NUMERICAL ASSESSMENT OF SOLAR UPDRAFT POWER PLANT INTEGRATED WITH EXTERNAL HEAT SOURCES

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ABSTRACT
The generation of electricity from solar energy is becoming a very exciting subject for numerous countries. However, despite the advantages of this type of energy source, the limited use of this source after sunset and at night is still a major challenge. In this study, a solar chimney model was selected as a system for generating electrical power. These types of plants remain interesting, especially in open areas far from cities. In this research, a numerical model has been proposed as a day and night functional solar system using waste heat or any external heat source to enhance the system performance and make it generate power for 24 hours. With the help of ANSYS Fluent software, the discrete ordinates radiation model was used to solve three-dimensional steady-state Navier-Stokes and energy equations in the cylindrical coordinate system. For the preliminary model, the results were validated using experimental measurements. Then the simulation was carried out on the proposed model with an external heat source by using thermal enhancing channels. Afterwards, the influence of the external heat source on the system performance was predicted and analysed. The simulation results showed that this system could enhance the plant during the day time and ensure its operation at night. The simulation showed a positive effect of the external heat source on solar chimney power plant efficiency by using the proposed model. Percentage enhancement was 6.5% and 13% for velocity and temperature respectively, in comparison with the preliminary model. Moreover, in this study, the power enhancement for the proposed system reached 37%.
Keywords: energy recapture, flue gas, hybrid energy system, SCPP, solar collector, thermal enhancing channels.

1 INTRODUCTION

Access to energy sources continues to represent the biggest challenge to human fears, especially after the increase of energy demand; therefore, human beings tried to diversify energy resources to dispel these apprehensions. Electrical power demand in the world still continues to increase. It is proposed that the use of traditional sources of energy to generate electricity cause many crises and problems for communities, especially in environmental pollution and global warming. The world’s electricity consumption and greenhouse gases (GHG) are increasing day by day from electricity generation; therefore, solar energy with its applications offers the best alternative sources of pollution-free energy and could play a leading role in future electricity demands. The solar chimney power plant (SCPP) system, in Fig. 1, is one of thermal solar systems which can be implemented in large-scale to generate electricity. This plant consists of four main components: canopy, ground (greenhouse), chimney and turbine (pressure gradient devices). The system can convert solar energy into thermal energy inside the collector and this energy is converted to kinetic energy inside the chimney. The kinetic energy of the air inside the collector rotates wind turbine which lies at the base of chimney. The turbine drives a generator to produce electricity. In 1903, for the first time, the Spanish colonel, Isidoro Cabanyes, introduced the idea of the updraft systems, which was later implemented by the Schlaich from Germany. Schlaich carried out the plant in Spain and he got support from the Spanish and German governments in an area called Manzanares, therefore, this plant was named as Manzanares power plant. Various researchers

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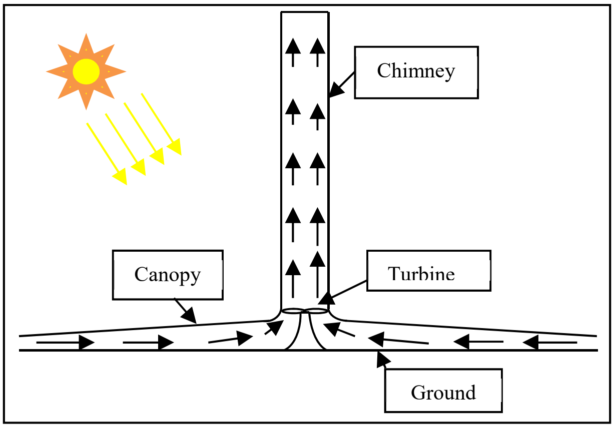

Figure 1: Schematic diagram of solar chimney power plant.

analysed the flow within the system numerically by using small-scale dimensions and fit the scale with Manzanares for validation, or large-scale dimensions to demonstrate the amount of electrical energy, which can be produced by this type of plants.

Ming et al. [1] executed numerical simulation for Manzanares power plant coupled with a turbine. Ming analysed the flow properties and focused on the influence of the turbine blade number on power output of the plant. Gholamalizadeh and Kim [2] also simulated and analysed three-dimensional flow for Manzanares power plant. In this simulation, the researchers focused on the effect of the greenhouse by using two-band radiation model; this study showed that the temperature and enthalpy for collector rise when the band radiation is considered, providing more accurate flow solutions to predict the characteristics of flow and heat transfer in the plant. Fasel et al. [3] investigated numerically by using ANSYS Fluent and developed CFD code the flow and heat transfer of the air inside the solar chimney power plant (SCPP). The researchers considered the Manzanares dimensions as a reference and then they used multi-scales by using cubic scaling as economic point of view. Ming et al. [4] also analysed the solar updraft power plant system numerically by using a proposed blockage to reduce the negative impact of wind speed on the performance of the SCPP. The researcher compared the use of proposed blockage for Manzanares dimensions plant with a normal one, and numerical results showed that the ambient crosswind effect is overcome especially when the crosswind velocity starts to increase greater than 5 m/s. A more comprehensive numerical analysis of the SCPP was conducted by Sangi et al. [5]. The researchers validated the CFD results with the experimental data of Manzanares as reported by Haaf et al. [6], and they mentioned that the maximum velocity value located at the base of the chimney and its value with temperature difference value furnished good agreement with Manzanares experimental data. Actually, many researchers analysed and investigated the flow characteristics inside SCPP. Some of them proposed modifications to the models to improve the performance of the plant and ensure the continuity of its work for the span of 24 hours, especially during the night, and this is one of the problems and obstacles for this type of plants. Al-Kayiem et al. [7] suggested the possibility of benefiting from thermal sources to support these types of power plants and make them work during night time, they also noted the possibility of using flue gases, which contains 50% of the fuel thermal energy as a waste heat. Chikere et al. [8] proposed a model to enhance heat transfer and the performance of the SCPP by using flue gas waste heat. The new model contains a flue gas channel, air exit chimney, absorber plates, greenhouse air flow channel that is restricted by the transparent cover at the bottom and the top of the absorber plate and flue gas exit chimney. Also, Dhahri and Orfi [9] used a coil of hot water tube as a spiral heat exchanger on the ground of the collector to enhance and improve the SCPP overnight. This numerical study was conducted using CFD software Fluent.

The main objective of this research study is to introduce a proposal model to improve the performance of SCPP and ensure the continuity of its work for 24 hours a day throughout a week. Furthermore, the aim of this research is to study and numerically analyse the physical properties and heat transfer of air flow inside the collector and chimney to show the enhanced performance of the system with the help of the proposed model and solve the weakness in the plant after using an external heat source.

2 PROPOSED MODEL DESCRIPTION

This research study presents a hybrid solar chimney power plant as a proposed model, shown in Fig. 2. This model would not only increase the efficiency of power plant during the day, but it would also provide power even when there is no sunlight or at night time. The technique in this model utilises the flue gases or exhaust gases from a nearby gas turbine power plant or any external waste heat source and convert the waste thermal energy in these flues or exhausts to thermal energy in the SCPP, considering a new form of waste heat energy recapture that is a perfect exploitation way. Thus, it is an ideal way to reduce global warming. In this way, the thermal energy of the air flow is increased in the solar collector of the plant by using hollow rectangular channels, known as Thermal Enhancing Channels (TECh), situated below the collector cover. The installation and distribution of these channels depend on the equal division of the circular collector (360 degrees) by the number of channels. The exhaust or flue gases are pushed through the channels by pipe holes and the gases passing through the channels cause heat transfer from walls of the channels to the air flowing below the collector (greenhouse). This phenomenon indicates that the air receives more kinetic energy in addition to that obtained from solar radiation, which in turn increases the temperature of air in an outlet collector, resulting in the enhanced performance of the plant.

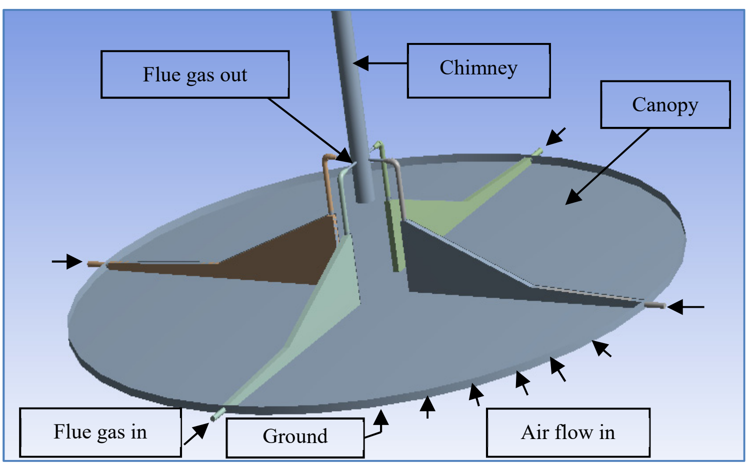

Figure 2: Schematic diagram of proposed model.

At the same time, this heat source helps the plant to operate at night. After that, the gases emerging from the channels enter the chimney and increase the updraft of the exit air flow from the chimney. Thus, this system enhances the two main parts of the plant, the collector and the chimney, making them hybrid collector and hybrid chimney. Hence, the plant is known as Hybrid Solar Chimney Power Plant (HSCPP).

3 NUMERICAL SOLUTION

The fluid motion inside the model is solved through the conservation equation of mass, momentum and energy (governing equations). According to the Fluent User Guide [10], the basic equations can be expressed in tensor form as given below.

Continuity equation:

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho.\vec{v}) = 0. \tag{1}$$

Momentum equation:

$$\frac{\partial}{\partial t}(\rho.\vec{v}) + \nabla.(\rho.\vec{v}.\vec{v}) = -\nabla p + \nabla.\left(\mu\left[(\nabla\vec{v} + \nabla\vec{v}\,T) - \frac{2}{3}\nabla.\vec{v}I\right]\right) + \rho\vec{g}. \tag{2}$$

In eqn (3) the Boussinesq model is used by setting up the problem with fluid density as a function of temperature. This model treats density as a constant value in all solved equations, except for the buoyancy term in the momentum equation:

$$(\rho - \rho_\circ)g \approx -\rho_\circ\beta(T - T_\circ)g$$

$$(\rho) = \rho_\circ(1 - \beta\Delta T). \tag{3}$$

Eqn (3) is valid when $(1 - \beta\Delta T) \ll 1$

Energy equation:

$$\frac{\partial}{\partial t}(\rho.E) + \nabla.(\vec{v}(\rho E + p)) = -\nabla.\left(k_{eff}\nabla T - h\vec{J} + \left(\mu\left[(\nabla\vec{v} + \nabla\vec{v}T) - \frac{2}{3}\nabla.\vec{v}I\right].\vec{v}\right)\right) + S_h. \tag{4}$$

This model accounts for the full bouncy effect, where the density varies with temperature, and the flow can be motivated by force of gravity which influences the change in density.

In eqn (4), S_h represents the heat source of the solar radiation. The radiation transfer equation was solved by Discrete Ordinates (DO) model. This model is one of the radiation models which solved the radiation equation by ANSYS Fluent. The DO model solves surface to surface radiation problems and radiation through semi-transparent materials like glass or Perspex.

The radiation equation solved by the software can be written as:

$$\nabla.(I_\lambda(\vec{r},\vec{s})\vec{s}) + (a_\lambda + \sigma_s)I_\lambda(\vec{r},\vec{s}) = a_\lambda n^2 I_{b\lambda} + \frac{\sigma_s}{4\pi}\int_0^{4\pi} I_\lambda(\vec{r},\vec{s})\varphi(\vec{s}.\vec{s}')d\Omega'. \tag{5}$$

The solar intensity in each direction $\vec{s}$ and position $\vec{r}$ can be written as follows:

$$I_\lambda(\vec{r},\vec{s}) = \sum_k I_\lambda(\vec{r},\vec{s})\Delta\lambda_k. \tag{6}$$

In eqn (6), the summation represents all wavelength bands. In this study, the canopy material was Perspex and assumed all the Perspex had the same behaviour for all wavelength bands.

4 BOUNDARY CONDITIONS AND DIMENSIONS

First, the eqns (1)–(6) were solved numerically with preliminary model geometry which were implemented in solar research site (SRS) at University Technology PETRONAS as shown in Fig. 3; the dimensions of the model are given in Table 1 and the experimentally measured

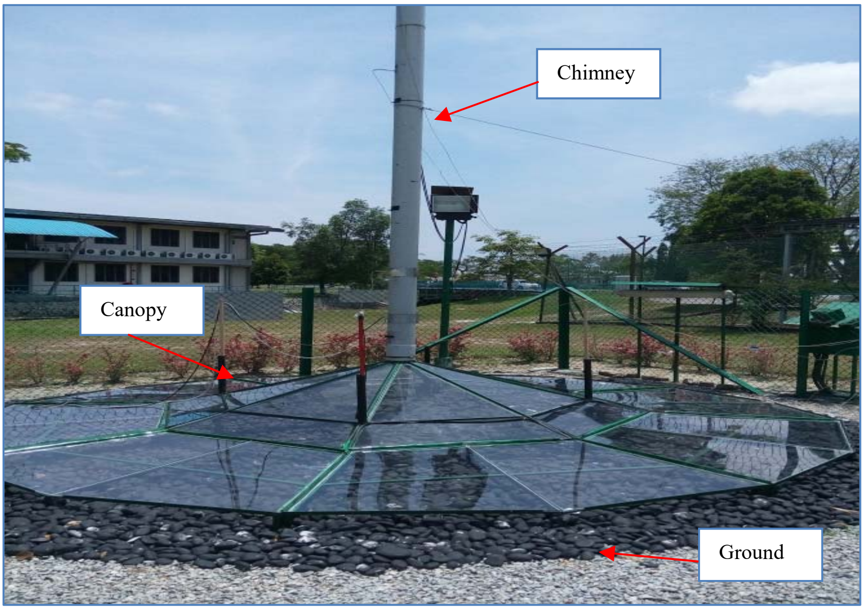

Figure 3: Solar chimney preliminary model.

boundary conditions are presented in Table 2. The value of solar radiation was 1000 W/m^2 according to the experimental data which specified the maximum solar intensity value at 2:00 PM in June 2015. Also, the geometry was tested with no load (without turbine).

Physical properties of the materials employed in the simulation are given in Table 3. A 3D and steady state flow with second-order upwind discretization and pressure-based coupled algorithm were used as a solver in CFD simulation.

Grid independency is considered in the solution; five mesh sizes were used. Tetrahedral cell sizes ranged between 0.1 m to 0.01 m were tested and mesh sizing (maximum size 0.03 m and minimum size 0.001 m) were used to get the solution for hybrid proposed model as shown in Fig. 4.

The comparison of the numerical solution with experimental readings was carried out for the preliminary model, and then the model was tested numerically by simulation after adding thermal enhancing channels by external heat source as a proposed model.

Table 1: Dimensions of the preliminary model.

Parameter	*Dimension(m)*
Collector radius	5
Collector height at inlet	0.05
Collector height at outlet	0.65
Chimney height	6.5
Chimney radius	0.075

Table 2: Boundary conditions from experimental preliminary model.

Place	*Type*	*Value*
Ground	Wall	330 K
Canopy	Semi-transparent wall	T_{canopy} = 309 k
Chimney	Wall	Adiabatic
Collector inlet	Pressure inlet	P_{gage} = 0, T_a = 307 k
Chimney outlet	Pressure outlet	P_{gage} = 0, T_a = 307 k

Table 3: Properties of materials used in simulation.

Physical property	*Perspex*	*Ground (black pebble)*	*Chimney (PVC)*
Absorption coefficient	0.06	0.9	0.04
Transmission coefficient	0.92	0	0
Density ρ (kg/m^3)	2700	2640	833
Specific heat (J/kg.k)	840	820	1170
Thermal conductivity (w.m/k)	0.78	1.73	0.19
Emissivity	0.9	0.9	0.91

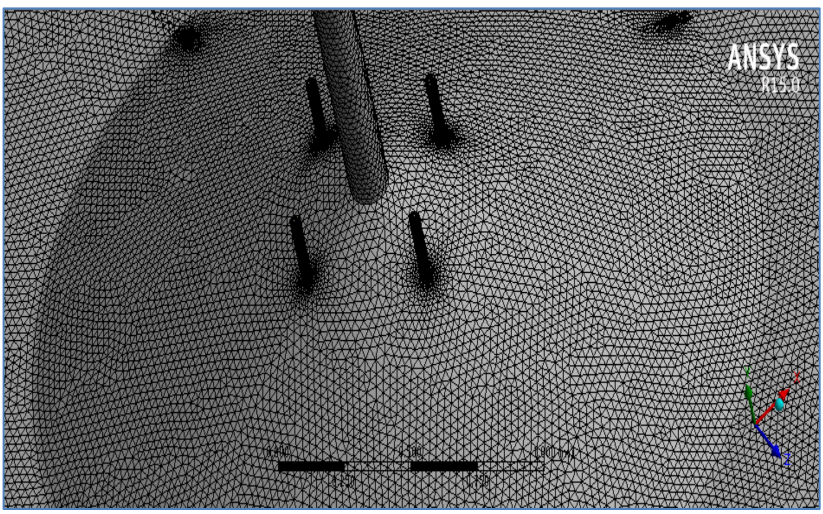

Figure 4: Mesh independency for proposed model.

5 RESULTS AND DISCUSSION

Velocity and temperature contour maps were considered based on simulation results with no load condition and solar intensity of 1000 W/m^2. The flow inside the model was laminar. For all wavelength bands of the Perspex cover, it could be observed that by simulation, the maximum velocity was observed at the base of the chimney and the temperature distributions increased when the solar insolation increased. Furthermore, the increase of solar intensity raised the temperature of storage media (pebble) inside the collector. Maximum temperature and velocity in simulation for preliminary model were in good agreement with the experimental readings depicting logical and reasonable error ratio as shown in Table. 4. The maximum velocity of the convenience preliminary model was 1.95 m/s and the temperature was 318 K ($\Delta T = 11°C$).

Proposed model was solved numerically by considering insulated wall boundary conditions for channels and same boundary conditions (BCs) in Table 2. The outcome depicts that the maximum velocity increased to 2.3 m/s that is corroborated with the reduction in outflow cross section area of the collector. The maximum temperature remained the same as in the previous case; these channels reduced the influence of wind speed as also reported by Ming et al. [4]. Subsequently, the proposed model was solved numerically using interface boundary conditions between the channel walls and air inside the collector in order to get a more accurate solution and to simulate the heat transfer problem close to reality. Same boundary conditions are given in Table 2 with the addition of channels and assumed external heat source as flue gas with 2 m/s and 100°C of channels inlet velocity and temperature respectively. Figs 5 and 6 illustrate the temperature and velocity distribution for the proposed model with interface B.Cs. The results show that the enhancement velocity and temperature for the working fluid of the model were 6.5% ($v = 2.46$ m/s) and 13% ($T = 325$ K, $\Delta T = 18°C$) respectively with no load as compared to the insulated channels case.

Moreover, in this research study, the proposed model was tested in night mode. The night operation mode showed that the proposed model was operated with maximum velocity (1.16 m/s) and maximum temperature (307 K) as shown in Figs 7 and 8. These values explain that the proposed model could produce 20% of the power generated in the daytime.

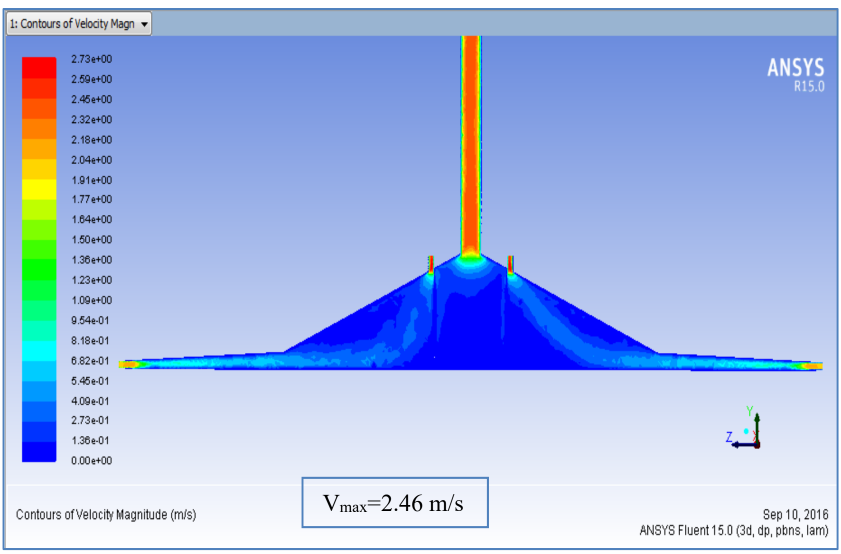

Figure 5: Velocity distribution for the proposed model.

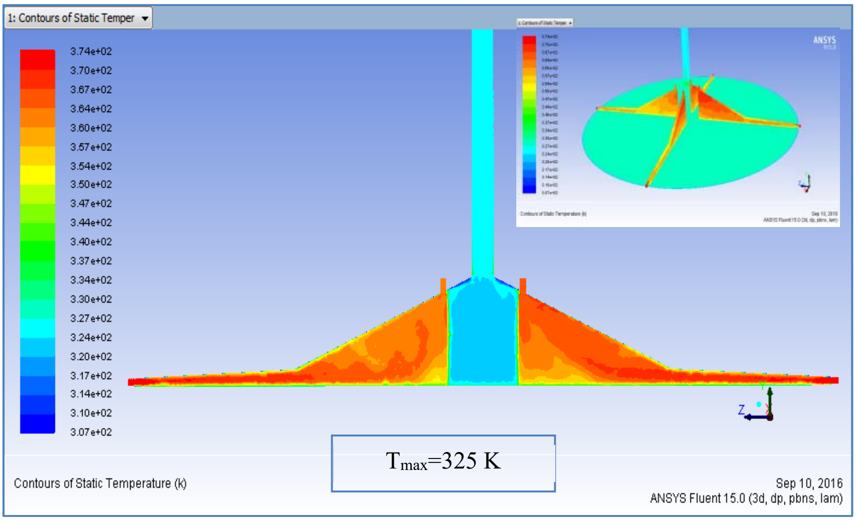

Figure 6: Temperature distribution for the proposed model.

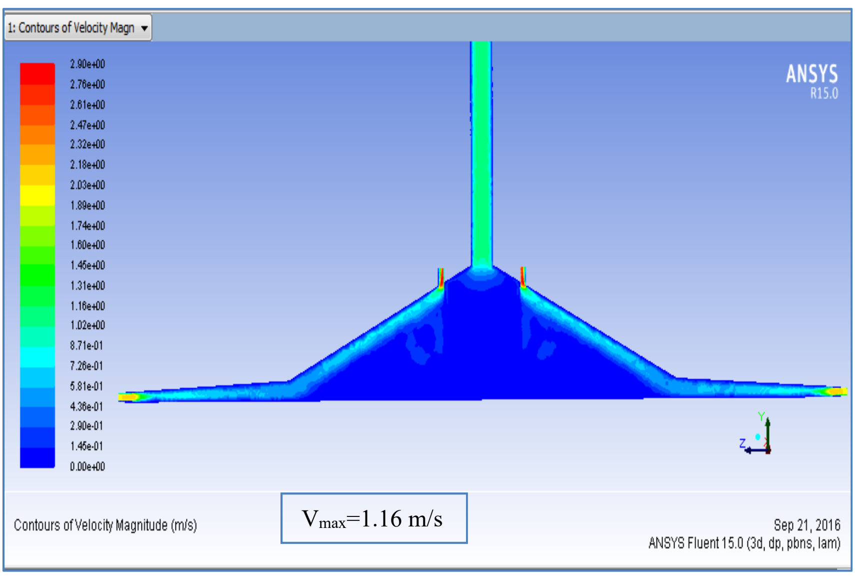

Figure 7: Updraft velocity distribution for the proposed model (night mode).

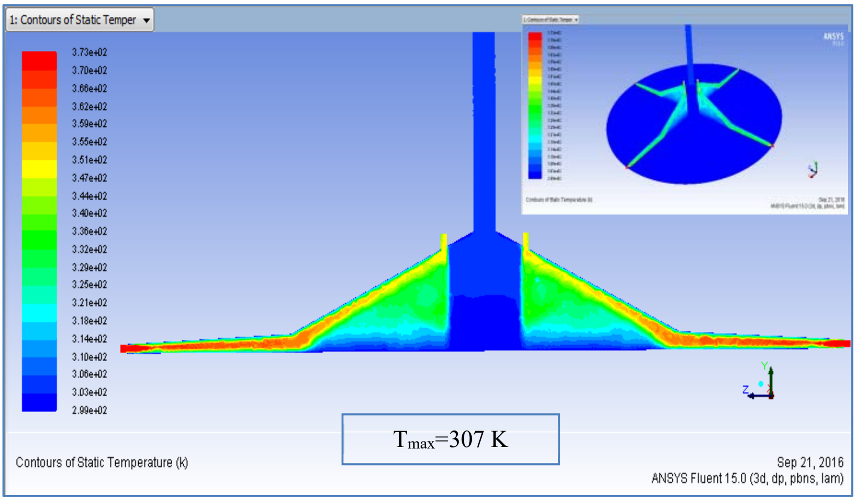

Figure 8: Temperature distribution for the proposed model (night mode).

The performance of the plant (collector efficiency and output power) was calculated according to Schlaich [11]. Table 4 shows the enhancement of the proposed model to the conventional one for velocity, temperature and performance.

Table 4: Experimental readings and simulation results.

Model	*Max. velocity (m/s)*	*Temp. Diff ΔT (K)*	*Collector thermal efficiency (%)*	*Power output (w)*
Preliminary model (experimental readings)	1.87	9.5	2	0.042
Preliminary model (simulation solution)	1.95	11	2.3	0.054
Proposed model (insula-ted channels)	2.3	11.5	2.9	0.063
Proposed model (interface B.Cs)	2.46	18	4.86	0.1
Proposed model (interface B.Cs at night)	1.16	7	64	0.02
Percentage of enhancement (%)	6.5	12.5	40	37

6 CONCLUSIONS

The simulation of the preliminary model showed good agreement with the experimental model measurements which were carried out in Solar Research Centre (SRC). In this study, the numerical results disclose that the proposed added heat source model has a momentous impact on the characteristics of the flow and system performance. The velocity and temperature percentage enhancement were 6.5% and 13% respectively. It can be concluded that there is a possibility to use the proposed model relying on solar energy with an external heat source to produce electricity 24 hours.

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