# Numerical Simulation of Flow in a Solar Chimney Power Plant

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## Abstract

In this study, a Finite Element Method (FEM) based program for steady-state viscous incompressible thermal flows is developed and utilized to simulate laminar flow in a Solar Chimney Power Plant (SCPP). The flow characteristics in the SCPP system is studied by comparing the distribution of velocity, temperature and pressure from three different types of connection between a solar collector and a chimney. It is found that the curved junction with a diffuser is the most suitable model for adopting the SCPP in practice.

**Keywords:** Solar Chimney, Finite Element Method, Viscous Incompressible Thermal Flows

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## Introduction

Recently, natural disasters become more severe, frequent, and destructive. For instance, it was found that a gap between the big tsunami waves at the western coast of Thailand and the great east Japan tsunami in Tohoku is only about years. Also, it can be investigated that the major floodings are often occurring in several countries even in Thailand. Or, the appearance of a large sinkholes worldwide or a killing of heat waves in Europe and Asia is regularly reported.

It is found that some of the aforementioned catastrophic events are caused due to the global warming effect. Increasing $CO_2$, one of the greenhouse gases, appears to dominate the effect of global warming. It was also revealed that most of the $CO_2$ from human activities comes from the consumption of fossil fuels (e.g. coal, petroleum and natural gas). This effect leads many countries to develop their own sustainable energy resources instead of using the fossil fuels.

Presently, renewable energy sources play an important rule for solving this challenging problem. One promising technology for rural areas, especially in the tropical countries where the solar radiation is highly available, is the Solar Chimney Power Plant (SCPP). The SCPP consists of three major components: the solar collector, the chimney and the power conversion unit (PCU) as depicted in Figure 1.

The SCPP generates electrical power by the buoyancy force of air which is heated under a transparent canopy by the greenhouse effect at the solar collector. Subsequently, hot air flows to a chimney's base located in the center of the collector and rises up along the height of the chimney to rotate a turbine for producing the power. A successful construction of the 50 kW Manzanares prototype in Spain has confirmed the possibility and reliability of this green technology.

The solar chimney technology was comprehensively reviewed by Zhou et al. (2010). Their paper provides the overall picture of research and development of SCPP technology over the past few decades, which consists of the evolution of experimental and theoretical studies, the details of construction process, cost analysis for competitiveness of power plant and physical phenomena of the system for the conventional SCPP as well as the information of an alternative types of SCPP.

After its first introduction (Cabanyes, 1903) and construction of the prototype in 1982, the researchers worldwide developed their theoretical and numerical models for studying the SCPP technology, e.g., Nizetic et al. (2008), Chergui et al. (2010), Hamdan et al. (2010), Larbi et al. (2010), Asnaghi et al. (2012). Most of the aforementioned literature utilized the fundamental of Computational Fluid Dynamics (CFD) to formulate governing equations of the flow in the SCPP. The commercial software (e.g., ANSYS and FLUENT) are generally used to analyze the problem numerically, and the results are compared with the data obtained from the

experimental results of the Manzanares pilot plant which are reported by Haaf et al.(1983) and Haaf (1983).

The purpose of this study is to develop a finite element program for steady-state viscous incompressible thermal flows (Dechaumpai & Kanjanakijkasem, 1999). The developed program is further used to find the most suitable model for constructing the SCPP based on three different types of connection between a solar collector and a chimney. It should be mentioned here that the effect of a turbine in PCU is not included in this study.

The paper will present briefly the fundamentals of CFD for steady-state viscous incompressible thermal flows. Then, the formulation by using the finite element method is introduced, followed by the numerical results of the SCPP. Lastly, the conclusions are addressed together with the recommendations for further research directions.

## Governing Equations

In this study, the Computational Fluid Dynamics (CFD) for steady-state viscous incompressible thermal flows, in the context of Finite Element Method (FEM), is employed to study the flow characteristics in the solar chimney. In order to accomplish the analysis, a set of coupled nonlinear Navier-Stokes differential equations which consist of three fundamental laws, i.e., (1) conservation of mass or continuity, (2) conservation of momentums and (3) conservation of energy equations need to be solved. By taking care of the thermal effect on the buoyancy force, the Boussinesq approximation is introduced into the momentum equations. The aforementioned can be written as follows:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \tag{1}$$

$$\rho\left(u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y}\right) = \frac{\partial \overline{\sigma}_x}{\partial x} + \frac{\partial \tau_{yx}}{\partial y} + \rho g_x\left(1 - \beta(T - T_0)\right) \tag{2}$$

$$\rho\left(u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y}\right) = \frac{\partial \overline{\sigma}_y}{\partial y} + \frac{\partial \tau_{yx}}{\partial x} + \rho g_y\left(1 - \beta(T - T_0)\right) \tag{3}$$

$$\rho c\left(u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y}\right) = \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right) \tag{4}$$
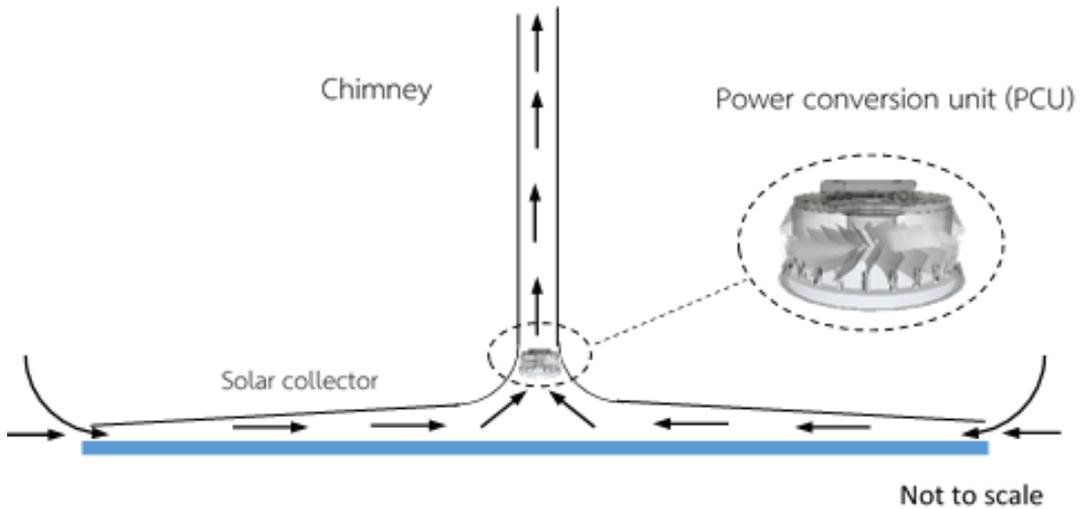
**Figure 1** The graphical presentation of solar chimney power plant

where u and v are the velocity components in x- and y-direction, the reference and fluid temperatures are defined by T0 and T respectively, ρ stands for the fluid density, the terms c and k are the fluid specific heat and fluid thermal conductivity, g is the gravitation constant and β is the volumetric coefficient of thermal expansion.

## Finite Element Formulation

Equations. (1-3) are composed of 4 unknown variables i.e. u, v, p and T which can be expressed by means of an approximation field as follows:

$$u(\mathbf{x}) = \sum_a^n N^a(\mathbf{x})u(\mathbf{x}^a) \tag{5}$$

$$v(\mathbf{x}) = \sum_a^n N^a(\mathbf{x})v(\mathbf{x}^a) \tag{6}$$

$$T(\mathbf{x}) = \sum_a^n N^a(\mathbf{x})T(\mathbf{x}^a) \tag{7}$$

$$p(\mathbf{x}) = \sum_b^n H^b(\mathbf{x})p(\mathbf{x}^b) \tag{8}$$

in which    $a = 1, 2, \ldots, 6$  is the quadratic shape function associated with velocity and temperature components,   $b = 1, 2, 3$  is the linear shape function for the pressure interpolation. Consequently, the six-node triangular element is used to discretize the problem domain in this study as depicted in Figure 2. It can be investigated that the pressure variables are interpolated only at the corner nodes of the triangle.
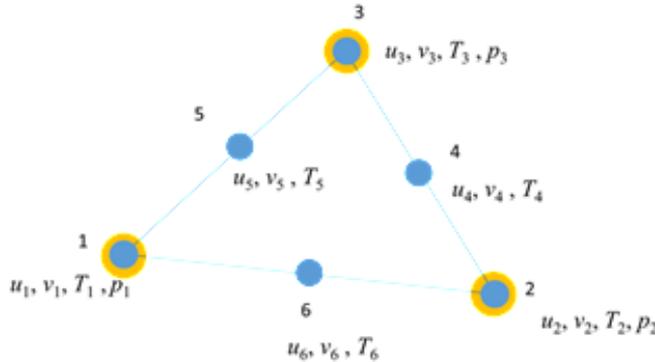


**Figure 2** The six-node triangular element.

Equations. (1-4) are solved by using the Newton-Raphson iteration method. The global system of nonlinear equations can be expressed as follows:

$$[\mathbf{K(x)}]\{\mathbf{x}\} = \{\mathbf{R}\}$$

(9)

where $[K(x)]$ is $n \times n$  matrix of nonlinear functions of $x$ ;  $x$ is $n \times 1$ the vector of unknown variables and R is $n \times 1$  the vector of known quantities. The iteration technique starts by assuming the initial value of $\{x\}$ and substitutes into Equation (9) leads to the unbalanced force vector as

$$\{\mathbf{F(x)}\} = [\mathbf{K(x)}]\{\mathbf{x}\} - \{\mathbf{R}\}$$

(10)

The final linearized system of equations with the incremental unknowns at the k th iteration is expressed as

$$
\begin{bmatrix}
K_u^\beta & K_v^\beta & K_T^\beta & K_p^\beta \\
K_u^\beta & K_v^\beta & K_T^\beta & K_p^\beta \\
K_u^\beta & K_v^\beta & K_T^\beta & 0 \\
K_p^{\beta u} & K_p^{\beta u} & 0 & 0
\end{bmatrix}
\begin{Bmatrix}
\Delta u^\beta \\
\Delta v^\beta \\
\Delta T^\beta \\
\Delta p^\beta
\end{Bmatrix}
= -
\begin{Bmatrix}
F_u^\alpha \\
F_v^\alpha \\
F_T^\alpha \\
F_p^u
\end{Bmatrix}
$$

(11)

The updated variables at the (k+1)th iteration can then be determined by

$$u_i^{k+1} = u_i^k + \Delta u_i^{k+1} \tag{12a}$$

$$v_i^{k+1} = v_i^k + \Delta v_i^{k+1} \tag{12b}$$

$$T_i^{k+1} = T_i^k + \Delta T_i^{k+1} \tag{12c}$$

$$p_i^{k+1} = p_i^k + \Delta p_i^{k+1} \tag{12d}$$

Equations (11-12) are repeated until the percentage of the overall error between the summations of incremental values and the present values is less than the tolerance value which is set to be 0.01% in this study.

## Numerical Simulation

In the following section, the flow in the solar chimney power plant, with three different types of connection between a solar collector and a chimney, is performed in 2D. According to the symmetry of the chimney, only one-half of the solar chimney is discretized with the unstructured six-node triangular element as shown in Figure 3.

Owing to the limitation of memory storage and to maintain the laminar flow in the analysis, the main dimensions used in the simulation are not the real conditions of the prototype built in Spain. The magnitudes used in the simulation are given as follows: height of the chimney, 1 m; diameter of the chimney, 0.1 m; radius of collector, 1 m; height from the inlet to its center, 0.05-0.08 m.

In addition, the velocity of the air moving to the solar collector at the inlet is set to be 3.81 m/s and the difference of the temperature in the system is assigned to.
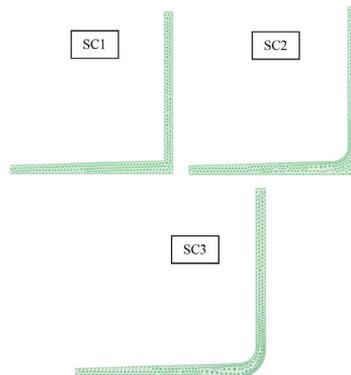


**Figure 3** Solar Chimney models used in the analysis

Figures 4-6 show the numerical results of various solar chimney models obtained by FEM. Plotted in Figure 4 are the temperature contours along the energy collector and the chimney. As can be seen, a smooth continuity of temperature distribution can be observed in SC2 and SC3 models while the discontinuity of the result presents at the corner of straight junction as illustrated in Figure 4(a). Furthermore, this phenomenon can also be investigated in the case of velocity and pressure distributions.

Figure 5 displays the velocity vectors of the flow. In the case of SC1 and SC2, it can be noticed that the velocity decreases and vanishes at the transition area from the energy collector to the chimney's base. Consequently, this transition area is unnecessary in the system. Furthermore, the velocity results obtained from SC3 model exhibits a smooth and continuous flow. Also, the maximum value of velocity can be obtained at the chimney's base where the power generator will be installed.
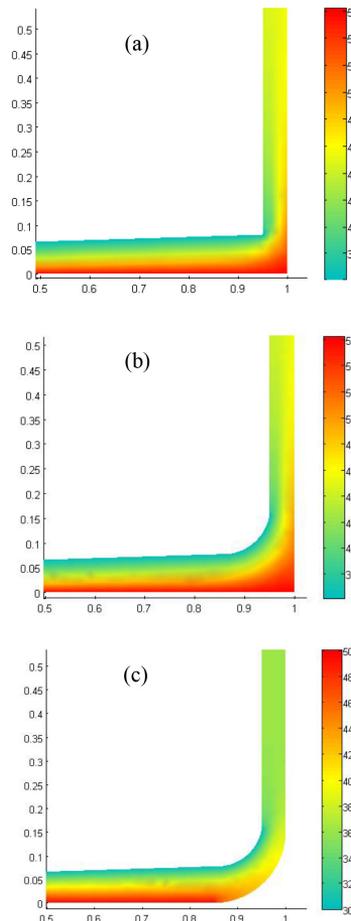


**Figure 4** Temperature distributions obtained by the present method

The pressure contours are illustrated in Figure 6. For all models, the maximum pressure value can be found at the inlet of the air flow channel and decreases through the radius of the collector. Then, it begins to vanish at the top of chimney where the air flow exits. Additionally, at the position of the power generator, the average pressure obtained from SC3 is higher than the rest of models.
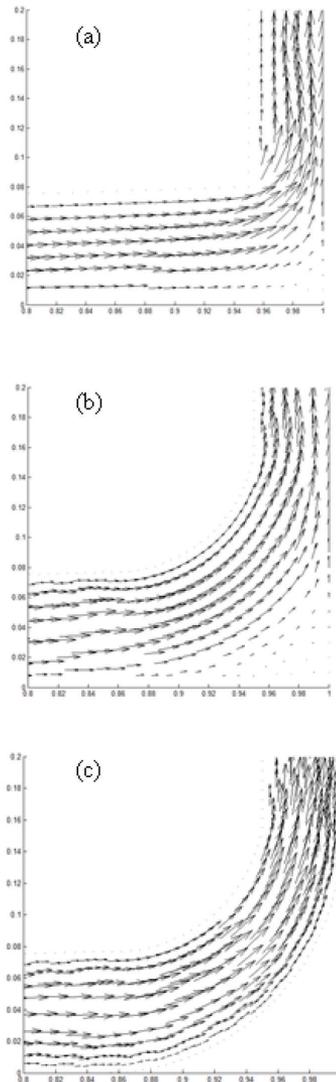


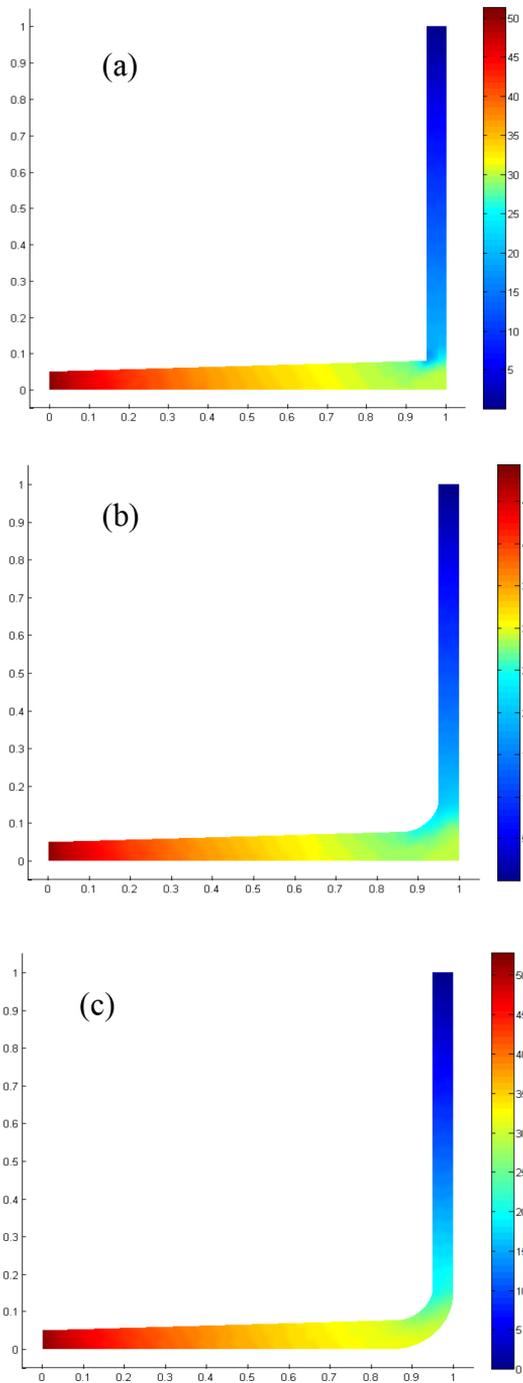**Figure 5** Velocity vectors obtained by the present method

**Figure 6** Pressure distributions obtained by the present method

## Conclusions

A finite element program for steady-state viscous incompressible thermal flows has been developed. The six-node triangular element is used to discretize the three different types of SCPP model. It was found that the proposed model can be applied successfully to study the localized characteristics of the flow. Also, it is discovered that the SC3 model provides the maximum of the average velocity and pressure at the power conversion unit. As a result, the SC3-junction type will be accepted in practice. However, more details are needed for analysis and design of the real SCPP system such as the effect of turbine installation or the shape of the chimney.

In addition, as the Asean Economic Community (AEC) is coming in the year 2015, this research can be considered as a starting point of CFD software development which can improve the international competitiveness in computational engineering research areas.

## Acknowledgements

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