSYS Fluent Workbench 15, Inc. specifically finite volume method was employed to build computational domain finite volume models. GAMBIT 2.4.6 preprocessing tool support 3D modeling air collector geometry of the solar system in accordance to the parameters of the prototype. Physical phenomena were all simulated using Computational Fluid Dynamics (CFD) techniques as well as prediction of air thermal properties and dynamic behavior of air in 3D cylindrical coordinates. The discretization of equations named; continuity, energy and Navier-Stoke's was performed utilizing Finite Volume Method (FVM)

### 3.1 Numerical Method

To analysis energy system, the 3D numerical simulation was depending on K-epsilon (k-ε) model. According to the features of the turbulent dispersion rate and the turbulence kinetic energy, the values of various constants adopted for k-ε turbulence model were presented in Table 1. The turbulence kinetic energy is specified from turbulence field, and defined as:

- The solar beam calculation in terms of diffuse and direct intensity are depending on system location. So, at specific location and time in regard to the solar beam, the user can be limiting them, and specifying of the solar values and directions are controlling by solar calculator. However, the intensity calculations are performed by utilizing the Discrete Ordinates (DO) method.
- The potential for grid error is due to extreme fluid domain distortion. Therefore, the dynamic mesh is used to simulate the transient flow behavior of the fluid domain and the aero elastic deformation. The adaptation of remeshing is however appropriate for large displacement and deformation. Therefore, nodes relocating is utilized in accordance to smoothing techniques.

Table 1. Various constants adopted for k-ε turbulence model.

Transport equations for standard k-ε model	
For turbulent kinetic energy $k$ :	
$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + P_k + P_b - \rho \epsilon - Y_M + S_k$	
For dissipation $\epsilon$ :	
$\frac{\partial}{\partial t}(\rho \epsilon) + \frac{\partial}{\partial x_i}(\rho \epsilon u_i) = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_\epsilon} \right) \frac{\partial \epsilon}{\partial x_j} \right] + C_{1\epsilon} \frac{\epsilon}{k} (P_k + C_{3\epsilon} P_b) - C_{2\epsilon} \rho \frac{\epsilon^2}{k} + S_\epsilon$	
$\mu_t = \rho C_\mu \frac{k^2}{\epsilon} \quad P_k = -\rho \overline{u'_i u'_j} \frac{\partial u_j}{\partial x_i} \quad P_b = \mu_t S^2$	
$S \equiv \sqrt{2 S_{ij} S_{ij}} \quad P_b = \beta g_i \frac{\mu_t}{Pr_i} \frac{\partial T}{\partial x_i} \quad \beta = -\frac{1}{\rho} \left( \frac{\partial \rho}{\partial T} \right)_p$	
Model constants	
$C_{1\epsilon} = 1.44, \quad C_{2\epsilon} = 1.92, \quad C_\mu = 0.09, \quad \sigma_k = 1.0, \quad \sigma_\epsilon = 1.3$	

### 3.2 Governing Equations

batches are considered to represent the flow of air in the chimney of the solar power plant along with the external air. this is because the air inflow in related to the system is contrast with internal collector temperature and some other environmentally influences such as humidity and wind. The determination of buoyant air of the solar power plant from the base of the collector exit(chimney) is illustrated in equation 1:

$$\frac{\partial}{\partial r} (\rho_{air} V_{coll} r_{coll} H_{g-c}) = 0 \quad (1)$$

based on equation 1, density and velocity of air are a function of the internal collector temperature area. While

the potential air volume in the system is determined of the collector canopy height that located above the ground. on the same manner, equation 2 described the continuity of air flow in the chimney. Hence, mass continuity and balance are considering.

$$\frac{\partial}{\partial h} (2\pi \rho_{air-ch} V_{air-ch} r_{ch} H_{ch}) = \frac{\partial}{\partial h} (\rho_{air-ch} \dot{V}_{air-ch}) = 0 \quad (2)$$

The buoyant air strength that reaching the turbine is described by the momentum of air flow in the collector. this air property is calculated using equation 3. On the other hand, the momentum of air flow flowing in the chimney is defined in equation 4.

$$\rho_{air-coll} V_{coll-exit} H_{g-c} \frac{\partial V_{coll-exit}}{\partial r_{coll}} = -H_{g-c} \frac{\partial p_{air-coll}}{\partial r_{coll}} - \tau_{air-coll} \quad (3)$$

$$\rho_{air-ch} \dot{V}_{air-ch} \frac{\partial \dot{V}_{air-ch}}{\partial h} = -\frac{\partial p_{air-ch}}{\partial h} - \frac{2\tau_{air-ch}}{r_{ch}} - \rho_{air-ch} g \quad (4)$$

in this study, the energy equation is the basic equation that considered for the simulation as given in equation 5.

$$u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} = \frac{\lambda}{\rho c_p} \left( \frac{\partial T^2}{\partial x^2} + \frac{\partial T^2}{\partial y^2} \right) \quad (5)$$

### 3.3 Cases of Simulation Parameter and Boundary Conditions

A radiation model was employed in the simulation in order to assist determining the different temperatures and velocities of the solar system power plant. based on results of simulation, the properties of thermo-physical followed three models along with skin solar air heater. The simulation boundary conditions are illustrated in table 2.

Table 2. Simulation boundary conditions of the media selection as heat storage.

Component	Boundary type	Value
Ground	Wall	Adiabatic system ( $q=0$ ), temperature values is a function of solar intensity, no-slip.
Glass of Model: normal, A, and B	Wall	Adiabatic system ( $q=0$ ), temperature values is a function of solar intensity, no-slip
Chimney walls	Wall	Adiabatic system ( $q=0$ ), temperature values is a function of solar intensity, no slip
Skin solar heater wall: normal, A, and B	Wall	Adiabatic system ( $q=0$ ), no slip, temperature values is a function of solar intensity. Whereas, the storage materials rely on thermal properties.

Collector inlet	Mass-flow inlet	Inlet parameters reliant on ambient condition.
Chimney	Pressure outlet	Pressure difference ( $\Delta p = 0$ )

In fig. 3 the double skin solar air heater along with the meshing of the 3D model geometry of the chimney pertaining solar power plant is shown. Separate solution of both fluid and solid domain was performed. thereafter, a periodic exchange between the solid and fluid for their interaction information. This concept able for saving time of the computational process and provide adequate precision in solving several complex non-linear problems. It I also used pressure-based type of solver. fine meshing nodes and elements pertaining all models are illustrated in Table 3. For all domains, number of cells in Table 3 selected for all simulation according to grid dependency as shown in Figure 4.

Table 3. Nodes and elements for SUTPP.

SUTPP	Dimensions	Nodes	Elements
Model-normal	Single skin solar air heater, with diameter 6m and height at inlet 0.05m Chimney diameter 0.15m, and height 6.65m	818341	689433
Model-A	Double skin air heater diameter, 6m	807893	671994
Model-B	Double skin air heater diameter, first skin diameter 6 m, and second skin diameter 2.8m	813987	684663

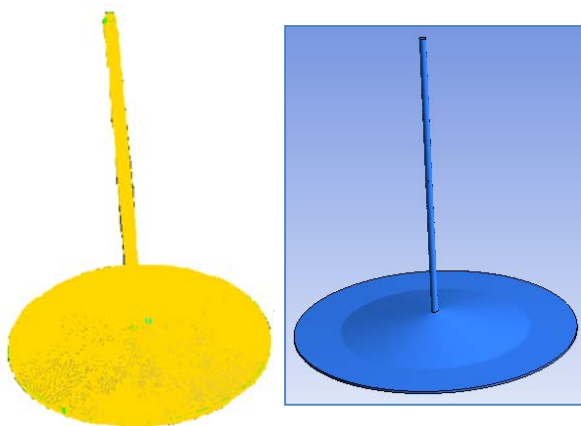


Fig. 3: Mesh and computational domain for the geometrical model of solar chimney power plant.

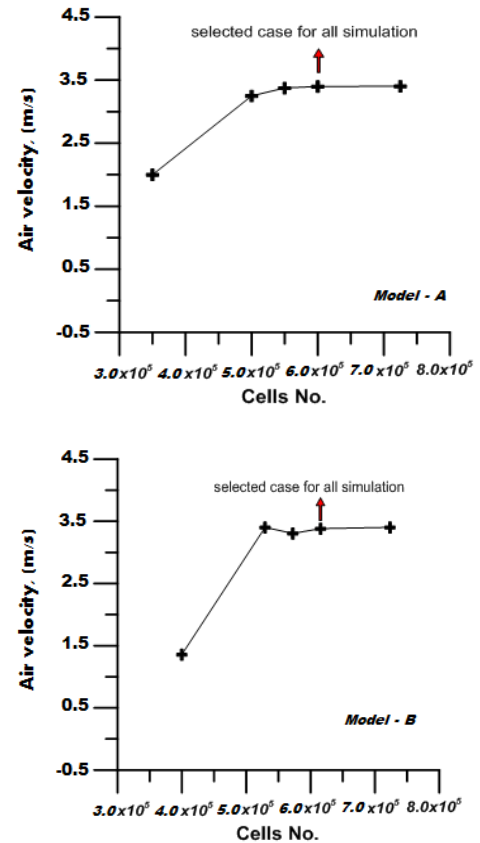
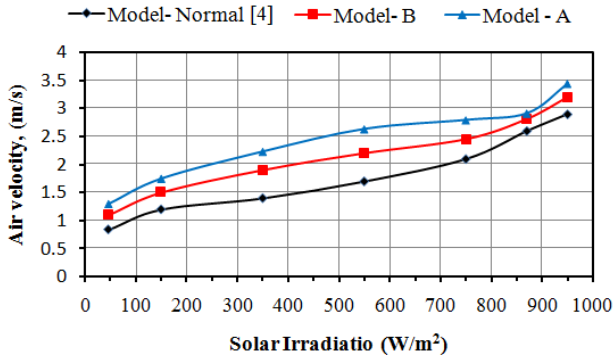


Fig.4: Cells selected for simulation models A and B.

## 4. Results and Discussion

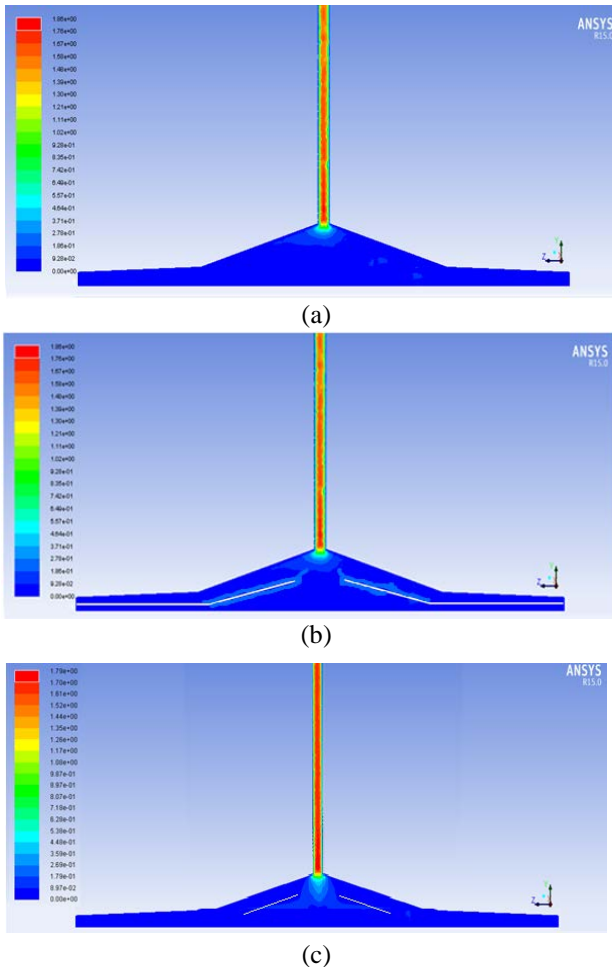
As discussed previously, three different operational models were processed numerical study, whereby Table 3 illustrated analyzed data.

The results of the three different cases of the proposed SUTPP has been explained and identified numerically in this section. normal design pertaining Case 1 is given by <sup>13)</sup> (single solar air heater with diameter 6 m). Case 2 is double skin solar air heater with diameter 6 m. Case 3 is double skin solar air heater with diameter 2.8 m, the operation performed at solar source for all cases in the daytime. The results of velocity were numerically predicted, and the presentation of solar intensity was ranging from 50 to 950W/m<sup>2</sup> with increment of 100W/m<sup>2</sup>. As can be seen in Fig.5, the maximum velocity values that found for the three cases named: normal, Model-B, and Model-A are 2.82, 3.18, and 3.36m/s, respectively, at 950W/m<sup>2</sup> solar radiation magnitude. These findings occurred at the base of the chimney.



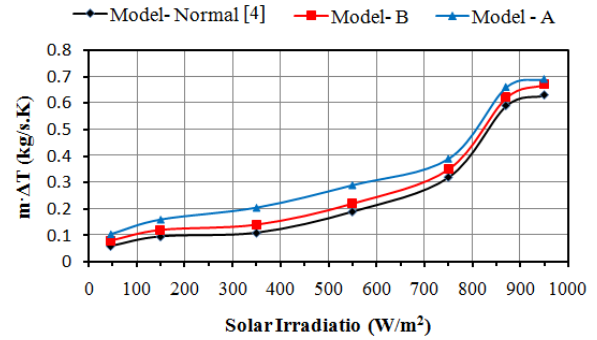
**Fig. 5:** Velocity of Air at the base of the chimney, for normal model, Model-B and Model-A.

Fig.6 shows the contour maps results of air velocity for different collector design when the solar irradiation at its maximum value. the conditions of the results presented is ranging from single skin solar air heater (normal model) to double skin solar air heater (Model-A and Model-B). The velocity of air at the base of chimney for Model-A has the highest value comparing to other models. This attribute to high internal energy of air in the double-skin solar air heater that having high thermal energy leading to buoyancy forces Stimulation.



**Fig. 6:** Velocity contours at daytime with solar intensity = 950 W/m²: (a) normal, (b) Model-A, and (c) Model-B.

The behavior of overall thermal property is explained the efficiency of SUTPP based on the (flow rate of the air mass multiply rising in air temperature [kg/s.K]). Fig. 7 shows that during the daytime hours, the double skin solar air heater having better results of thermal performance when the diameter is 6m. The improvement in this model is attributed to the increment in the energy that stored at daylight hours as a result of solar radiation explosion. whereby, continues increasing of the solar radiation is occur. Consequently, the collector's efficiency with double-skin air heater is enhanced when compare to the normal model<sup>13)</sup>, and Model-B, especially at the afternoons. The validation of simulation results with the literature review reported in Table 4.



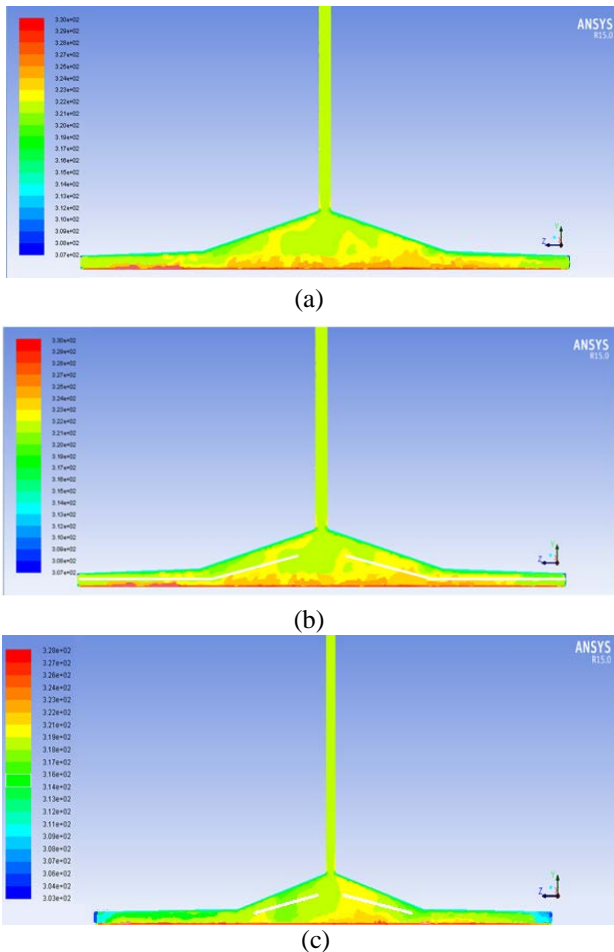
**Fig. 7:** The performance of SUTPP for the different models.

Table 4. The validation of simulation results for the performance of SUTPP.

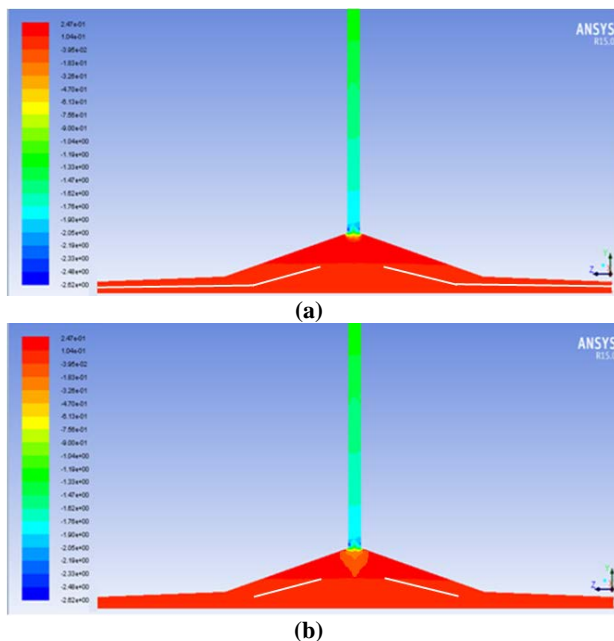
Refs		ΔT. (°C)	Percentage error (%)
Current work	Model-A	12.3	4.6%
	Model-B	11.4	6.3%
Rifat et al <sup>4)</sup> (normal model)		8.4	-
Wahhab and Al-Maliki <sup>8)</sup>		7.4	13.4%

Temperature contours is presented in Fig. 8 as resulted from the computational simulation of three models: (a) normal model<sup>10)</sup>, (b) Model-A, and (c) Model-B. At 950 W/m², the temperatures results are found to be approximately 51°C, 54°C, and 52.4°C for three models, respectively. At 1 Pm The rising of air temperature, are 17°C, 20°C, and 18.4°C. The increasing number of skin solar air heaters or the area of skin solar air heater in SUTPP increases the heating range of the internal air flow of the collector. this increment explained raising the kinetic energy as well as air temperature. pressure contours are shown in Fig. 9 as an outcome of the computational simulation of models: (a) Model-A, and (b) Model-B.





**Fig. 8:** Temperature contours for the SUTPP at daytime with solar intensity = 950 W/m<sup>2</sup>: (a) normal model, (b) Model-A, and (c) Model-B.



**Fig. 9:** Pressure contours for the SUTPP at daytime with solar intensity = 950 W/m<sup>2</sup>: (a) Model-A, and (b) Model-B.

## 5. Conclusions

A numerical modeling for a new structure of double-skin air solar heater is investigated in this study. An analytic solution was performed on three different collector design models. The simulation findings are in a good agreement with the previous published work in the same area. The results revealed that as the number of skin and area of solar air heater in the collector increases, the system performance enhances. The air velocity at the base of the chimney is increased as the number of skin solar air heater in collector increased due to the lower thermal losses to the environment. Also, the results of the simulation show temperatures variation of about 51°C, 54°C, and 52.4°C for three models, respectively. on the other hand, at 1 Pm the raising of air temperature, were found 17°C, 20°C, and 18.4°C.

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## Nomenclature

- $C_p$  - Specific heat of air (J/kg. K)  
 $V_{coll}$  - Air velocity at the collector (m/s)  
 $V_{coll-exit}$  - Air velocity at the collector exit (m/s)  
 $V_{air-ch}$  - Air velocity at the chimney (m/s)  
 $\dot{V}_{air-ch}$  - Air flow rate at the chimney (m<sup>3</sup>/s)  
 $p_{air-ch}$  - Pressure at the chimney (N/m<sup>2</sup>)  
 $r_{coll}$  - Radius of the collector (m)  
 $r_{ch}$  - Radius of the chimney (m)  
 $H_{g-c}$  - Height from collector ground to the canopy (m)



$H_{ch}$  - Height of the chimney (m)

$\rho_{air}$  - Air density (kg/m<sup>3</sup>)

$\rho_{air-coll}$  - Air density at the collector (kg/m<sup>3</sup>)

$\rho_{air-ch}$  - Air density at the chimney (kg/m<sup>3</sup>)

$\tau_{air-ch}$  - kinetic energy source term (N/m<sup>2</sup>)