ICREGA'14 - Renewable Energy: Generation and Applications
Springer Proceedings in Energy 2014, pp 513-524
DOI 10.1007/978-3-319-05708-8_41

Numerical Investigation of Solar Chimney Power Plant in UAE

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***Abstract*—The paper presents a numerical results for a steady airflow inside a solar chimney power plant. The standard k-epsilon turbulence model is used to model a prototype solar chimney in AlAin in UAE. A 8.25 m high chimney with 24 cm diameter is used to draw air from a 100 m^2 solar collector. The CFD analysis is used to determine the location of the turbine using available power quantity.**

The CFD data shows that collector height and chimney size is highly affect each other since for current design a stagnant zone exist inside the collector which reduce air flow rate inside the chimney. Also the CFD results show that nozzle design is needed at the entrance of the chimney to reduce pressure loss.

NOMENCLATURES

CFD	computational fluid dynamics
D	diameter, m
g	gravity acceleration, m/s^2
h	convection coefficient, kJ/kg
P	static pressure, Pa
Pr	Prandtl number
r	radius, m
R	air gas constant, kJ/kg K
T	temperature, K
T'	temperature fluctuation, K
u	velocity, m/s
u'	velocity fluctuation, m/s
UAE	United Arab Emirates
x	dummy coordinate variable
z	height, m

Greek symbols

ε	dissipation rate, m^2/s^3
μ	dynamic viscosity, $kg/m.s$
ρ	density, kg/m^3
τ	shear Stress, N/m^2

Subscripts

amb	ambient condition
avg	average
i	first counter for tensor notation
in	inlet
j	second counter for tensor notation
out	outlet

I. INTRODUCTION

THE solar chimney power plant (SCPP) operates using the concept that hot air raises. In solar chimney power plant, the air is heated inside the collector which trap solar energy by the greenhouse effect. The hot air is funneled and directed though a chimney which assure that a draft of air is consolidated at the bottom side of the chimney. The concept have been used for passive air ventilation however recently more researcher start exploring this concept for power generation. The solar energy stored in the hot draft air is harvested using a wind turbine. The wind turbine is used to convert the air kinetic energy into mechanical work. The main advantages of a solar chimney system are (1) the low maintenance cost, (2) the simplicity of operation and (3) the durability of the system.

Solar chimneys have been conventionally used in agriculture for air replenishment in barns, silos, greenhouses, etc. as well as in drying of crops [1], grains, fruits or wood [2]. Natural ventilation in buildings is another popular application of solar chimney where natural passive ventilation is used to improve the quality of indoor air and to increase the comfort index for inhabitants [3]. Recently, more interests are developed to utilize the solar chimney to harvest solar energy [4]-[20]. The shortage of available energy resources and the continuous growing energy demands have drove the energy cost to record high levels and fostered the search for more reliable renewable energy. Scientists are exploring several techniques focusing on different aspects including minimizing operational costs, simplifying and lowering maintenance cost, minimizing the use of toxic materials due to health and environmental concerns, and increasing reliability.

The solar chimney is one of the techniques that have a strong potential as a green source of energy which has many advantages and has huge potential in energy generation. Therefore it has a broad range of applications and can contribute substantially to our future energy needs. In the 1980s, a pilot plant was built and tested in Manzanares, Spain and data collected from this pilot plant were published by Haaf [4], [5] in which a brief discussion of the energy balance, design criteria, and cost analysis was presented. The Manzanares pilot plant was rated at 36-kW and produced electricity for 8 years which was used to prove the efficiency and reliability of this novel technology. No full scale solar chimney power plant has been built to date however many proposal have been investigated in different parts of the world. The cost of chimney construction is directly affect the cost of energy produced which needs more investigation since it depends on location, labor cost and material cost which vary

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dramatically based on region. It was reported that the price of the electricity produced by a solar chimney power plant in the Mediterranean region is considerably higher compared to the other power sources [6].

A recent of review study [7] found that solar chimney power generation is a promising approach for future applications. Different studies have evaluated and modeled the performance of SCPP. Using a detailed thermal analytical model, Bernardes et al. [8] showed that the height of chimney, the factor of pressure drop at the turbine, the diameter and the optical properties of the collector are the most important parameters for the solar chimney design. Zhou et al. [9] reported that the maximum height for convection and the optimal height for maximum power output increases with larger collector radius. Hamdan [10] presented a thermal mathematical model which related the power generation by SCPP to the geometry and size of the chimney and collector. The feasibility of SCPP was evaluated by different experimental study [11], [12].

Different scientist evaluated the SCPP numerically [13]-[15]. Maia et al. [13] numerical results showed good quantitative agreement with earlier experimental work which also indicated that the height and diameter of the tower are the most important physical variables for solar chimney design.

Different approaches were proposed to improving the performance of SCPP including double glass collector, phase change material, thermal storage [11], tilted chimney [16], swirl generation [21], and system integration to generate fresh water [21]. The heat transfer coefficients have direct effect on performance of the solar chimney since it affects the air temperature and draft [22].

The purpose of this numerical work is to understand the flow characteristics and the effect of the geometry on the solar chimney performance for the prototype that was built in Alain in 2011. The study evaluates the flow behavior and thermal performance based on the experimental data that is collected by Hamdan and Rabbata [20].

II. NUMERICAL ANALYSIS

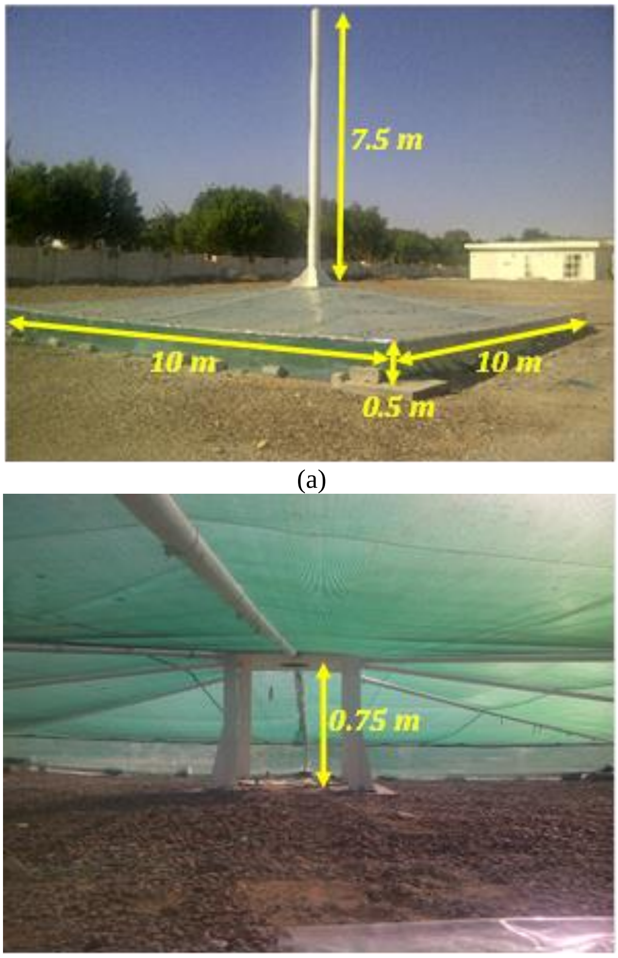
A. Problem Formulation

The physical dimensions investigated in this model is shown in Figure 1, which shows the solar chimney that was built in AlAin in UAE during 2011 [20]. A schematic diagram of the computational domain is shown in Figure 2 with the boundary conditions used in the CFD simulation.

The numerical analysis is carried out using finite volume scheme via commercial software FLUENT® 6 and the mesh is generated using GAMBIT mesh generator software. A uniform fine quad map mesh is used with refined mesh near the wall. A grid refinement procedure has been performed through numerical experiments to assure the grid independence.

To reduce computation time and due to geometry and boundary condition symmetry, the solar chimney power plant is modeled using axi-symmetry analysis using 2D mesh in the radial and axial direction. The collector used in the experimental study is square shape with 10x10 m. An equivalent collector diameter of 11.28m, based or are size, is used in the CFD model to create the 2D axi-symmetry numerical study. In this study the following assumptions are adopted:

1) Cylindrical coordinate is used with axi-symmetry approach.
2) The flow is steady, incompressible ideal gas which is applicable for moderate air speed with Mach number well below 0.3. The volume expansion coefficient is only function of temperature.
3) The collector surface and chimney surface is assumed under natural convection condition with heat flux of $10\ W/m^2K$ and ambient temperature given in table 1. For example for solar heat flux of 222 Wm2 the ambient temperature is 20.3 ºC.
4) The chimney wall is assumed insulated.
5) The inlet pressure is 1 atm and the outlet pressure at 8.25m chimney height is assumed 1 atm which is appropriate for such short chimney.
6) The solar heat flux and ambient temperature that is used as boundary condition in the numerical study are extracted from the experimental study done by Hamdan and Rabbata [20] and is shown in table 1.
7) The gravity in the positive z-direction is -9.81 m/s^2 while zero on all other direction.



(a)

(b)

Fig. 1: Pictures of solar chimney prototype with some dimensions at UAE University, UAE; (a) from outside, (b) under the plastic cover collector.

The analysis is based on steady flow assumption which is an approximation because solar radiation is transient in nature. This assumption is very useful to investigate the main parameters overall effect that influence the solar chimney performance.

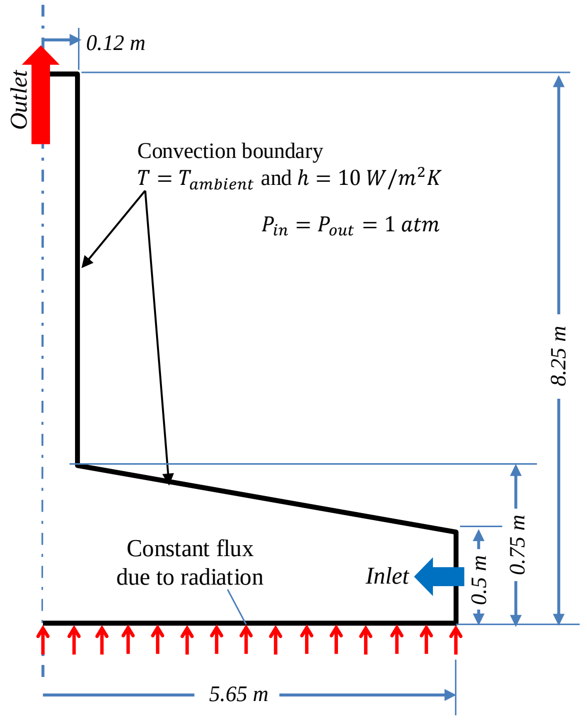


Fig. 2. A schematic diagram of the solar chimney tower power plant computational domain with boundary conditions.

TABLE I
THE EXPERIMENTAL DATA FOR SOLAR HEAT FLUX AND AMBIENT TEMPERATURE THAT IS RECORDED ON DECEMBER 2ND 2011 [20].

Time(h)	Ambient Temperature [°C]	Measured Heat Flux $[W/m^2]$	Velocity measure at the chimney entrance $[m/s]$
10:00 AM	20.3	222	2.9
11:00 AM	21.8	340	3.3
12:00 PM	23.4	402	3.4
1:00 PM	25.0	474	3.3
2:00 PM	27.8	365	3.2
3:00 PM	29.2	178	3.0

B. Numerical Solution

Since the purpose of this investigation is to understand the flow characteristics and the effect of the geometry on the solar chimney performance that was built in Alain in 2011, not the assessment of turbulence models, it is decided that a standard $k-\varepsilon$ model would serve the purpose which is also adopted by other investigators [25-26]. The conservation equations and the standard $k-\varepsilon$ turbulent model used in this study is shown below:

Ideal gas equation:

$$P = \rho RT \tag{1}$$

Continuity equation:

$$\frac{\partial u_i}{\partial x_i} = 0 \tag{2}$$

Momentum equation:

$$\rho u_j \frac{\partial u_i}{\partial x_j} = -\frac{\partial P}{\partial x_i} - g_i + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) - \rho\overline{u'_\iota u'_\jmath}\right] \tag{3}$$

Energy equation:

$$\rho u_j \frac{\partial T_i}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\frac{\mu}{Pr}\frac{\partial T}{\partial x_j} - \rho\overline{T'u'_\jmath}\right] \tag{4}$$

Reynolds stresses $-\rho\overline{u'_\iota u'_\jmath}$ in this study are solved using the standard high Reynolds number $k-\varepsilon$ model [27] with wall function to resolve the wall bounded effects. The kinetic energy of turbulence, $k = u_i'u_i'/2$, and the rate of dissipation of k, $\varepsilon = (\mu/\rho)\,\overline{(\partial u'_\iota/\partial x_\jmath)(\partial u'_\jmath/\partial x_\iota)}$ are solved using the following transport equations:

$$\rho u_j \frac{\partial k}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + P_k - \rho\varepsilon \tag{5}$$

$$\rho u_j \frac{\partial \varepsilon}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] + C_{1\varepsilon}P_k\frac{\varepsilon}{k} - C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} \tag{6}$$

Where, μ_t is the turbulent eddy viscosity, P_k is the production of the turbulent kinetic energy and $-\rho\overline{T'u'_\jmath}$ is the turbulent heat flux, which are calculate in equations (6), (7) and (8) respectively.

$$\mu_t = C_\mu \rho \frac{k^2}{\varepsilon} \tag{7}$$

$$P_k = -\rho\overline{u'_\iota u'_\jmath}\left(\frac{\partial u_j}{\partial x_i}\right) \tag{8}$$

$$-\rho\overline{T'u'_\jmath} = \frac{\mu_t}{\sigma_t}\left(\frac{\partial u_j}{\partial x_i}\right) \tag{9}$$

For the standard $k-\varepsilon$ model, the various constants used in the equations (4)-(8) are taken as $\sigma_k = 1$, $\sigma_\varepsilon = 1.3$, $\sigma_T = 0.85$, $C_{1\varepsilon} = 1.44$, $C_{2\varepsilon} = 1.92$, and $C_\mu = 0.09$.

Once equation (4) and (5) are solved for k and ε, the turbulent Reynolds stress in equation (2) are calculated as follow:

$$-\rho\overline{u'_\iota u'_\jmath} = \left[\mu_t\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right] - \frac{2}{3}\rho k\delta_{ij} \tag{10}$$

III. RESULTS AND DISCUSSION

The study is carried out based on the AlAin prototype solar chimney that was built on 2011 [20]. In the present paper, the steady state numerical results is calculated using the solar heat flux and ambient temperature thatt were measured for AlAin solar chimney prototype [2] and shown in table1.

Figure 3 and 4 show the experimental and numerical results for maximum flow velocity and air temperature, respectively, at the chimney entrance point. As shown in Figure 3 and 4, there is some discrepancy between the CFD model and the experimental data which emphasize the importance of the experimental testing. The numerical model shows good prediction of the experimental data at few point mainly at 10 AM where heat flux is 222 W/m^2, ambient temperature of 20.3 °C and chimney maximum velocity of 2.9 m/s. Using the heat flux and ambient temperature at 10 AM as an input, the CFD model is capable to predict the maximum velocity of 2.83 m/s and an average temperature of 42.9 °C which match the experimental data shown in Table 1. The data shown on figure 3 and 4 shows that the numerical model is not capable to predict the performance of the solar chimney power plant at all operating point since the flow inside the solar chimney is transient and heat flux is continuously changing with time. Also the numerical model does not count for any external wind and condition that will affect the performance of the solar chimney. Nevertheless since the main objective of the study is to evaluate the flow behavior and thermal performance of the actual solar chimney, a steady state CFD analysis can be of great help in designing such system.

To better evaluate AlAin solar chimney prototype, the point at 10 AM with solar heat flux of 222 W/m2 and ambient temperature of 20.3 ºC are used in the numerical analysis for all the figures from 5 to 9.

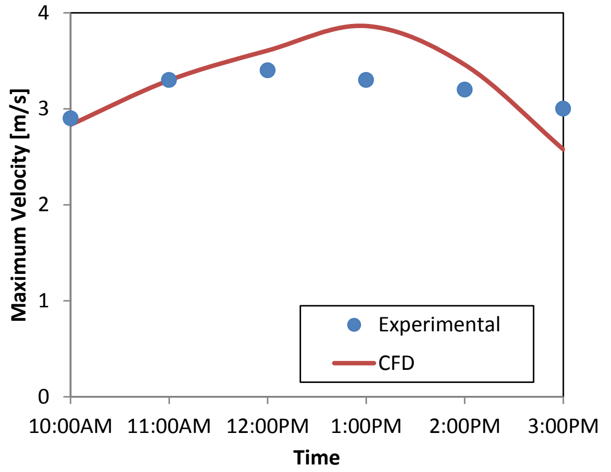


Fig. 3. The maximum velocity at the entrance of the chimney which is determined using numerical model versus the measured velocity using anemometer.

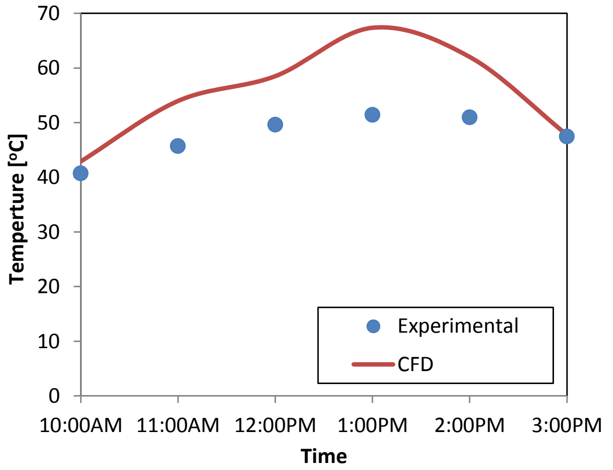


Fig. 4. The average temperature at the entrance of the chimney which is determined using numerical model versus the measured temperature using thermal couple recorder.

Figure 5 shows that the maximum velocity is occurring inside the chimney at 0.25m from the chimney entrance and that the velocity inside the collector is small compared to the velocity inside the chimney. From the low velocity at the velocity contours, it is clear that collector height can be reduced or in other word that chimney diameter can be increased. Such small chimney diameter will force air to circulate inside the collector and will cause air circulation. Hence it is expected that some of air will be trapped and circulated inside the collector and even some air will leave from the collector entrance as shown in Fig 6. Using constant inlet static pressure and constant outlet static pressure in which both equal atmosphere pressure of 101 kPa, the velocity at the inlet of the collector is plotted on Fig. 6. It is clear from figure 6 that some air enters near the ground (positive velocity), while some air leaves near the collector cover (negative velocity). Nevertheless the overall flow rate is positive and air is flowing at the entrance of the collector and leaving at the chimney outlet with mass flow rate of 0.1093 kg/s.

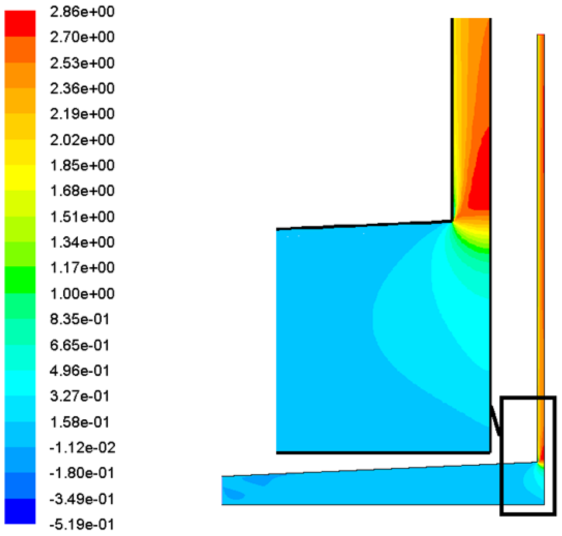


Fig. 5. The velocity contour inside the solar chimney tower with a close-up image for the region between the collector and the chimney.

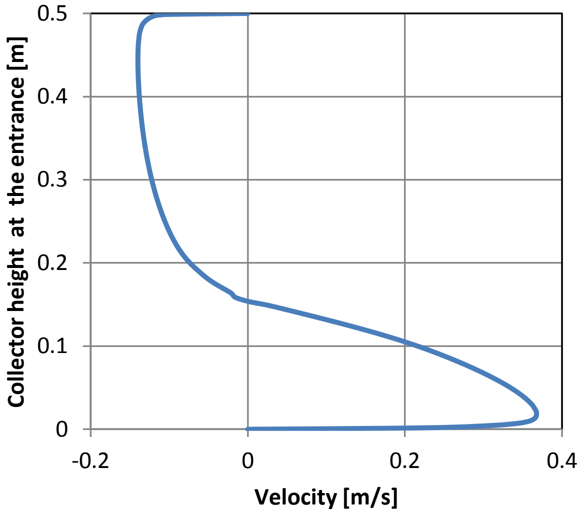


Fig. 6. The velocity profile at the entrance of the collector where positive pointing inflow and negating pointing to outlet flow. The average inflow velocity is 0.00321 m/s.

The temperature contours inside the solar chimney is shown in Fig. 7. Figure 7 shows that the air temperature is increasing as the air flows from the collector to the chimney which is predicted since more heat is transferred to the air. Also it shows that not counting the effect of the ground as heat dissipating medium will lead to unrealistic temperature of the ground mainly at the center of the collector. It observed that using constant heat flux at the ground would over predict the ground temperature but it will give more realistic results for air temperature. Nevertheless, authors believe that using constant hear flux as boundary condition is more realistic than using constant ground temperature as used by Patel et al. [28]. The variation of ground temperature was reported by Sangi et al. [15] which indicates that using constant heat flux at the ground is more appropriate than constant ground temperature. More accurate results can be obtained by considering the ground in the computation which can be explored in future work.

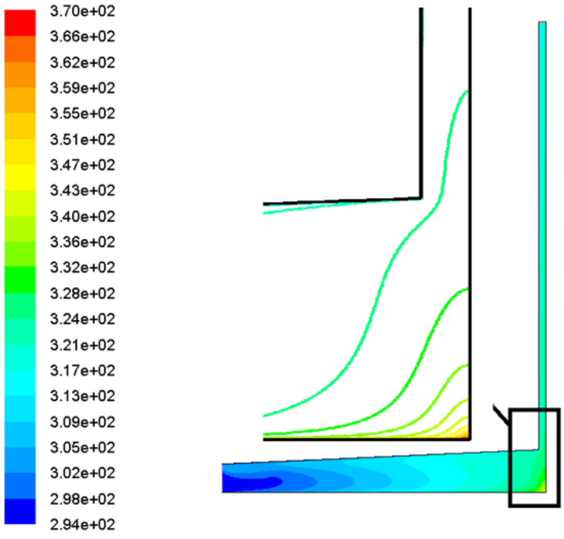


Fig. 7. The temperature contour inside the solar chimney tower with a close-up image for the region between the collector and the chimney.

Using the CFD model, the velocity at the centerline of the chimney and mass weighted temperature average inside the chimney is shown in Fig. 8. It is clear that maximum velocity is achieved near the entrance of the chimney which resulted from the sharp edge entrance of the chimney which caused separation and forced the flow to move near the center. Eventually this get dissipated by the viscous force and the flow become hydro-dynamically fully developed. Since the chimney is assumed natural convecting heat to the ambient with convection heat transfer coefficient of $10\,W/m^2K$, it is expected that the air temperature will drop as shown in Fig. 8. Such drop need to be validate by additional experimental future work.

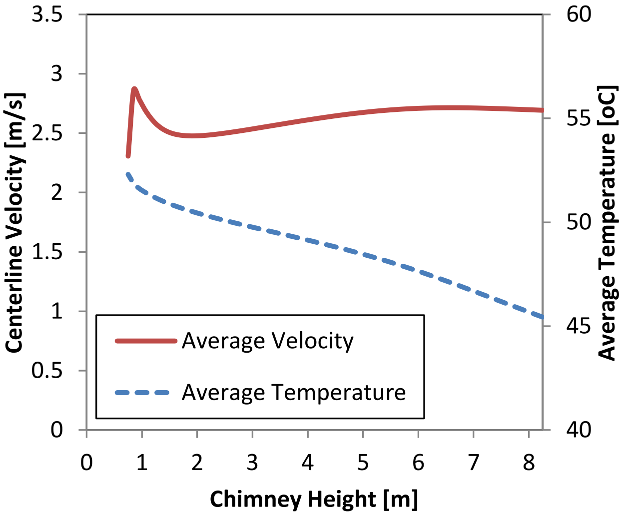


Fig. 8. The temperature contour inside the solar chimney tower with zoom on the region between the collector and the chimney.

IV. CONCLUSION

The mathematical thermal model presented in this study shows a good agreement with published experimental work for AlAin solar chimney system. The model shows that collector height is directly related to chimney diameter and one needs to consider this solar chimney design. Using constant heat flux boundary condition at the ground is more appropriate than using constant temperature however isoflux will lead over predicted ground temperature mainly at the center. Main chimney losses will occur at the entrance and it is recommended to use a nozzle to reduce such losses.

ACKNOWLEDGMENT

The author would like to acknowledge the support provided by United Arab Emirates University. This work was financially supported by the Faculty of Engineering in the United Arab Emirates University through seeds project funding.

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