Numerical Study about Concentrated Solar Updraft-tower Power Generator

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Abstract— **This paper examines the velocity distribution of updraft wind inside the concentrated solar updraft-tower. According to analysis of the traditional solar updraft-tower power plant, it has been found that when the updraft moves upward, the heat energy converts into potential energy, which causes the air temperature to decrease. Thus, this paper proposes to use concentrated sunlight to supplement the lost heat of the tower for increasing buoyant force. The flow speeds inside the various types of solar updraft-towers are simulated by the CFD calculation method, and a significant increase of flow speed is confirmed.**

Index Terms— **renewable energy, solar updraft-tower power generator, concentrated sunlight, solar sun power**

I. Introduction

NOWADAYS, the renewable energy has been intensively developed in order to build a carbon-free society. The vast majority of them are generated by photovoltaic panels and wind turbines. The benefits of using solar and wind powers are sustainable, pollution-free and applicable for everywhere. However, the rapid increase of the renewable energy is endangering the whole power supply, because both solar and wind power generators are very susceptible to short-term changes of weather. However, as the amount of renewable energy increases now, the stability of whole power supply system becomes poor.

To overcome this technical issue, solar thermal power generators are expected to be adopted. As one sort of thermal powers, SUPG (Solar Updraft-tower Power Generator) has been proposed. A SUPG system generally consists of a collector, a vertical chimney, and a turbine. The collector is a large greenhouse, which harvests the solar energy, warms the air and send upwind to the chimney. The vertical chimney is a pathway for the upwind from the collector. Every component of this power plant is a simple structure and easy to maintain. The advantages of SUPG system are a huge amount of generated electricity, a hybrid system of solar and wind powers, and maintenance-free. However, its energy conversion efficiency is still very low, because the heat of upwind inside the chimney is lost outside and the buoyancy decreases.

This study aims to improve the efficiency of SUPG system by re-heating the tower. Since the heat source, technology of concentrated sunlight by mirror reflection is employed, this new type of structure is called a C-SUPG (Concentrated Solar Updraft-tower Power Generator) system. A conceptual diagram of C-SUPG system is shown in **Fig. 1**. In this study, the velocity distribution of updraft wind in this system is numerically simulated. According to this result, the efficiency problems in this system that need to be improved are discussed.

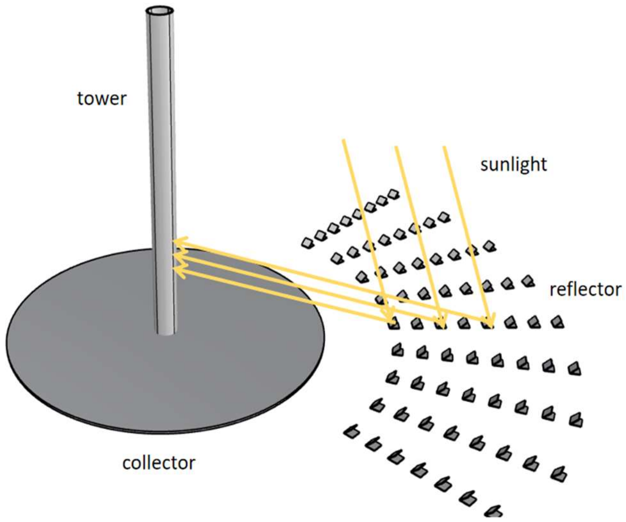

Fig. 1. A conceptual diagram of C-SUPG system: Around SUPG system, several reflectors(mirrors) are deployed to concentrate sunlight onto updraft tower for re-heating the updraft flow.

A SUPG system is a robust green-power generation system, generally built in desert areas where solar energy is abundant. In a conventional SUPG system, collector is covered by a semitransparent roof to let the solar radiation pass through. This solar radiation mainly warms the ground, which works as a heat trap. Then the long wavelength radiation is emitted from the ground and warms up the air. Because the warmed air becomes lighter than the atmosphere surrounding the SUPG system, a buoyancy force begins to act on it. As the density difference between the airs inside and outside of the collector, the thermal updraft wind is created inside the tower. Subsequently, the wind rotates the turbines at the entry of the chimney and generates electricity.

An experimental SUPG model was established in Spain in the 1980s [1]. This system was consisted of a 195m chimney, and a collector of which radius is 122m. The maximum power output achieved 50kW. The generated power seemed to be not so large, while the model is huge. Mohammed [2] calculated the energy conversion efficiency of conventional SUPG and showed that the maximum value did not reach 0.25%. Before building a SUPG system, it is necessary to improve the efficiency.

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Pasurmarthi and Sherif [4] investigated the performance of SUGP in California and confirmed the effect of air temperature and velocity on electricity generation. That work showed a fine result to use the desert region for gaining the benefit of sunlight by SUPG system. In a desert of Inner Mongolia, Inner Mongolia University of Science and Technology built a prototype of SUPG system and had observed its performance for 4 years since 2010. This project achieved 70kW power output merely with a 50m high tower.

On the other hand, it is known that as the wind speed increases, the power generation efficiency of wind turbine increases in proportional to the cube of wind velocity. Thus, Nagai Tomoyuki [5] offered a method for improving the efficiency by using a diffuser tower. That work presented that a diffuser tower provides better performance than a standard cylindrical tower, because the speed of thermal updraft wind inside chimney is increased. The current study adopted similar approach.

As solar thermal power systems, there are different types from a SUPG system. One of them is CSP (Concentrated Solar Power) system. CSP system uses mirror reflections to concentrate sunlight to heat fluid in tube or boiler. Therefore, that the electricity can be generated by conventional steam turbine generator in CSP system. As the fluid used in CSP is generally extremely hot, the power generation efficiency is also high. Since CSP system could trap huge sunlight into one absorbing device, this mechanism can be adopted in the vertical chimney of SUPG system to compensate for heat loss.

This work combines the advantages of SUPG and CSP systems, and proposes a hybrid system, called C-SUPG system. The fluid behavior is numerically simulated through 3D model.

II. Numerical Simulation of C-SUPG

The numerical simulation model and the grid model are shown in **Fig.2** and **Fig.3**, respectively, and the parameters of C-SUPG and the physical coefficients are shown in **TABLE I**. The adopted numerical model can consider the fluid compressibility, viscosity and turbulence, but neglects the effect of viscous dissipation.

The heating device that absorbs sunlight reflected by mirrors was installed on the chimney in a range of height from 20m to 120m.In order to analyze how the height affects the wind speed in the tower, we made three numerical models with height of 500, 600 and 700 meters. The collector radius of all models is set at 200 meters, and collector area is 125600 m^2. Diffuser tower is used in C-SUPG system. The diameter of tower at bottom is 30 meters, and the tower divergent angle is 4° in three models.

In previous research of CSP system, solar power is assumed as1 kW/m^2 [6]. By the Fluent radiation model, the ground and glass of the collector respectively receive 0.723 kW/m^2 and 0.242kW/m^{2}of solar energy. The energy of concentrated sunlight received by the heating device on the chimney was assumed at 3 kW/m^2, and the reflection efficiency of mirror was assumed to be 63% [7]. The reflector has an area of 44857 m^2.

In order to observe the turbulence that caused by ambient wind, the C-SUPG system numerical model is placed in a cubic atmospheric model. The ambient airflow enters from left at 1 m/s and leaves through other sides. Temperature of airflow is assumed as 298 K.

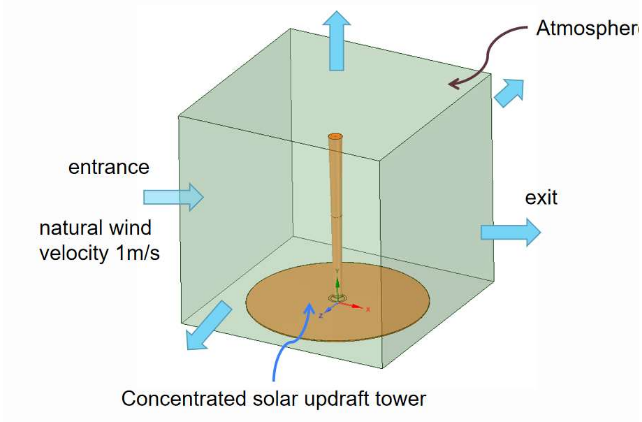

Fig. 2. The numerical simulation model of C-SUPG systems

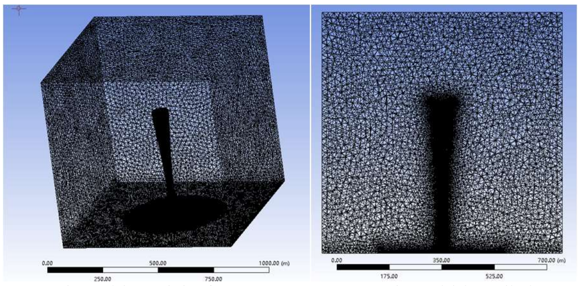

Fig. 3. The grid model of C-SUPG systems: The grid is split into two different zone, inside and outside of C-SUPG systems. The maximum size of grid of the outside zone is set as 10 meters, and that of the internal air flow grid is set as 1 meter. The transition zone between two zone with 10 layers. The skewness of this grid ranges from 0.23 to 0.25.

TABLE I
The Parameters of C-SUPG system & the Physical Coefficients

Symbol	Quantity	Unit	Value
H	Tower Height	m	700
R_c	Collection Radius	m	200
H_{heat}	Heating device Height	m	100
D	Tower diameter	m	30
γ	Tower Divergent angle	degree	4
c_p	Specific heat capacity	KJ/Kg	1
ρ	Density	Kg/m^3	
p	Pressure	pa	
T	Temperature	K	
t	Time	s	
r	radial coordinate		
θ	angle coordinate		
z	axial coordinate		
k	Turbulence kinetic energy		
ε	dissipation rate of k		
C_1	Constant		1.44
C_2	Constant		1.92
σ_k	Constant		1.0
σ_ε	Constant		1.3
C_μ	Constant		0.09
β	Thermal expansion coefficient		
g_i	component of the gravitational vector		

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μ	viscosity coefficient
a	speed of sound

In cylindrical coordinate system, the governing equations can be expressed as follows:

The continuity equation can be expressed by

$$\frac{1}{r}\frac{\partial(rv_r)}{\partial r}+\frac{1}{r}\frac{\partial v_\theta}{\partial\theta}+\frac{\partial v_z}{\partial z}=0 \tag{1}$$

where r, θ, and z denote radial coordinate, angle coordinate and axial coordinate, respectively. The fluid velocities are represented by v_r, v_θ, and v_z, respectively.

The momentum equation can be expressed by

r-scale

$$\frac{\partial v_r}{\partial t}+(V\cdot\nabla)v_r-\frac{1}{r}v_\theta^2 =-\frac{1}{\rho}\frac{\partial p}{\partial r}+\frac{F_r}{\rho}-\frac{1}{\rho}\left(\frac{1}{r}\frac{\partial}{\partial r}(r\tau_{rr})+\frac{1}{r}\frac{\partial\tau_{r\theta}}{\partial\theta}-\frac{\tau_{\theta\theta}}{r}+\frac{\partial\tau_{rz}}{\partial z}\right) \tag{2}$$

θ-scale

$$\frac{\partial v_\theta}{\partial t}+(V\cdot\nabla)v_\theta-\frac{1}{r}v_r v_\theta =-\frac{1}{\rho r}\frac{\partial p}{\partial\theta}+\frac{F_\theta}{\rho}-\frac{1}{\rho}\left(\frac{1}{r^2}\frac{\partial}{\partial r}(r^2\tau_{r\theta})+\frac{1}{r}\frac{\partial\tau_{\theta\theta}}{\partial\theta}+\frac{\partial\tau_{\theta z}}{\partial z}\right) \tag{3}$$

z-scale

$$\frac{\partial v_z}{\partial t}+(V\cdot\nabla)v_z =-\frac{1}{\rho}\frac{\partial p}{\partial z}+\frac{F_z}{\rho}-\frac{1}{\rho}\left(\frac{1}{r}\frac{\partial}{\partial r}(r\tau_{rz})+\frac{1}{r}\frac{\partial\tau_{\theta z}}{\partial\theta}+\frac{\partial\tau_{zz}}{\partial z}\right) \tag{4}$$

where

$$(V\cdot\nabla)=v_r\frac{\partial}{\partial r}+\frac{1}{r}v_\theta\frac{\partial}{\partial\theta}+v_z\frac{\partial}{\partial z} \tag{5}$$

$$\nabla^2=\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial}{\partial r}\right)+\frac{1}{r^2}\frac{\partial^2}{\partial\theta^2}+\frac{\partial^2}{\partial z^2} \tag{6}$$

The energy equation can be expressed by

$$\rho c_p\left[\frac{\partial T}{\partial t}+(V\cdot\nabla)T\right]=k\nabla^2T+\mu[2\varepsilon_1+\varepsilon_2] \tag{7}$$

$$\varepsilon_1=\varepsilon_{rr}^2+\varepsilon_{\theta\theta}^2+\varepsilon_{zz}^2$$
$$\varepsilon_2=\varepsilon_{\theta z}^2+\varepsilon_{rz}^2+\varepsilon_{r\theta}^2$$

Where

$$\varepsilon_{rr}=\frac{\partial V_r}{\partial r}\quad \varepsilon_{\theta\theta}=\frac{1}{r}\left(\frac{\partial v_\theta}{\partial\theta}+v_r\right)\quad \varepsilon_{zz}=\frac{\partial v_z}{\partial z}$$

$$\varepsilon_{\theta z}=\frac{1}{r}\frac{\partial v_z}{\partial\theta}+\frac{\partial v_\theta}{\partial z}\quad \varepsilon_{rz}=\frac{\partial v_r}{\partial z}+\frac{\partial v_z}{\partial r}$$

$$\varepsilon_{r\theta}=\frac{1}{r}\left(\frac{\partial v_r}{\partial\theta}-v_\theta\right)+\frac{\partial v_\theta}{\partial r}$$

Viscous stress

$$\tau_{rr}=2\mu\varepsilon_{rr}\quad \tau_{\theta\theta}=2\mu\varepsilon_{\theta\theta}\quad \tau_{zz}=2\mu\varepsilon_{zz}$$

$$\tau_{r\theta}=\mu\varepsilon_{r\theta}\quad \tau_{\theta z}=\mu\varepsilon_{\theta z}\quad \tau_{rz}=\mu\varepsilon_{rz}$$

k-ε model is used to deal with turbulence.

k-ε equations can be expressed as

$$\frac{\partial(\rho k)}{\partial t}+\frac{\partial(\rho k u_i)}{\partial x_i} =\frac{\partial}{\partial x_i}\left[\frac{\partial k}{\partial x_j}\left(\mu+\frac{\mu_t}{\sigma_k}\right)\right]+G_k+G_b-\rho\varepsilon-Y_M \tag{8}$$

$$\frac{\partial(\rho\varepsilon)}{\partial t}+\frac{\partial(\rho\varepsilon u_i)}{\partial x_i} =\frac{\partial}{\partial x_j}\left[\frac{\partial\varepsilon}{\partial x_j}\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\right]+C_1\frac{\varepsilon}{k}G_k-C_2\rho\frac{\varepsilon^2}{k} \tag{9}$$

Where

$$G_k=\mu_i\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)\frac{\partial u_i}{\partial x_j}$$

$$G_b=\beta g_i\frac{\mu_i}{Pr_t}\frac{\partial T}{\partial x_i}$$

$$\mu_t=\rho C_\mu\frac{k^2}{\varepsilon}\quad Y_M=2\rho\varepsilon M_t^2\quad M_t=\sqrt{\frac{k}{a^2}}$$

In the k-ε equations, G_k represents the generation of turbulence kinetic energy due to the mean velocity gradients, and $G_b$represents the generation of turbulence kinetic energy due to buoyancy. μ_t , Y_M and M_t represents turbulent viscosity, the contribution of the fluctuating dilatation in compressible turbulence and the Mach number of turbulent, respectively.

III. Result and Discussion

Considering the computational cost, the models simulated is used to perform a calculation of that C-SUPG systems work for 120 seconds. Then following results are obtained. The velocities of updraft wind inside tower at 150m height of three numerical models are 10.1m/s, 11.6m/s and 12.2m/s, respectively. These results may be explained by the fact that the higher the tower is, the higher the velocity of the updraft wind. On the other hand, the efficiency improvement rate of height increase seems to be decreased as the height increases. This suggests that there might be an optimum height for chimney. Therefore, a possible explanation is that the second derivative of the height with respect to the velocity, has a negative tendency.

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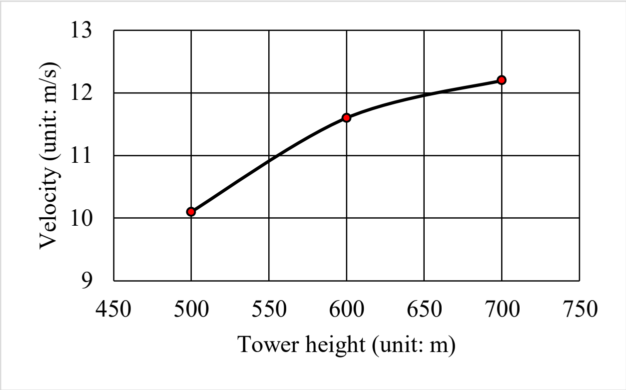

Fig. 4. "The relationship between tower height and velocity of updraft in C-SUPG systems at 150m height"

Based on the results of numerical simulation, some imperfections were found in above-mentioned design of C-SUPG system. At the area near to heating device inside tower, unstable convective flow exists, and at the bottom of tower, collision of airflow from different directions is observed. In the above two phenomena, the kinetic energy of the airflow is transformed into other forms of energy that cannot be used to drive the turbine.Due to airflow around C-SUPG system, in the collector, the heated air is not concentrated towards the chimney. This phenomenon will cause the solar energy loss. These three phenomena are shown in **Fig.5**, **Fig.6** and **Fig.7**.

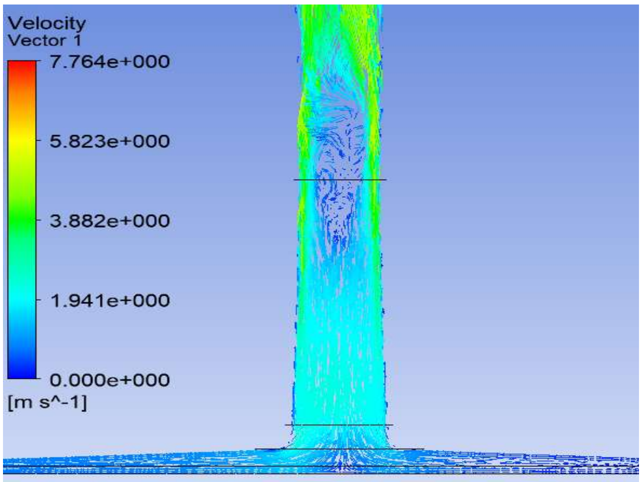

Fig. 5. Unsteady convective flow inside tower

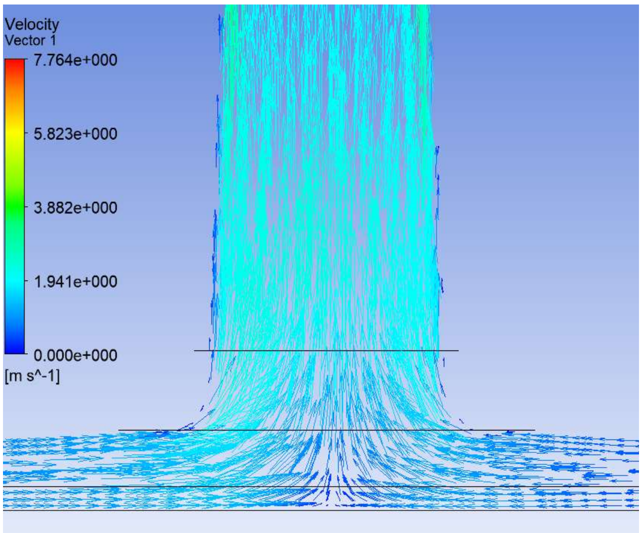

Fig. 6. The collision of flow occurs at the bottom

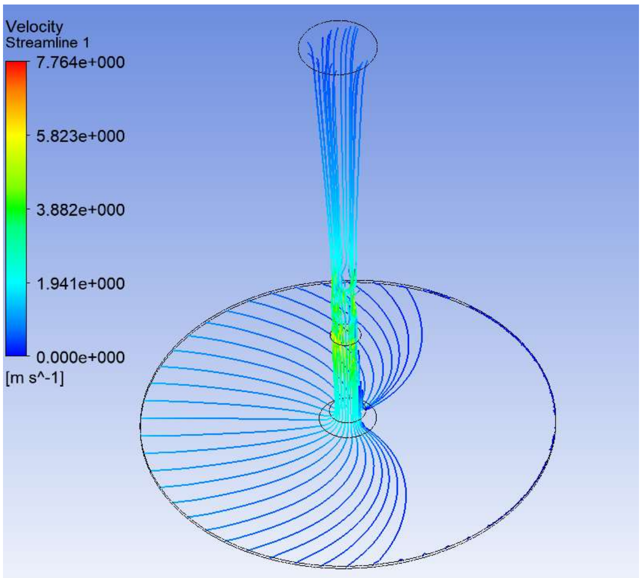

Fig. 7. Thermal energy loss occurs in the collector

IV. Conclusion

In this study, we proposed a C-SUPG (Concentrated Solar Updraft-tower Power Generator) system to improve the power generation efficiency of conventional SUPG system.

3D numerical models of C-SUPG system are created by using Ansys fluent software, and velocity distribution of updraft flow inside chimney is obtained. After examining the results, unsteady convective flow, collision of flow and solar energy loss can be observed. These three phenomena which can reduce the energy conversion efficiency of C-SUPG system were found. Although, this defect of C-SUPG system cannot be ignored, the potential of this system to improve the performance of SUPG system can be presumably expected.

Further research should be carried away to establish a greater degree of accuracy. First, finding a way to eliminate the unsatisfactory influence from above mentioned three phenomena. Second, comparing the efficiency of conventional SUPG system and C-SUPG system. Finally, verifying the efficiency of C-SUPG system through physical experiment.

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