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Numerical Simulations of Solar Chimney Power Plant with Thermal Storage

Merera Senbeto
Department of Mechanical Engineering,
Marwadi Education Foundations Group of Institutions,
Gujarat, Rajkot, India– 360003,

***Abstract*: The performance of solar chimney power plant (SCPP) is analyzed numerically using computational fluid dynamics (CFD) commercial ANSYS Fluent. Two dimensional axisymmetric model of the only one prototype in Manzanares updraft tower is considered. Solar radiation generates small pressure difference inside the chimney during the day-time. However, during the night- time due to unavailability of solar radiation, the power generation does not remain continue. To overcome this problem one can use thermal storage material to store the energy available during the day-time and release during the night-time. A standard K-ε turbulence model and Boussinesq approximation for buoyancy driven flow is considered. The numerical simulation results show that: (1) Solar chimney power plant with thermal storage as water will reduce the variation of power output due to fluctuation of solar radiation; (2) As solar radiation intensity increases, the velocity of the system also increases significantly; (3) The average surface temperature of the energy storage layer increases significantly with gravel as thermal storage.**

Index Terms— Solar chimney, Energy storage layer, CFD, Collector, Chimney

1. INTRODUCTION

Solar chimney power plant is a promising large-scale green technology, which converts the absorbed both direct and diffused solar radiation into electric power. The air enters through collector opening and the warm air underneath the collector due to buoyancy and the temperature difference between the warm and ambient air moves toward the center of the collector where the chimney is located then after due to the pressure difference created air moves up the chimney. A turbine is set at the chimney inlet through which air escapes to change the kinetic energy of the fluid flow into a mechanical rotating shaft to generate electricity. A Solar chimney was first designed by J. Schlaich and the prototype was built in 1981, Spain [1]. The Manzanares prototype was generated 50-KW of electricity for 8 consecutive years, indicating the feasibility of the solar chimney power plant technology. Haff et al [1,2] developed the evaluation of an experimental and preliminary test result of the prototype. The analysis and numerical modeling of solar chimney with the heat transfer characteristics under the collector using thermal analysis were developed by Bernardes et al. [3]. The performance of solar chimney power plant with a large scale is evaluated and numerically modeled by Pretorius et al.[4] .Heat transfer in the collector of solar chimney power plant was summarized by Bernardes et al. [5] From a two comprehensive study of Pretorius and Bernardes paper.

In this study, two-dimensional axisymmetric flow of fluid with the effects of different thermal storage on the power output of solar chimney power plant (SCPP) is simulated with ANSYS Fluent. Two configurations of solar chimney power plants are used as a physical model.

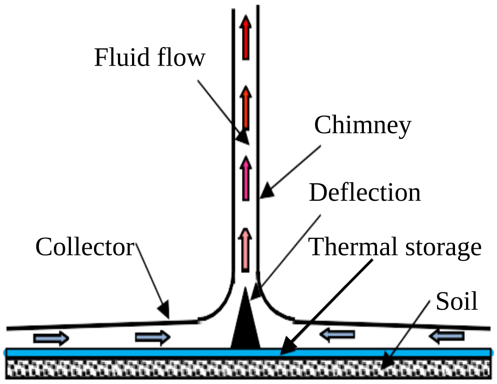

Fig.1 The physical model (SCPP) with water as thermal storage

2. NUMERICAL SIMULATION

2.1 System description

For our simulation case, a physical model of the prototype of Spanish solar chimney power plant is taken as in Fig.1. The prototype has a 195m and 5m height and radius of chimney respectively and collector with 120m and 1.7m radius and height from the ground respectively. However, in our analysis, the axisymmetric flow of air is assumed. The Boussinesque approximation is assumed to be valid.

2.2 Computational model

For our study, the governing equations, continuity, Navier–Stokes, Energy equation in cylindrical coordinates were solved using the SIMPLE algorithms and the calculation was carried out using ANSYS Fluent. To show the flow of air and heat transfer inside the collector and chimney, the two-equation turbulence model of a Standard k-ε model is used. The convective and diffusive terms were discretized with a second-order-accurate upwind scheme. The number of cells inside the collector and tower was 34 x 380 and 34 x 460, respectively. The total number of cells including the ground and thermal storage was 190,960. A simple energy balance model with a time-dependent solution of the governing equations was sought and the calculation is therefore regarded as Unsteady (time dependent).

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2.3 Boundary conditions

The static pressure difference Δp at the same height is zero *Pastohr et al*.[9]. So that Δp ~0Pa for both at the collector inlet and outlet of the chimney with respect to environment and temperature at the collector inlet is considered approximately equals to the ambient temperature and T_{outlet} ~ ($T_{ambient}$ − 0.0065x chimney height) at chimney outlet [10]. An Adiabatic condition is considered for the wall of the chimney and the absorbed solar radiation in the thermal storage with a thickness of 10cm is considered as a source during the night session. Constant temperature condition has been considered for the bottom of energy storage layer and soil with a depth of 5m is included in the model.

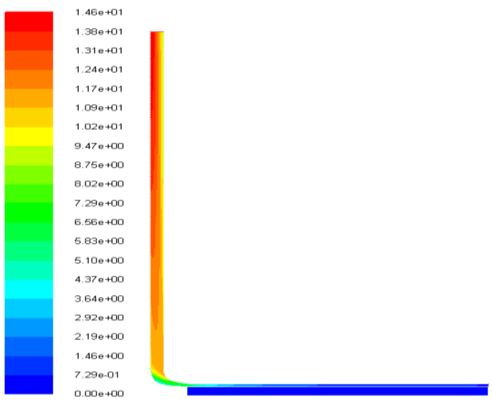
3. RESULTS AND DISCUSSIONS

Comparison between the computed result and measured data of the 2nd of September 1982 from Haff's paper [1] of the Spanish prototype and is carried out in order to validate the numerical simulation in this paper. The comparison of simulated and measured velocity and the temperature is shown in Table 1. As we can see from the table 1, the numerical simulation result well agreed with the experimental results, which indicates that the computational method applied in this paper is reliable

Table 1 Measured and simulated results for validations

Parameters	Measured [2]	Present computations
Average chimney inlet Velocity [m/s]	7-9	10.71
Temperature rise of air[K]	15-20	22

The cause for the difference is that the presence of the turbine at the inlet of the chimney which leads reduction of velocity magnitude that this paper did not consider since we are considering two-dimensional axisymmetric geometry of solar chimney and uncertainty of some parameters, like the density of gases, air humidity optical and property parameters. For comparison purpose, water, soil and gravel are used as the materials of the liquid and solid matrix of the energy storage layer.



a)

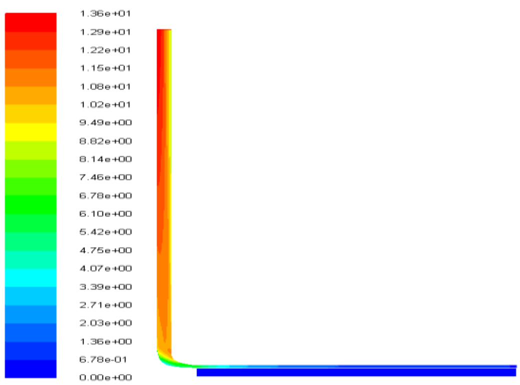
b)

Fig 2. a)velocity contour and b)temperature of solar chimney power plant with soil as thermal storage

The property of water are ρ_{wate} =998.2 kg/m^3, Cp_{water} = 4182 J/kg.K. k_{water} = 0.6 W/(m K). The properties of soil are as flows: ρ_{soil} = 1700 kg/m ^{3}, Cp_{soil} = 2016 J/(kg K), k_{soil} = 0.78 W/(m K). The properties of gravel are: ρ_{gravel} = 2555 kg/m^3, cp_{gravel} = 814.8 J/(kg K), k_{gravel}= 2.00 W/ (m K). The absorptivity of the surface and the porosity of the energy storage layer are selected as 0.9 and 0.6, respectively. Fig. 2 illustrates the air velocity of increases as it moves from collector inlet to outlet whereas maximum temperature is attained under the collector. The velocity rises sharply at the inlet of the chimney. The air velocity increases within few distances from the surface of the ground and then remains almost constant. This is because of the low viscosity of air. The temperature at the ground becomes very high in a depth of few units and almost constant throughout the chimney.

3.1 Effects of water as thermal storage

One of the advantages of thermal storage for solar chimney power plants is improving the efficiency of the system by continues supply of electricity regardless of day-night cycle. The power output of SCPP is greatly affected by the thermal performance of the thermal storage layer since the chimney inlet velocity is highly dependent on the surface temperature of the energy storage layer. The power output is highly dependent on the thermal storage especially at night and cloudy days.



a)

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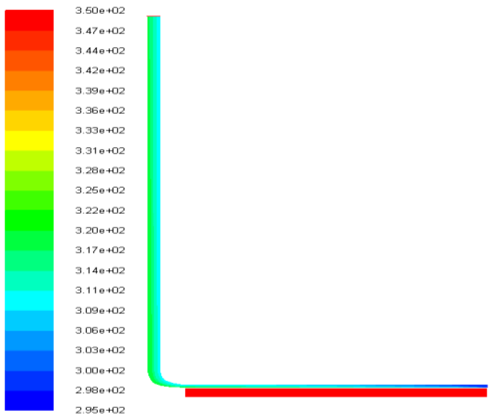


b)

Fig.3 a) Velocity contour and b) Static Temperature of solar chimney with Water as thermal storage

The water as thermal energy storage filled tubes under the collector was originally suggested by Schlaich et al. [11]. Maximum velocity is attained between 18:00-20:00 PM. In solar chimney with soil as thermal storage (SCPP without thermal storage) power is not generated after 18:00 PM throughout the night. Additionally, there is a big variation of power output as we can see on Fig 4. When thermal storage is used as one part of the system the velocity and temperature variation is solved and power can be generated at night.

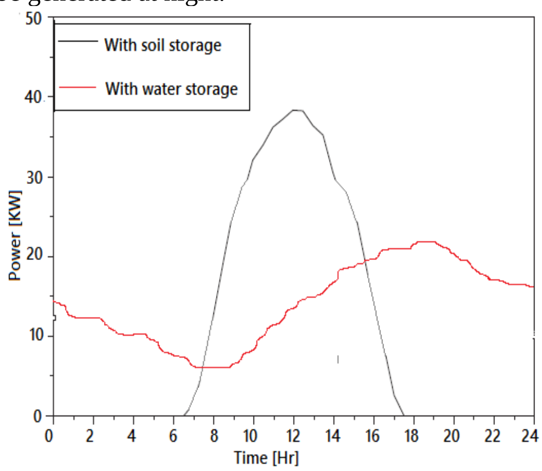
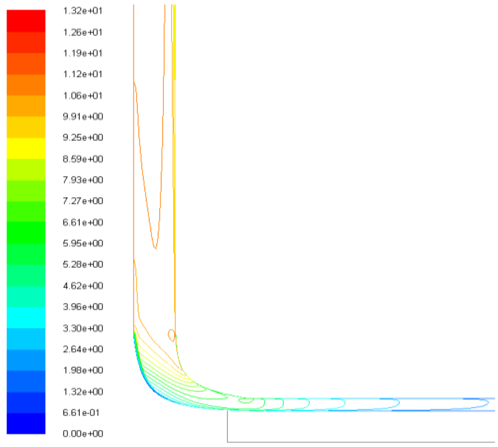
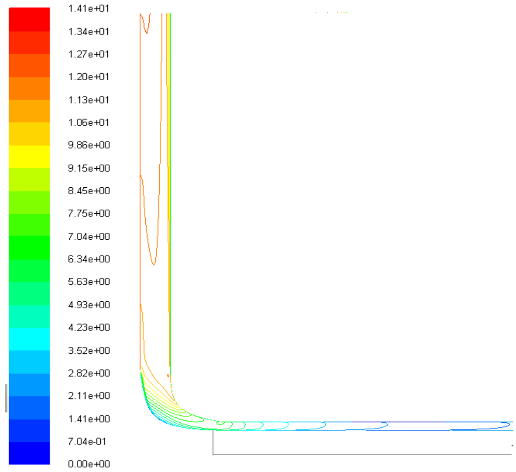


Fig.4 Comparison of soil and water as thermal storage based on Power output with respect to time.

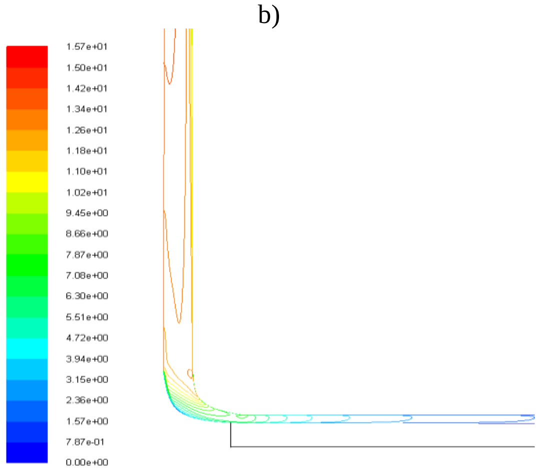
The output power variation between the maximum and minimum was reduced significantly by using water as thermal storage comparing with soil as we can see on the Fig.4.As it shown that when water storage is used in the system the power increases at night while it decreases during the day so that it acts as a source system during unavailability of solar radiation. The energy stored inside the tube during the day will be released during the night where there is no radiation, at which air in the collector starts to cool down so that the air under the collector starts to be heated which leads to increase velocity and power generation will continue throughout the night. So that solar chimney power plant with water as thermal storage works more efficiently than soil alone. Fig 5 shows the velocity distributions of the SCPP with gravel as thermal storage system with different solar radiation intensity. That velocity of the air in the system increases as we can see from the figure when solar radiation varies from 400 to 1000 W/m^2 and the maximum velocity lies at chimney inlet. For the solar radiation intensity of 400,600 and 800W/m^2, the maximum velocity inside the chimney is 13.2, 14.1 and 15.7m/s respectively.



a)



b)



c)

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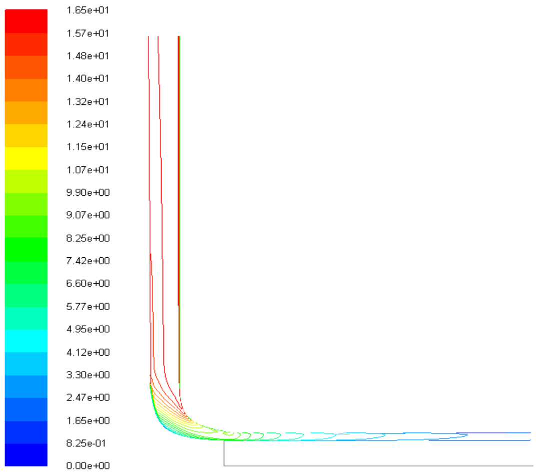

d)

Fig. 5 Velocity distribution of SCPP with a) I=400 W/m^2 and b) I=600W/m^2 c) I=800W/m^2 d) I=1000 W/m^2 solar radiation intensity

The maximum chimney inlet velocity without turbine is around 16.5 m/s as solar radiation intensity is 1000W/m^2. So we can say that solar radiation plays a great role for the velocity of the flowing fluid by increasing the temperature under the collector which by turn increases the density difference by creating buoyancy force so that pressure difference is generated.

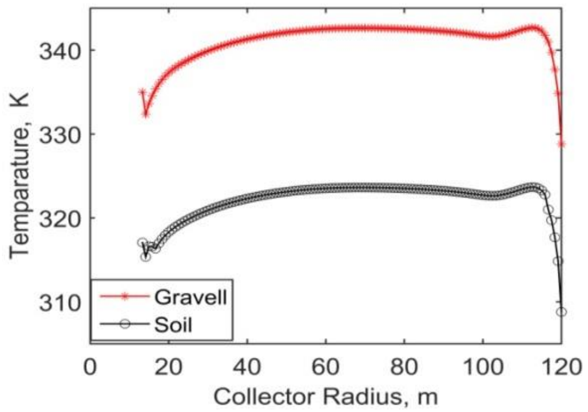

Fig.6 Comparison of the Surface temperature profile of Soil and Gravel as thermal storage layer under the collector with radiation intensity 800 W/m^2.

The energy transfer mechanism inside the heat storage layer is highly influenced by the conductivity and capacity of flowing fluid on the heat storage layer. For the distribution of temperature inside the gravel is significantly affected by the mechanisms of radiation and convection; so there is a notable difference between Soil and Gravel as simulated above.

4. CONCLUSION

A Numerical computation has been performed on the commercially available finite volume code, Ansys Fluent. The effects of thermal storage have been incorporated in the model. The computed performance of SCPP with Soil, Water, and Gravel as a thermal storage show that the water as a thermal storage reduces the fluctuation of the power over a period of 24 hrs. For same radiation intensity, the surface temperature of gravel is found higher which generates the higher velocity of air inside the chimney which generates more output power. Thus, the use of thermal storage enhances the performance of SCPP and avails power for 24 hrs.

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