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NUMERICAL MODELING FOR A SOLAR CHIMNEY

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ABSTRACT
In the current study, potential improvements in both flow field and heat transfer characteristics of a prototype solar chimney for power generation through passive flow control approaches have been numerically examined. The numerical modeling was conducted for three different schemes to enhance the velocity magnitude at the entrance of the chimney. The first scheme is concerned with the effect of the number of turbulent generators on the maximum flow speed obtained while the second scheme deals with the effect of throat area at the entrance of the chimney. The last scheme is related to investigating the effect of making round edges having different radii at the entrance of the chimney.

Keywords: Solar chimney power plants - CFD - Passive flow control

	Nomenclature		
F	**external body force (N)**	**T**	**Time (s)**
H	**Energy (J)**	**A**	**Area (m^2)**
I	**Unit tensor**	**Q**	**Heat flux (W/m^2)**
S	**Source term**	**K**	**Thermal conductivity (W/m.k)**
T	**Temperature (K)**		***Greek letters***
V	**Velocity component (m/s)**	**μ**	**Dynamic viscosity (kg/m.s)**
P	**Pressure (Pa)**	**P**	**Density (kg/m^3)**
G	**Gravitational acceleration (m/s^2)**	**T**	**Shear stress (N/m^2)**

INTRODUCTION
Energy is one of the critical inputs for socio-economic growth and the rate at which it is being expended by a nation often reflects the level of prosperity that it could achieve. Global population is developing day by day; accordingly, the energy demand is also increasing. Conventional energy sources based on fossil fuel such as crude oil, coal, and natural gas have verified to be highly effective drivers of economic progress. However, they damage both the environment and human health. These traditional energy sources face an increase in global demand due to the increase of the global population. Unfortunately, these traditional fossil fuels are limited resources and will be depleted soon. It is estimated to last within 100 years. Now it is clear that any effort made to satisfy the great energy demand cannot be based mainly on the conventional energy resources. Accordingly, alternative energy sources should be provided to overcome the growth of energy demanded, meanwhile such an alternative energy sources should be environmentally friendly as well [1].

An enormous amount of solar energy radiates by the sun every day, which is more than the world energy use in one year. Solar energy has most efficient advantage that is causes no pollutions, no noise at all and it will last forever. Solar chimney is a type of passive solar heating and cooling system that depends on a principle has been proposed for solar power generation, using a large greenhouse at the base rather than depending solely on heating the chimney itself [1]. One of the primary explanations of a solar chimney power plant station was discussed in 1903 by Isidoro Cabanyes [2]. In the face of the inventive perceptions, the first prototype for the solar chimney for power generation was erected and developed in 1982 in Manzanares, it generates 50 kW plant prototype built in Manzanares [3]. Remarkable research efforts have been conducted to experimental studies [4-6] of the fluid procedure leading to energy conversion phenomena in Solar Chimney Power Plants, which have contributed to a more profound understanding of the occurring thermal and dynamic processes.

Herman Coetzee [4] introduced a prototype model for solar chimney but the power output was very small thereby he used a converging nozzle to increase the velocity of the warm air form 3.53m/s to be 15m/s. Moreover, Xinping Zhou [5] studied the temperature distribution for the collector around the day time to determine the time at which the maximum speed takes place. He recommended to enhance the material of the collector to increase the energy transformed to air.

Furthermore, Mehran Ghalamchi [6] constructed a proto type for solar chimney and he changed the inlet dimension and he found that as the height of the inlet decrease the air film temperature increase which leads to increase of inlet velocity to 1.3 m/s.

In addition to experimental studies, several numerical researches [7-14] have been conducted to model the experimental work and make enhancement on the simulated model.

Ramon Molina Valle [7] made a mathematical model based on (Navier-Stokes and Energy Equations) using Finite Volumes Method in Generalized Coordinates. The mathematical explanation was found in a fixed computational domain without depending on the geometrical shape of the physical system. In addition, Xinping Zhou and Jiakuan Yang [8] developed a mathematical model to investigate the performance of the system, to make optimal arrangement of chimney and collector sizes that can be selected for the requested power output, based on the simulation and the specific construction costs at a certain site. Moreover, T. Z. Ming, Y. Zheng [9] performed numerical analysis on both the flow pattern of working fluid within various parts of solar chimney system and a thermodynamic cycle, starting from the solar collector inlet, passing from collector to the chimney outlet and finally back again to the collector inlet from the environment. They found that the performance of the solar chimney resembles the performance of Brayton cycle.

Besides Ali K. Al-Abadi [10] Built 2D numerical modeling using ANSYS FLUENT, based on solving the governing equations with suitable assumptions and boundary conditions for model components such as the collector area, the chimney height, the ambient temperature, and exit area of the chimney. He found that the numerical results presented a good matching with experimental results. The simulation was suitable to estimate the performance of the solar chimney inaddation to cost saving for the experimental procedures.

In addition, Jing-yin Li [11] made a numerical model by using Runge Kutta [12] method to simulate the experimental data of the Spanish prototype and this model found that there is a restriction on maximum collector radius, beyond which the attainable power output of the solar chimney increases very slowly. On the contrary, no such restrictions was placed on the chimney height exists.

Furthermore, Atit Koonsrisuk [13] introduced numerical model that was validated with the experimental results of the prototype from Manzanares, Spain.

Hakim Semai [14] established numerical model using Saturne and Syrthes direct access codes. He found that the storage system (water and soil storage system) is the best one where it gives continuous operation of the chimney for power generation with a better efficiency the diffuser-shaped duct placed at the junction of the collector output and the chimney inlet gives an significant velocity of the fluid flow compared to the systems without diffuser just at the outlet of the collector and to the inlet of the chimney.Ehsan Shabahang [15] carried out numerical study to examine three different flow control obstacles rectangular, triangular, and semicircle profiles. studying the shape of the obstacles which shows that all the different shapes provide boundary layer agitation and fluid mixing however, obstacle with triangular profile supplies more thermal performance enhancement since not only the fluid flow pattern throughout the chimney is not blocked but also guidance toward the chimney is supplied to the flow.

The current study investigates numerically the effect of the number of baffles to enhance the maximum kinetic energy obtained within a prototype of Solar Chimney for power generation. The numerical model was validated based on Ehsan Shabahang [15] model. furthermore, the effect of throat with different area ratio on the maximum speed generated were studied.

This study aimed to enhance the exist kinetic energy form the solar chimney proto type. Different models were studied to get the maximum velocity at the chimney inlet. all the models were studying passive flow in the solar chimney without turbine as mention below:

2. METHODOLOGY

2.1 Computational Domain

Fig. 1 shows a schematic of the solar chimney, which was numerically simulated. Dimensions of this prototype are mentioned in Table 1 as demonstrated in, [15]. The numerical model examined the effect of using (Passive Flow Control Devices) with different number to investigate the performance of the (triangular Passive Flow Control Devices) on enhancing the kinetic energy output from the solar chimney [15].

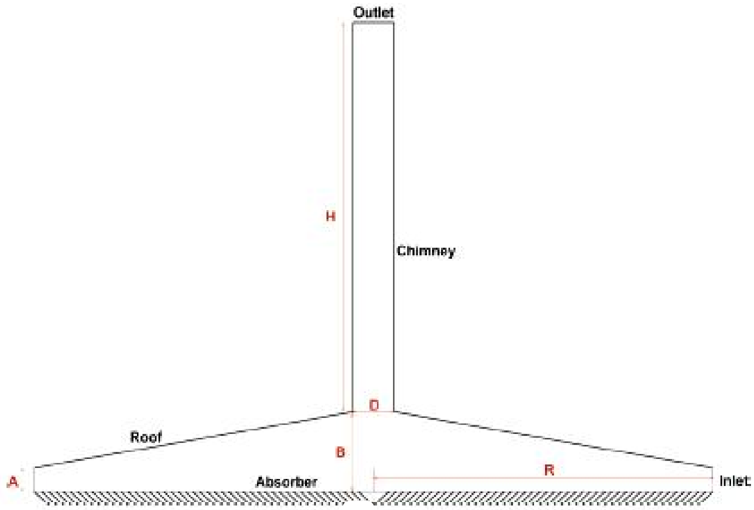

Fig. 1. Schematics of the prototype Solar Chimney [15].

Table 1: Geometry of Solar Chimney Power Plant [15].

Description	Symbol	Dimension (m)
Inlet height	A	0.15
Chimney entrance height	B	1
Collector Radius	R	5
Chimney diameter	D	0.25
Tower height	H	12

2.2 Computational grid

The initial grid is comprised of 100,000 quadratic elements of high resolution employed near the collector boundary wall, the center line, and absorber surface since these regions represent significant importance in boundary layer and they have high velocity gradients as showed in fig.2

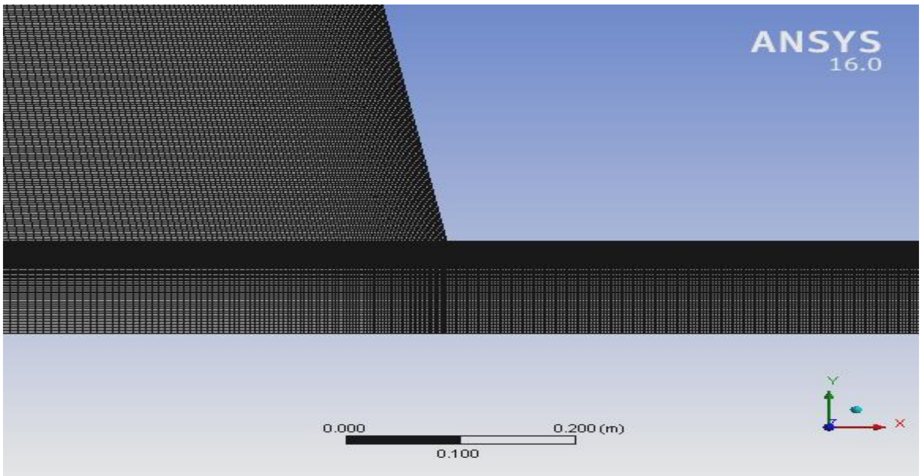

Fig. 2. Grid structure.

Noting that this initial grid around the collector, absorber and chimney will undergo mesh adaption (refinement) in the process of the simulation, to obtain grid independency.

Numerical results using different grid strategies for grid refinement and distributions indicate that the grids are very fine to obtain grid-independent solutions.

Grid independency test was achieved with four different grid designs (100,000 element – 250,000 element – 600,000 element – 970,000 element), as showed in the below Fig. 3

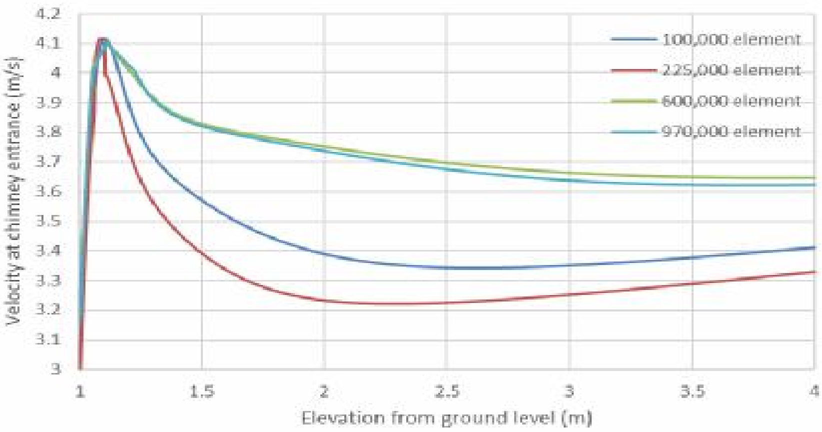

Fig. 3. Grid independence test

Figure 3 shows that the results of interested variable flow velocity become independent after 600,000 element grid so numerical model can be run for calculating without any doubt that number of grid will affect the solution.

2.3. Computational model.

In order to check which model is more stable and stable in numerical solution to simulate the base case Ehsan [14] fig. 4 below shows model test using different cases in solving the numerical model as k-ε which is divided into 2 cases (RNG – Realizable) in addition to k-ω SST model.

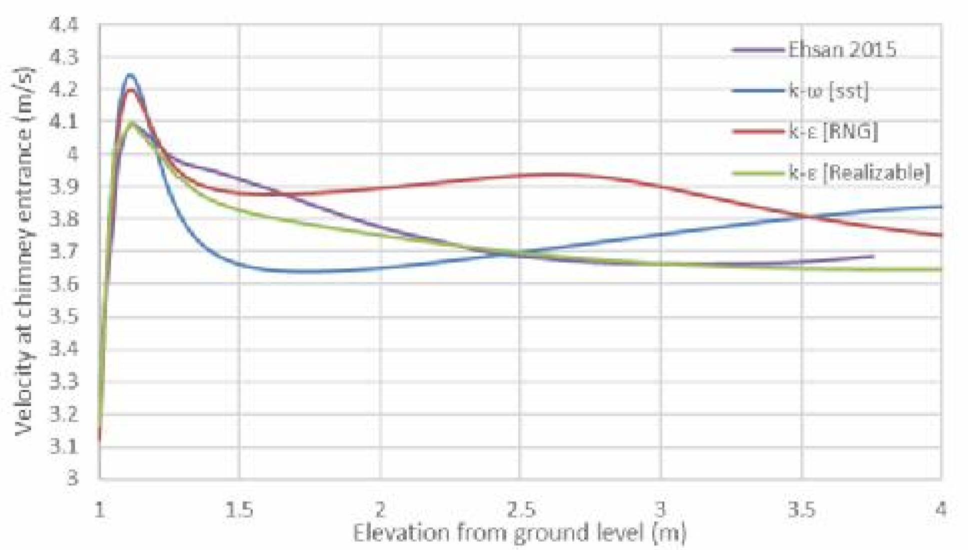

Fig. 4. Model test

Figure 4 shows that the results of interested variable flow velocity become nearly like Ehsan 2015 in using k-ε [Realizable] model which gives the same results and validates the numerical model.

2.4. Numerical details.

Fluid flow in Solar Chimney is a kind of buoyancy-driven flow due to density difference, the flow regime with heat transfer of which is usually determined by the Rayleigh number. Rayleigh number less than 10^8 [16] indicates a laminar flow, with a transition to turbulent flow occurring over the range of 10^8 <Ra <10^{10} [16]. The Rayleigh number in a Solar Chimney is evidently higher than 10^{10}, and its inner airflow should be a turbulent flow. Therefore, the RNG k-ε turbulence model enhanced wall was selected with Y+ nearly equal to 1 to model the airflow inside the system. The Boussinesq model was adopted in this simulation. This model solve density as a constant value in all solved equations, except for the buoyancy term in the momentum equation.

$$g(\rho - \rho_a) \approx \rho_a \beta g(T - T_a) \text{ [17] (Eq. -1)}$$

The above equation is used with free convection cases, where ρ_a is the density of ambient air, T_a is the ambient temperature, and β is the thermal expansion coefficient. For the buoyancy driven flow, for faster convergence for the solution can be achieved by using the Boussinesq model than by setting air density as a function of temperature only.

The PERSTO algorithm was applied to the couple of pressure velocity where it is suitable for free convection heat transfer cases, and the body force weighted algorithm was selected as the discretization method for the pressure term. The second-order upwind scheme was chosen for the all convective terms and viscus term. Two main criteria are majorly considered to guarantee the convergence of the solution.

(1) Mass conservation for the collector inlet and the chimney outlet.

(2) Enhanced wall function Y+ nearly equal to one.

2.5 Boundary conditions

Since the geometry and all boundary conditions of the problems were treated as 2-D axially symmetric model, where half of a 2-D model of the for-power generations examined. Fig. 1 shows the 2-D computational domain of the Ehsan case [15].

Both the collector inlet and chimney outlet were set as pressure-inlet and pressure-outlet boundaries, respectively. For a buoyancy-driven flow problem with pressure boundary conditions, pressure is atmospheric at inlet and outlet of the chimney. Following previous researchers [18-19], pressures at the collector inlet and the chimney outlet were both set atmospheric.

In addition, both, the collector and the chimney were considered as opaque surface when do not emit or absorb any heat the only source of heat is the ground with constant heat flux 100 W/m^2 as mentioned in the table 2 below.

A numerical model based on energy balance has been developed to investigate the performance of the solar chimney thermal power output at different conditions. The following assumptions are made:

1. Air follows the ideal gas law.
2. The numerical model is in steady state.
3. Leakage can be neglected in the system.
4 Only the buoyancy force is considered as the driving force for the flow inside the chimney, and wind-induced natural ventilation in the ambient is not included.
5. The temperature of the natural ground under the heat insulator bed is equal to that of the ambient.

Table 2 shows the boundary conditions which was taken in solving the numerical model

Table 2: the boundary conditions.

Place	Type	Description
Centerline	Axis	Symmetry
Absorber	Wall	100 W/m^2
Roof	Wall	Insulated
Chimney	Wall	Insulated
Inlet	Pressure inlet	P_{atm}
Outlet	Pressure outlet	P_{atm}

2.6 Governing equations [Navire–Stokes equations]

The numerical model for the study of fluid dynamics problems is based on the fundamental mass, momentum and energy conversation principles. The approach used in this study is Reynolds Averaged Navire–Stokes (RANS) modeling as demonstrated in [20].

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho \vec{v}) = S_m \qquad \text{(Eq.-2)}$$

$$\frac{\partial(\rho \vec{v})}{\partial t} + \nabla.(\rho \vec{v} \vec{v}) = -\nabla.p + \nabla.\bar{\bar{\tau}} + \rho \vec{g} + \vec{F} \qquad \text{(Eq.-3)}$$

$$\frac{\partial(\rho H)}{\partial t} + \nabla.(\vec{v}(\rho H + P)) = \nabla.(K_{eff} \nabla T) + S \qquad \text{(Eq.-4)}$$

$$\bar{\bar{\tau}} = \mu\left[(\nabla \vec{v} + \nabla \vec{v}^T) - (\frac{2\nabla}{3}).\vec{v}\, I\right] \qquad \text{(Eq.-5)}$$

2.7 validation of model

The numerical model was validated by a prototype which was mentioned in Ehsan study [15]. The mass flow rate was leveled when the number of iteration was 600 or more. The velocity at elevation one meter from the chimney entrance agreed with the results of Ehsan [15] as shown in fig. 5

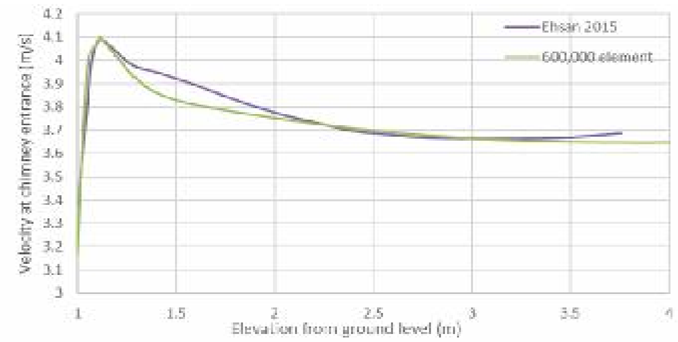

Fig. 5 validation with Ehsan [15]

2.8 Studied schemes

i) Passive flow control device scheme

the passive control devices have been examined by Ehsan [15] for different shapes which are round, rectangular, triangular shapes and his results showed that the triangular shape gives the maximum kinetic energy at the chimney entrance with two passive devices. Here, the effects of increasing the number of for triangular shape with dimension 0.1 cm x 0.1 cm on the maximum kinetic energy obtained in the chimney entrance were studied as mentioned in table 3.

Table 3: Tree possible arrangements the triangular shape

Description	No. of control device
arrangement 1	1
arrangement 2	2
arrangement 3	3

Fig. 6 shows the different arrangment for the tringular shaps on the absorber area.

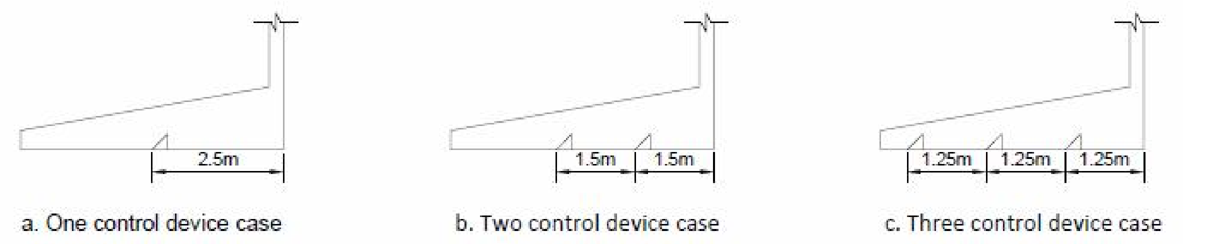

Fig. 6 Control device scheme

ii) Throttling scheme

The effects of throat shape with different area ratio at the chimney entrance on the maximum flow velocity generated were examined. There are three modules of throat area ratio which are listed in Table 4 where

area ratio = $A_{\text{chimney}} / A_{\text{throat}}$

Table 4: Throating area ratios

Description	Area Ratio
Throat 1	1.29
Throat 2	1.73
Throat 3	2.44

Fig. 7 shows the different throatling areas at the chimney entrance.

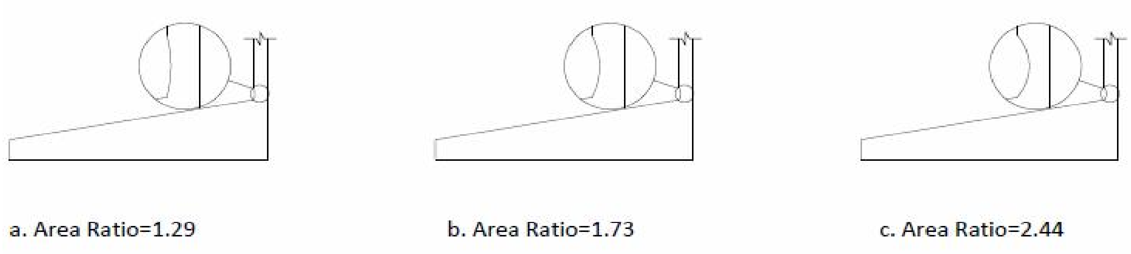

Fig. 7. Throttling scheme

iii) Round scheme

The effects of the shape of the connection between the collector and chimney was examined round shape with different radius were studied. Three proposed designs are presented with different round radii as mentioned in Table 5

Table 5: Three proposed curvature

Description	Curvature Radius [m]
shape 1	0.05
shape2	0.1
shape3	0.15

Fig. 8 Shows the different different round radii used between the chimney wall and the collector.

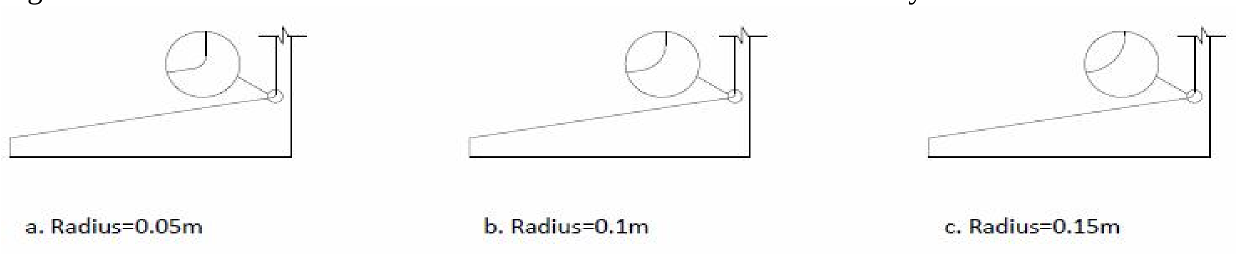

Fig. 8. Round scheme

3. RESULTS AND DISCUSSION

3.1 Passive control device scheme results

Fig. 9 shows that as number of passive control device increase the maximum velocity magnitude increases at the entrance of the chimney which mean that more amount of kinetic energy generated.

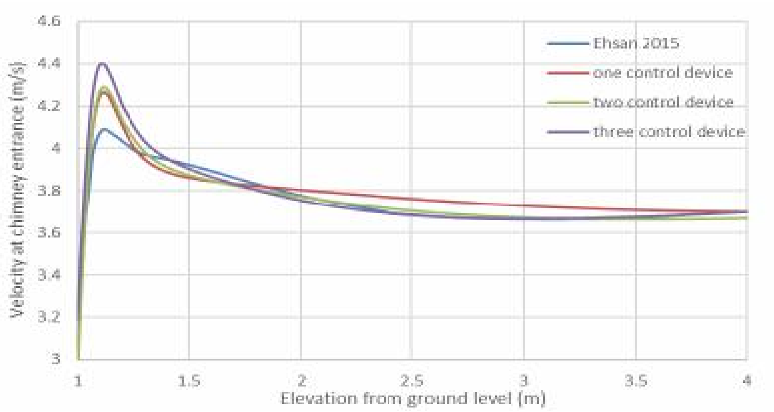

Fig. 9 Velocity magnitude throughout the chimney entrance with different number of baffles.

This may attribute to enhancement of the heat transfer coefficient where the velocity in the case of one passive control device was 4.1 m/s and enhanced to 4.4 m/s by using three control devises. Fig. 10 shows the influence of increasing number of passive control devices on the mass flow rate of the air passes through the chimney. the mass flow rate increases with the increase of number of baffles by 7%.

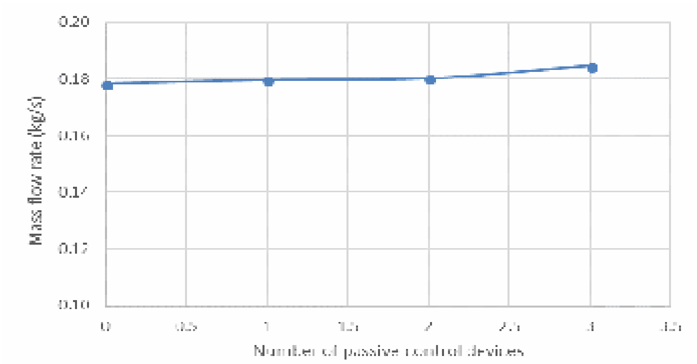

Fig. 10. Mass flow rate throughout the chimney with different number of baffles.

3.2 Throttling scheme results

It can be shown from fig. 11 that the as area ratio increase the maximum velocity magnitude increase which mean that more amount of kinetic energy generated.

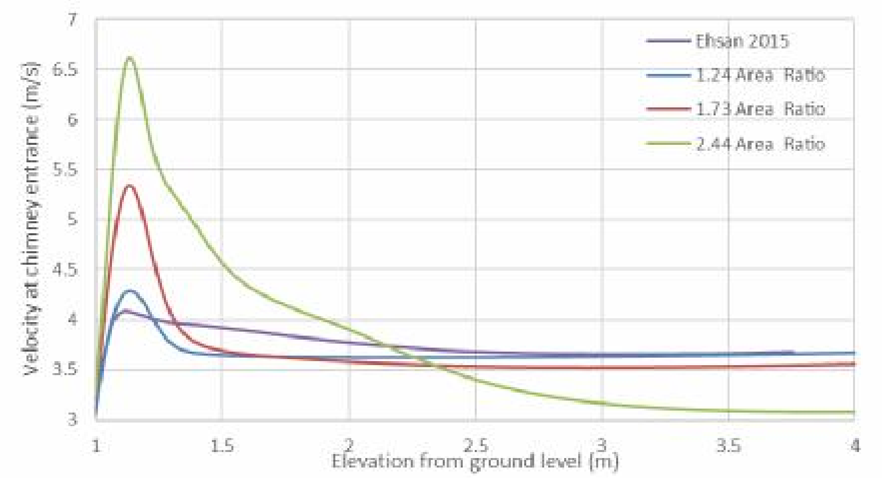

Fig. 11 Velocity magnitude throughout the chimney entrance with different area ratio.

Where the velocity magnitude at the chimney entrance in Ehsan case [15] is 4.1 m/s and enhanced to 4.3 m/s in using 1.3 area ratio and 5.3 m/s in using 1.7 area ratio and 6.6 m/s for 2.4 area ratio but it must be taken in consecration the air flow rate inside the chimney.

Moreover, fig. 12 below shows the influence of increasing area ratio on the mass flow rate of the air passes through the chimney the mass flow rate nearly constant until 1.73 area ratio and a sudden decrease happen when area ratio increases to 2.44.

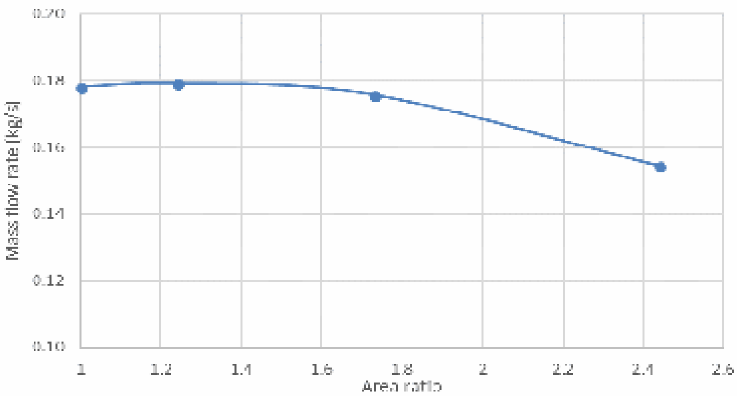

Fig. 12 Mass flow rate throughout the chimney for different throttling Area ratio.

3. 3 Round scheme results

Fig.13 shows the influence of increasing the curvature radius between the collector and chimney wall on the maximum velocity generated in the chimney.

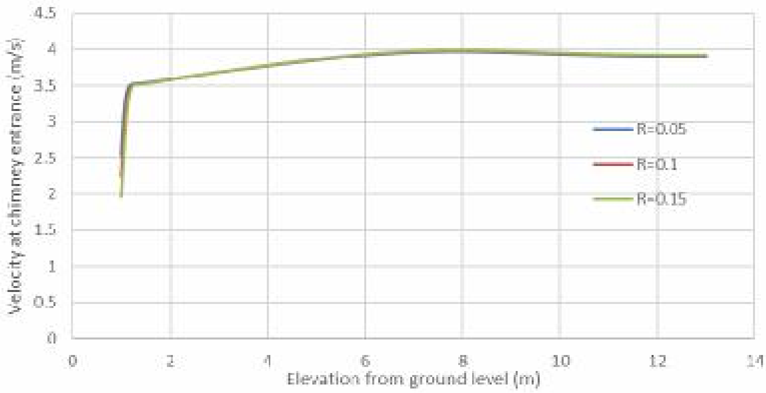

Fig. 13 Velocity magnitude throughout the chimney with different curvature radius.

From the above figure the change in flow velocity magnitude at the entrance of the chimney decreases for different curvature radius compared with Ehsan case [15] in addition to the maximum velocity obtained at 8 m elevation from the chimney. This is evidence on the nearly constant mass flow rate of the air passes through the chimney, as show in Fig. 14.

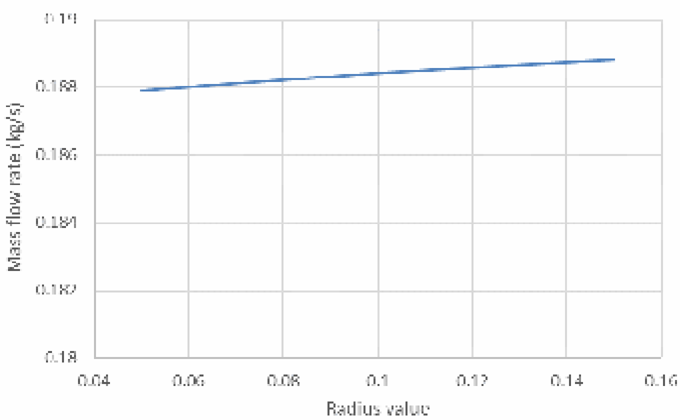

Fig. 14 Mass flow rate throughout the chimney for different curvature radius.

4. CONCLUSIONS

In the current paper, three different approaches have been examined to enhance and to improve both the maximum speed obtained at the entrance of the chimney and the heat transfer characteristics of the solar chimney prototype approaches have been analyzed in this work. The first approach is concerned with studying the influence of increasing number of obstacles on the maximum speed obtained, where the second approach is related to studying the influence of making throats having different area ratios at the entrance of the chimney, and the last approach deals with making round edges with diffract radii at the entrance of the chimney.
The numerical model is conducted through a 2-D axisymmetric incompressible steady state finite volume C.F.D. solver ANSYS-Fluent [21].
The obtained results showed that:

1- Increasing number of passive control devices leads to enhancement in the maximum speed obtained at the entrance of the chimney by 7%
2- Although the throttling approach enhances the velocity magnitude at the entrance of the chimney by 29% keeping nearly the same mass flow rate, yet it causes decrease in mass flow rate when the area ratio exceeds 1.7
3- Round scheme decreases the velocity magnitude at the entrance of the chimney which is not recommended.

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