Indian Journal of Engineering & Materials Sciences
Vol. 27, August 2020, pp. 837-843

# Computational investigation of solar updraft tower for power generation in sultanate of Oman

Afzal Husain[a*], Mohammad Zunaid[b*], Mohammed AL Brashdi[a], Fahad Al Maqbali[a], Emad Al-Jabri[a]& Abdulmonem Al-Mahrizi[a]

[a]Department of Mechanical and Industrial Engineering, Sultan Qaboos University, Muscat, PC-123, Oman

[b]Department of Mechanical Engineering, Delhi Technological University, Delhi, 110 042, India

*Received: 26 May 2020*

The current study is aimed at harnessing solar power through solar updraft tower (SUT) and explored the local environmental factors conducive to SUT installation. The SUT collects solar insolation to raise the air velocity, which is then allowed to pass through a ducted turbine. An alternator is installed with the air turbine to generate electricity. The study presents a performance analysis of SUT based on local thermal radiation and wind velocity. Three-dimensional numerical modelling of SUT is carried using computational fluid dynamics (CFD) solver. The model is validated with the experimental results available in the open literature. The collector temperature profile obtained through CFD modelling matches well with the experimental results. A maximum temperature rise of 20 ºC was ob-served in the collector modelled and solved numerically using CFD solver. The air velocity increases as the flow move from the collector periphery to the center of the SUT and reach to its maximum just before the center of the SUT. However, for the chimney, the temperature was observed to be increased continuously due to its continuous heating through the chimney walls, which receives solar radiation. The performance of SUT is examined with the change in inlet air velocity based on the local conditions in the Sultanate of Oman.

**Keywords:** Solar updraft tower, Computational fluid dynamics, Renewable energy, Solar collector, Solar chimney, Pressure drop, Power generation

## 1 Introduction

The rising scale of global warming and depleting fossil fuels have encouraged researchers to explore conventional and unconventional energy-saving techniques and develop renewable energy harnessing methods. The abundance of several forms of renewable energy such as geothermal, tidal, solar and wind, which is available freely in the environment, has motivated the scientific and engineering community to harness its potential. The Solar Updraft tower (SUT) is one of the techniques, which utilizes solar irradiation to heat and move the air inside the collector space towards the chimney placed in the middle to run the turbine and consequently generate electric power.

Hanns Gunther first introduced the concept of SUT power generation in 1931[1]; however, it took almost half a century to realize that concept, and it took a form of a prototype in 1982 in Manzanares, Spain, with an installed capacity of approx. 50 MW[2]. The development of SUT was dawdling in the beginning decades, and only a few studies were contributed. Haaf *et al.*[2] discussed the details of the first SUT pilot power plant with economic considerations. The SUT consists of several components, *i.e.* collector, absorber, chimney, and a turbine. The collector traps the solar irradiation and the air flowing inside the collector is heated up and moves towards the chimney as a result of buoyant forces developed due to the temperature gradient. Consequently, the air passes over the turbine, which is located at the base of the chimney and rotates it to produce electric power with the help of a generator. Further, the heating capacity of flowing air is increased by installing a heat storage material that can provide energy even when there is no sun to heat the air[3]. Absorber stores the solar radiation at the time of the sun and releases stored energy when there is no sun. The main constraint towards the realization and commercial usage of SUT technology is its lower efficiency. Several materials are proposed to be used as storage material; however, the water-filled black coated tubes at the base of the SUT is one of the cheapest storage methods which can be used to enhance the SUT efficiency and adaptability[3].

---

*Corresponding author (E-mail: mzunaid3k@gmail.com)

Several studies are devoted to realize the concept and evaluate performance characteristics of SUT. Zhou *et al.*[4] experimented on a pilot SUT system, having a collector of 10 m diameter. The collector is placed at a certain angle to maximize efficiency. The setup produced a power of 5 W with a temperature difference in the ambient and the air at the outlet of the collector of about 24 $^{o}$C that generated a driving force and a velocity of about 2 m/s in the chimney. Kasaeian *et al.*[5] conducted an experimental study of SUT with 12 m chimney height and 10 m collector diameter. The maximum air velocity achieved was 2.9 m/s, and the maximum temperature rise was 25 $^{o}$C.

Ghalamchi *et al.*[6] carried out an experimental study on a pilot SUT with a 2 m chimney height and 3 m collector diameter. The maximum temperature rise obtained was 26.3$^{o}$C, and the performance was unchanged with the change of collector slope given the small collector diameter, and chimney height explored in this study. Balijepalli *et al.*[7] carried out a performance investigation of a prototype for power output while discussing the various collector and heat storage materials. Further, authors[8] reported the design details and performance of a pilot SUT power plant and theoretically calculated the chimney and overall efficiencies of the setup.

The environmental conditions such as wind speed and direction, dirt, dust and sand storms play a significant role in structural stability, efficient operation and sustainability of the SUT system. Harte *et al.*[9] discussed the structural and sustainability aspects of the SUT system. The authors highlighted the impacts of environmental conditions such as wind speed, dust and dirt, and load carrying capabilities of SUT on the system performance. Further, the author discussed the material selection given thermal stresses, pressure losses, and stresses on the structure. Jafarifar *et al.*[10] investigated the effect of strong crosswind on SUT prediction. They carried out a theoretical comparison of two locations, one with intense solar irradiation and others with mild solar radiation but strong wind. Authors observed that the SUT at strong crosswind location provided up to 70% of the power produced by the SUT located at an intense solar irradiation region[11].

Several design parameters play a significant role in defining system performance and overall efficiency[12]. A lot of effort has been made to comprehend the influence of the SUT design parameters, i.e., inlet height, collector slope and diameter, chimney diameter, height and profile. In a computational study, Patel *et al.*[13] studied the effects of collector diameter, inlet and outlet openings, chimney diameter, height, and inlet opening on the SUT performance and proposed optimal configuration in dimensional form. Ghalamchi *et al.*[14] carried out parametric performance optimization for the pilot prototype.

Lal *et al.*[15] conducted experimental and CFD studies on a lab-scale SUT power system and demonstrated flow and thermal characteristics. The authors discussed energy and exergy efficiency and demonstrated the regression model for the influence of solar insolation, inlet temperature, and chimney height on performance. Cottam *et al.*[16] presented an analytical approach to model SUT with different solar collector canopy profiles and observed that the collector height had an impact on power generation to some extent and beyond that, the power generation became independent to collector shape. A segmented collector profile showed almost similar performance as that of exponential pattern and required less maintenance and construction cost.

The effective management of renewable energy is inevitable to realize the potential of solar energy[17,18]. Further, efforts have been made to enhance the efficiency of the SUT system. In a quest to improve the efficiency of the SUT system, Das and Chandramohan[19] carried out a numerical study on a scaled model to investigate the effects of dimensional design parameters such as chimney base, collector roof angle and observed an improvement in air velocity, overall flow rate and temperature profile. The authors found a decrease in efficiency with an increase in collector diameter from 3.5 m to 12 m. Eryener *et al.*[20] investigated a SUT prototype using transpired solar collectors. The transpired portion of the collector was designed to facilitate direct heating of air while the glass collectors first heatup the ground before they heat up the air in the vicinity. About 80% of solar insolation is converted into heat energy, which consequently increases collector efficiency up to 80% with a rise of temperature by 16 $^{o}$C in the collector area. The author observed a three-fold increase in collector efficiency as compared to the glazed collector.

The baffles inside the collector space play an important role in guiding the flow and enhance heat transport from the heat absorber at the base to the air. Lee *et al.*[21] conducted a computational investigation to find out the effects of height and width of baffles and the influence of adiabatic and heat transfer baffles. Although baffles interfere main flow in the collector space, they enhance the heat transfer rate from the collector base to the air. Kayiem *et al.*[22] proposed a hybrid technique to provide continuous power generation by utilizing an external heat source to complement solar energy at the time of no sun. The authors suggested a collector design with flue-gas channels that carry hot gases from an external source and run from collector inlet to chimney inlet. The hybrid design showed an efficiency enhancement of approximately 7 %.

The above literature review shows that the power generated by SUT is directly related to the solar irradiation, collector diameter, and inlet size, chimney diameter, profile and height, heat absorber and collector flow manipulators. The present study demonstrated thermal and flow characteristics for SUT, power generation. A three-dimensional numerical model is developed and validated with the experimental results, and performance characteristics are obtained.

## 2 SUT design and numerical modeling

The schematic with components of the SUT considered in the present study was shown in Fig. 1. The geometry of SUT was generated in SOLIDWORK[23], while meshing and model set up were performed in ANSYS CFX[24]. The air enters through the circumferential inlet, heated up on its way to the middle of the collector and reaches to the chimney. The heated air transfers energy to the ducted turbine and leaves through the stack.

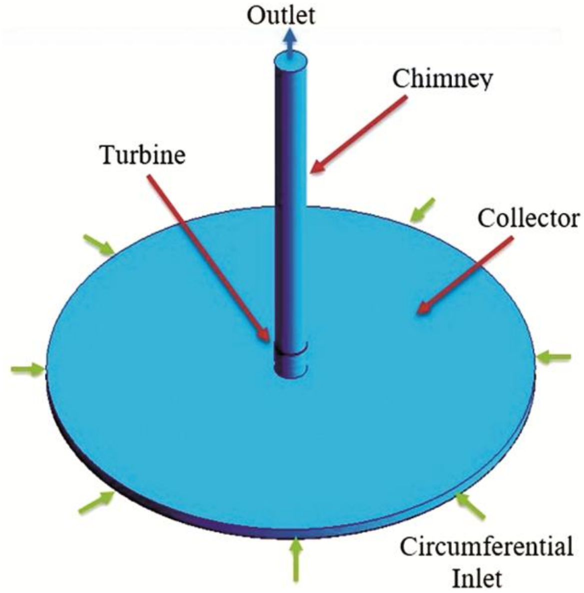

Fig. 1 — Schematic and components of a parallel plate SUT.

A structured mesh was generated for collector and chimney; however, a high-density tetra mesh was filled in the turbine zone. An inflation layer was used to accommodate gradients near the walls. The details of the computational grid structure used in the present study are shown in Fig. 2.

The air density inside the collector changes significantly due to the change in air temperature, which is modelled using Boussinesq approximation for buoyancy-driven flow in a closed domain. A four-bladed wind turbine, FX W-151-A is inserted at the inlet of the chimney to mimic the SUT power generation. The SUT is modelled using ANSYS CFX[24] for low-velocity turbulent flow using k-ε turbulence

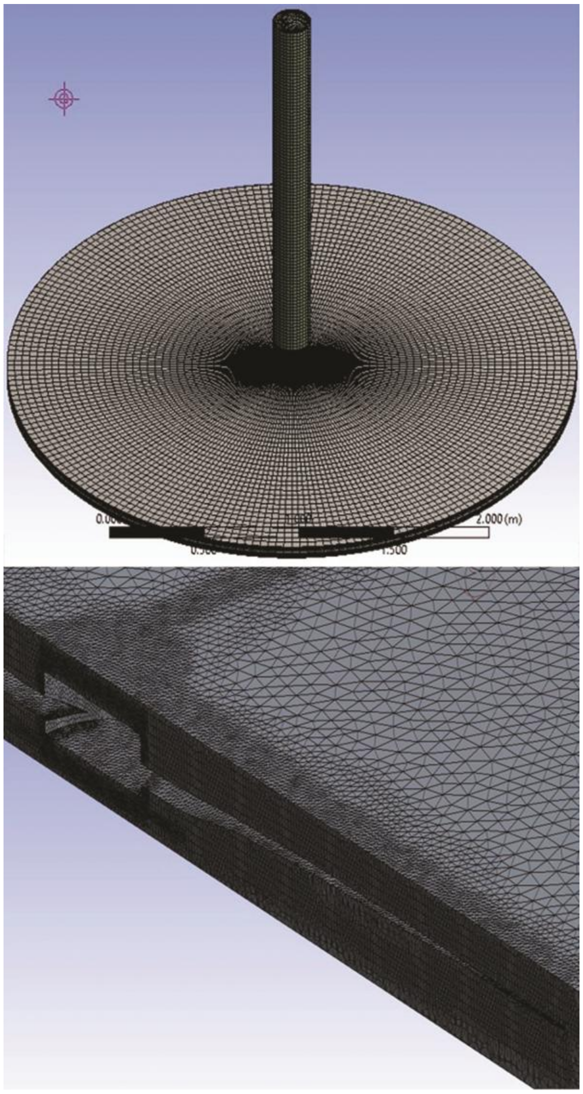

Fig. 2 — Details of the computational domain and mesh structure; (a) SUT, and (b) Turbine zone.

closure. The following are the model equations solved by the solver to mimic the SUT flow field:

Continuity equation:

$$\frac{\partial}{\partial \chi_i}(\rho u_i) = 0 \qquad \ldots (1)$$

Momentum equation:

$$\frac{\partial}{\partial x_j}\left(\rho u_i u_j\right) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \right.\right.$$

*23δij∂ul∂xl+∂∂xj−ρui'uj'+ρg* … (2)

The pressure drop is obtained from the solver across the turbine which is used to calculate power generation.

A grid test was carried out to obtain grid-independent solutions for the SUT. The number of elements and nodes changes in a sequence from low to high and the performance parameters were noted to optimize the chosen grid for further analysis that minimizes the time and resources consumed. The velocity and temperature are obtained through the numerical model along the line from inlet to the center of the SUT.

Figure 3 shows the results of the grid test for a typical SUT with a chimney height of 2 m and a collector diameter of 3 m. In view of the local flux density, a heat flux of 850 W/m$^2$K is applied at the top of the collector surface, and the inlet temperature is set as 298 K. The velocity at the ground level is set as 1.0 m/s, however, due to the small height of the entrance, the effect of atmospheric boundary layer has been ignored, and a uniform velocity is assigned at the inlet. The velocity and temperature of air are increased as the air moves from the inlet towards the center of the tower and it is decreased as the air reaches close to the center. There are some changes in velocity and temperature distribution for a change of mesh from 1 million to 2.2 million nodes; however, these changes are insignificant for an increase in mesh from 2.2 million to 3.4 million nodes. Therefore a mesh with a total of about 2.2 million nodes is adapted for further study.

## 3 Results

The validation of the SUT numerical model was carried out for temperature distribution in the collector without operating an air turbine within it. The varying rate of heat flux was applied, and temperature and velocity distributions were noted at a constant inlet velocity of 0.056 m/s. The comparison of temperature distribution was made with the experimental results of Ghalamchi *et al.*[14] as shown in Fig. 4. The two distributions match reasonably well for the range of heat flux (350 to 850 W/m$^2$K) investigated in this study.

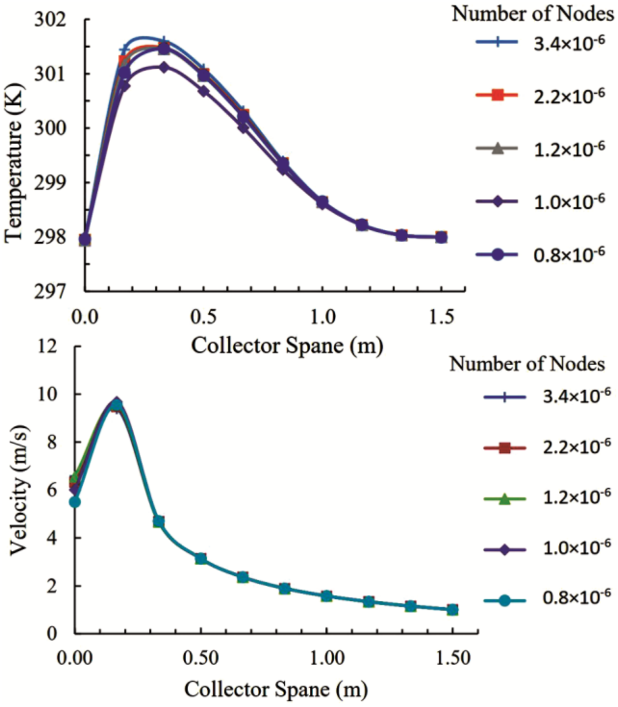

Fig. 3— Temperature and velocity distribution along a line from inlet to centre of SUT.

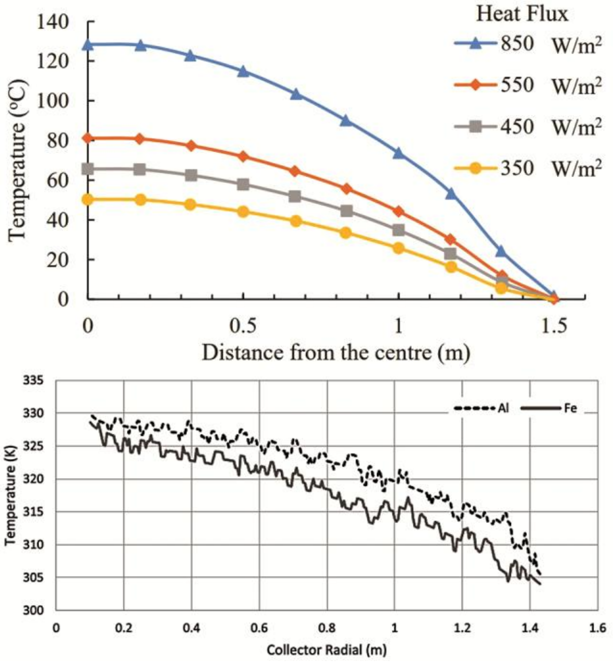

Fig. 4 — Comparison of temperature variation in the collector between current model prediction and the experimental results[14].

### 3.1 Parametric study

The performance of the SUT was investigated over a range of inlet air velocity (0.722 m/s to 1.0 m/s) under the constant heat flux applied at the collector. The effect of the inlet air velocity was investigated on velocity and temperature distribution in the collector space, the pressure drop and power developed by the turbine placed at the foot of the chimney.

Figure 5 shows temperature and velocity distributions at the middle plane of the SUT. The low temperature and velocity regions can be seen at the inlet, and high temperature and velocity regions can be seen near the turbine region in the middle of the SUT and in the chimney downstream of the turbine. The temperature and velocity are increased as the air moves towards the center due to the solar heating in the collector and further in the chimney.

The buoyancy-driven airflow velocity is a function of temperature which necessitates the investigation of temperature and velocity rise in SUT. Several cases were investigated for changing inlet air velocity to predict an increase in temperature and velocity at the inlet to the turbine. The air velocity near the ground is relatively small due to the atmospheric boundary layer and is varied from 0.07 m/s to 1 m/s for computations. The study is focused on investigating temperature and velocity rise and distribution, the turbine pressure drop and the power output.

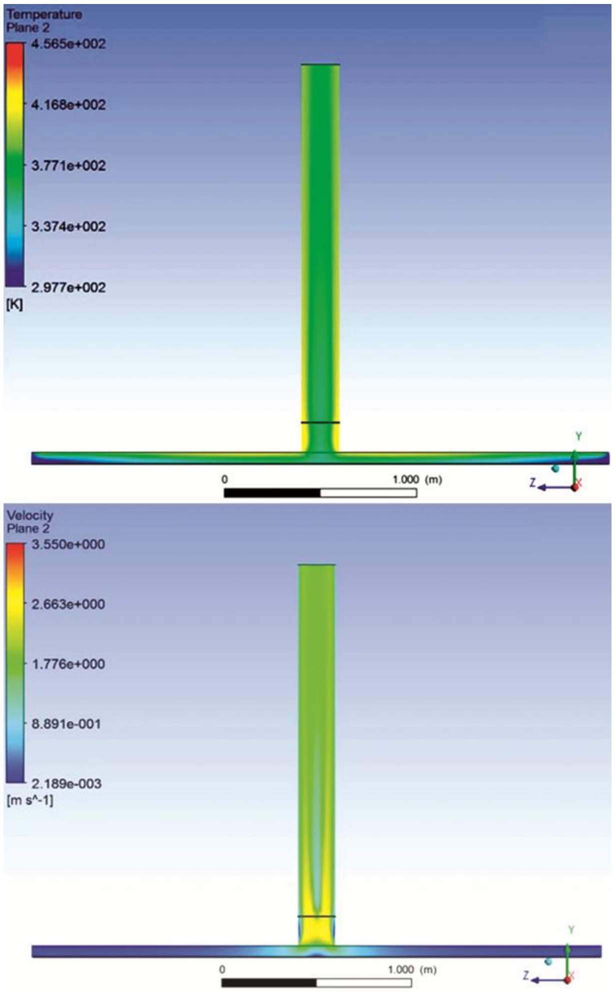

Fig. 5 — (a) Temperature and (b) Velocity, distributions at the middle plane in SUT.

Figure 6 shows temperature and velocity characteristics on a line radially drawn at the middle height of the collector space form inlet to the middle of the SUT. As the air enters the SUT, its temperature and velocity are increased monotonously due to the heat received through the collector surface until it reaches near the center where it encounters the stagnation of the circumferentially incoming flow. The heated air enters the SUT from all radial directions and meets at the center of the SUT. The stagnation is formed due to the radially incoming flow at the center of the SUT, as shown in Fig. 5. The temperature and velocity are reached to the respective maximum values just before arriving at the center. The temperature and velocity decrease at the center due to the stagnation effects.

Further, higher temperature and velocity were achieved for low inlet velocity, and the temperature and velocity are increased with the increase in inlet velocity.

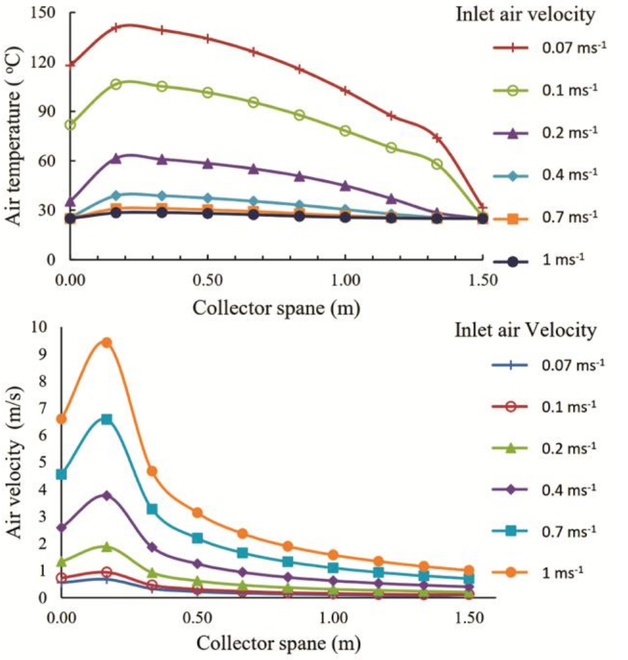

Fig. 6 — (a) Temperature and (b) Velocity, rise in the collector for a range of inlet velocity.

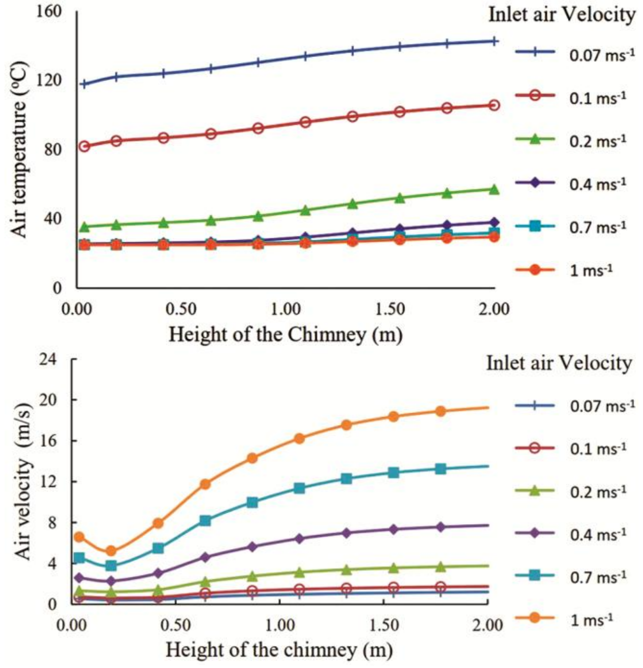

Fig. 7 — (a) Temperature and (b) Velocity, rise in the chimney for a range of inlet velocity.

Table 1 — Parametric performance using computational fluid dynamic model.

| Inlet air velocity (m/s) | 0.07 | 0.1 | 0.2 | 0.4 | 0.7 | 1.0 |
|---|---|---|---|---|---|---|
| $\Delta p_{tur}$ (Pa) | 0.34 | 0.7 | 2.92 | 11.83 | 36.31 | 74.17 |
| Power (W) | 0.003 | 0.01 | 0.081 | 0.604 | 3.13 | 8.886 |

The temperature and velocity distribution were further investigated for the flow through the chimney, as shown in Fig. 7 for several inlet velocities. The temperature in the chimney is increased monotonously along with the height from the turbine downstream to chimney exit since the air is heated through the chimney walls, which is open to solar radiation. However, velocity is decreased as the flow passes through the turbine and it is increased further monotonously after passing through the turbine until it is reached to the chimney exit. The maximum temperature and velocity rise are achieved at low inlet air velocity due to the higher resident time for air in the collector space while passing through the collector and chimney.

The performance parameters were calculated at inlet velocity varying from 0.07 m/s to 1.0 m/s and presented in Table 1. The pressure difference was calculated across the turbine ($\Delta p_{tur}$) in the SUT. The output power was calculated using the pressure difference and flow rate across the turbine.

## 4 Conclusions

The current study presented a numerical modelling and performance analysis of a solar updraft tower (SUT). A computational model is setup for steady, incompressible turbulent flow using three-dimensional RANS analysis with the k-ε turbulence closure model. The variation of density is modelled using Boussinesq approximation. The validation of the CFD model predicted results show reasonable qualitative agreement with the experimental results available on SUT in the open literature. Further, the study casts a light on the effects of inlet air velocity on temperature and velocity rise and distribution in the SUT. The pressure drop across the turbine and the estimated power conversion by the SUT are calculated. The air velocity and temperature in the collector and chimney are increased from inlet to the middle of SUT and from the centre of the collector to the chimney exit. The pressure drop and power generation in SUT are enhanced with an increase in inlet air velocity.

## References

1 Ghalamchi M, Kasaeian A & Ghalamchi M, *Renew Sustain Energy Rev*, 43 (2015) 425.
2 Haaf W, Friedrich K, Mayr G & Schlaich J, *Int J Sol Energy*, 2 (1983) 3.
3 Schlaich J, Bergermann R, Schiel W & Weinrebe G, *J Sol Energy Eng*, 127 (2005) 117.
4 Zhou X, Yang J, Xiao B & Hou G, *Appl Therm Eng*, 27 (2007) 2044.
5 Kasaeian A B, Heidari E & Vatan S N, *Renew Sustain Energy Rev*, 15 (2011) 5202.
6 Ghalamchi M, Kasaeian A & Ghalamchi M, *Renew Sustain Energy Rev*, 43 (2015) 425.
7 Balijepalli R, Chandramohan V P& Kirankumar K, *Energy Convers Manag*, 150 (2017) 451.
8 Balijepalli R, Chandramohan V P & Kirankumar K, *Heat Transf Eng*, 41 (2020) 562.
9 Harte R, Höffer R, Krätzig W B, Mark P & Niemann H J, *Eng Struct*, 56 (2013) 1698.
10 Jafarifar N, Behzadi M M & Yaghini M, *Renew Energy*, 136 (2019) 937.
11 Pretorius J P& Kröger D G, *J Sol Energy Eng*, 128 (2006) 302.
12 Sanalkumaran Nair V & Prabhakaran Nayar S R, *Indian J Radio Sp Phys*, 38 (2009) 134.
13 Patel S K, Prasad D & Ahmed M R, *Energy Convers Manag*, 77 (2014) 424.
14 Ghalamchi M, Kasaeian A, Ghalamchi M & Mirzahosseini A H, *Renew Energy*, 91 (2016) 477.
15 Lal S, Kaushik S C & Hans R, *Energy Technol Assessments*, 13 (2016) 13.
16 Cottam P J, Duffour P, Lindstrand P & Fromme P, *Sol Energy*, 129 (2016) 286.
17 Mishra A, Chakravarty M N & Kaushika N D, *J Sci Ind Res*, 65 (2006) 355.

18 Sekar K & Duraisamy V, *J Sci Ind Res*, 74 (2015) 325.
19 Das P & Chandramohan V P, *J Therm Anal Calorim*, 136 (2018) 133.
20 Eryener D, Hollick J & Kuscu H, *Energy Convers Manag*, 142 (2017) 286.
21 Lee S, Kim Y S & Park J Y, *Energies*, 11 (2018) 2230.
22 Al-Kayiem H H, Aurybi M A, Gilani S I U, Ismaeel A A & Mohammad S T, *Energy*, 166 (2019) 490.
23 User Guide, SOLIDWORKS 2017.
24 User Guide, ANSYS CFX 17.