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Thermal-CFD Analysis of Combined Solar-Nuclear Cycle Systems

Nima Fathi[1], Patrick McDaniel, Peter Vorobieff, and Cassiano de Oliveira

Department of Mechanical Engineering
Department of Nuclear Engineering
The University of New Mexico

Sal Rodriguez

Sandia National Laboratories, Advanced Nuclear
Concepts

Seyed Sobhan Aleyasin

Department of Mechanical Engineering
The University of Manitoba

Abstract- The aim of this paper is evaluating the efficiency of a novel combined solar-nuclear cycle[2]. CFD-Thermal analysis is performed to apply the available surplus heat from the nuclear cycle and measure the available kinetic energy of air for the turbine of a solar chimney power plant system (SCPPS). The presented idea helps to decrease the thermal pollution and handle the water shortage supply for water plant by replacing the cooling tower by solar chimney power plant to get the surplus heat from the available warm air in the secondary loop of the reactor. By applying this idea to a typical 1000 MW nuclear power plant with a 0.33 thermal efficiency, we can increase it to 0.39.

Keywords: Nuclear Power Plant, Combined Cycle, Solar Chimney Power Plant, Thermal Pollution, Water Shortage Problem

[1] Corresponding Author, Tel:+15052778003, Email: nfathi@unm.edu

[2] The idea has been patented; application number 14/695,046. GRP ART UNIT: 3749.

1. Introduction

While renewable energy is steadily improving its global share (Trancik 2014) the challenge is convincing the industry to invest more money in renewable energy, and to make it even more attractive by decreasing the capital cost. Until recently, the fluctuation of funding was a limitation of renewable energy, especially in the US, and was one of the barriers for progress. Another limitation of many renewable energy systems is the variability in their output, which makes them unsuitable for baseline power production. Solar chimneys are one of the rare examples of renewable energy power plants that can produce baseline power. During the daytime, the sun heats the ground under the collectors, and in the night time, the heated ground continues warming the air, thus sustaining the power-generating updraft flow. A major drawback of the solar chimneys is that to provide 24/7 power and to be economically competitive, they must be built on a massive scale, requiring corresponding upfront investments.

We are trying to increase the performance of solar chimney systems resulting in building of smaller (and thus cheaper) solar chimney plants and consequently decreasing the levelized cost of the produced electricity. The main goal is to make the final cost competitive with electricity produced from gas and coal. Any efficiency improvements of solar chimney towers can play an important role in global energy savings. A combined solar cycle has many advantages such as enhancing thermal efficiency of the solar chimney power plants.

In a solar chimney plant, the energy of buoyant hot air is converted to electrical energy. The plant consists of a collector at the base covered with a transparent roof that collects the solar radiation, heating up the air inside and the ground underneath. In the center of the collector, there is a tower, and a turbine is located at the base. The hot air flows up the tower as a result of the buoyancy effect, and its energy is extracted and converted to electrical energy by means of the turbine. A typical solar chimney is shown in Figure 1. Research on solar power plants started around 1970, leading to construction of the first prototype in Spain. This plant operated between 1982 and 1989, and its electricity was used as a part of the local electrical network (Haaf et al., 1983; Haaf, 1984). Padki & Sherif in 1989 used information from the Manzanares prototype for extrapolation to large scale models for a solar chimney power plant system (SCPPS). In 1991, Yan et al. developed a detailed model for an SCPPS by using a practical correlation. They considered several key parameters, such as air velocity, air flow rate, output power, and thermal efficiency. Several researchers studied the effect of different geometrical parameters on plant efficiency. Padki and Sherif in 1999 reported that the converging-top chimney could increase the power and efficiency of the solar plant. The mathematical model of Chitsomboon in 1999 revealed that a converging top did not improve the power and efficiency; and they remained almost constant. Von Backstrom and Gannon in 2000 applied a one-dimensional compressible flow model that included chimney height, wall friction, additional losses, internal drag, and area change. They found that for a given chimney height, an increase in area ratio results in higher pressure drop in the chimney. In 1995 Schlaich reported that according to his mathematical model, there were no optimal dimensions for a solar chimney; however, by considering construction costs, a thermo-economically optimal plant configuration might exist.

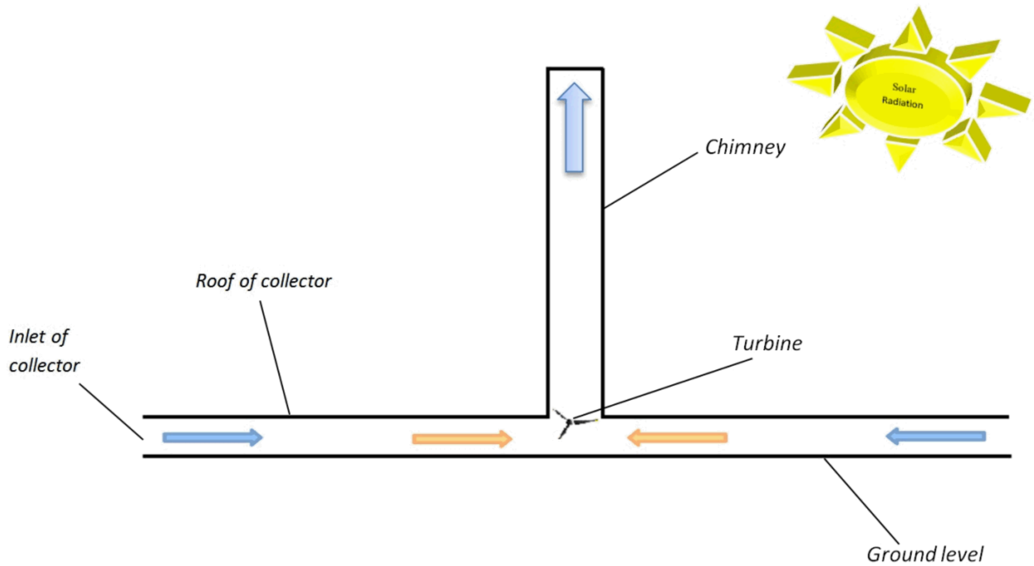


Figure 1 Schematic of a solar chimney power plant.

According to numerical studies conducted by Pretorius and Kroger in 2007, the power is dependent on both the shape of collector roof and height of the inlet. Maia et al. in 2008 carried out a simulation study and noted that the most important geometric dimensions are the height and diameter of the chimney. Zhou et al. in 2009 reported the maximum chimney height in order to avoid negative buoyancy, and the optimal chimney height for maximum power output. They found that the maximum and optimal heights increase with collector radius. A common feature in these findings is that the plant efficiency is very low; however, it increases with plant size.

It is usually assumed that the tall chimney follows a conventional design (rigid construction, foundation, guy wires, etc.). Such a construction on the scales suitable for a commercially viable SCPPS is not only very expensive, but presents a challenge in terms of surviving an extreme weather event. Recently, a novel free-standing inflatable design was proposed to reduce the construction costs and increase the survivability of a solar chimney (Putkaradze et al., 2013). This design has also been experimentally demonstrated on a small scale for code calibration and validation analysis (Fathi et al., 2014). The prototype was able to withstand very strong winds (Vorobieff et al., 2014, Chi et al., 2015).

Another problem of all SCPPSs proposed (or built) so far, is an extremely low efficiency in the utilization of solar energy input – 0.5% to 5%. In this paper, we show that this efficiency can be greatly improved by having the circulating system use the heat waste of any thermal engines and capacitances. Heat waste from power plants (conventional and nuclear) can be applied, and the degree of increase in thermal efficiency depends on seasonal variations.

2. Methodology, Improved SCCPS

One of the important heat sources that can be applied in SCPPSs is the heat produced from the thermal cycles in power plants. In nuclear power plants such as the Very High Temperature Reactor (VHTR), the outlet temperature is in the range of 1175 to 1275 K. The ratio of heat output from a power plant that is actually converted into electrical energy is called the thermal efficiency, η_{th} of the system; thus, in a nuclear facility, one can write (Zohuri et al., 2015)

$$\eta_{th} = \frac{Electrical\ Energy\ Generated}{Heat\ Produced\ by\ the\ Reactor} \qquad (1)$$

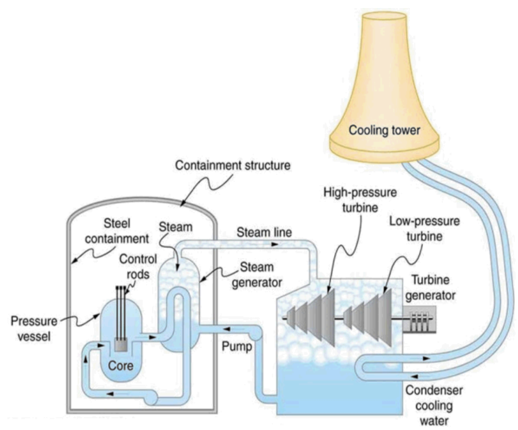


Figure 2 Schematic diagram of a pressurized water reactor and the steam turbines that convert work into electrical energy.

By combining the solar chimney tower system with a nuclear power plant, the overall thermal efficiency can increase because of the extra electrical power produced by the turbine in the SCPPS. The issue is how to apply the waste heat from nuclear power plants, such as pressurized water reactor (PWR, Figure 2), molten salt reactor (MSR), or VHTR. We suggest replacing the cooling tower with an SCPPS to extract more heat from the overall system.

Figure 3 Schematic diagram of a combined solar cycle with a pressurized water reactor.

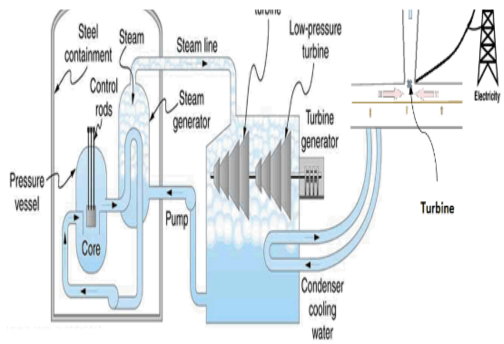


Figure 3 explains our idea schematically. We replace the cooling tower (Figure 2) with a solar chimney tower. Instead of being discharged to the atmosphere, some of the waste heat is converted to additional electricity by the SCPPS. Figure 4 shows schematically the arrangement of a combined solar cycle for an MSR.

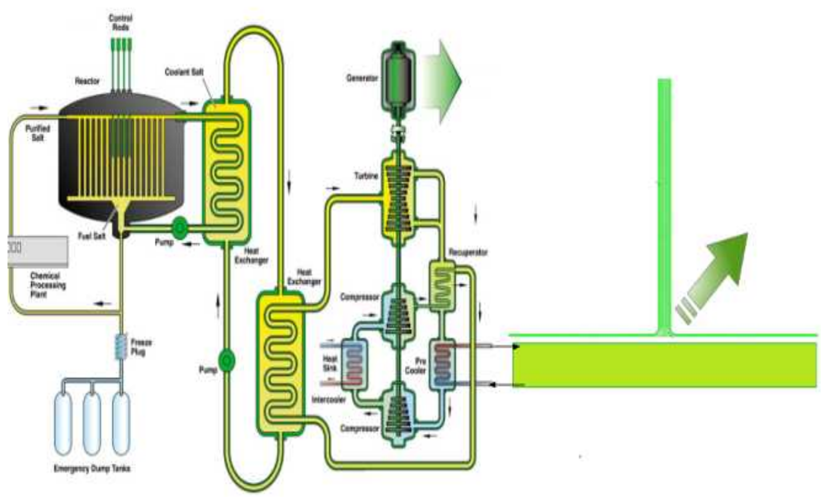


Figure 4: Schematic diagram of a combined solar cycle in a Molten Salt Reactor.

3. Numerical Analysis

Computational fluid dynamics (CFD) modeling using the finite volume method was employed to investigate the effectiveness of SCPPSs when they are replaced with normal cooling towers. To date numerous numerical models with various coupling between the collector, turbine, and chimney have been introduced to evaluate SCPPS (Ming et al., 2008). In order to simplify the analysis, initially the chimney design is optimized without considering the rest of SCPPS. Then the effects of the collector and turbine are considered. One of the issues corresponds with the numerical modeling of a large-scale SCPPS prototype is computational cost. A best approach to avoid the huge cost is applying dimensional analysis methodology. In this way the effective parameters are found and combined into dimensional variables to reduce the number of calculations (Koonsrisuk et al., 2007). In the present modeling the mass flow rate, obtained from the CFD results, along with other parameters were used to evaluate the maximum mechanical power for each case. ANSYS ICEM (Integrated Computer Engineering and Manufacturing) CFD was employed to generate a quadrilateral cell mesh. The calculations were done using a four-core, 32 G RAM Xeon computer. The meshed SCPPS axisymmetric model is shown in Figure 5 with more details on the zoomed parts.

To perform the CFD simulation, the standard k-ε, which is classified as a two-equation model, was applied. The standard k-ε model is a common turbulence model in industrial CFD since it was proposed by Launder and Spalding. This is due to its robustness, economy, and reasonable accuracy in simulation of certain turbulent flows in engineering applications. However some k-ε models are not suitable in evaluation of flows in which adverse pressure gradients or separation are present. They typically predict a delayed and reduced separation relative to observations. This can result in overly optimistic design evaluations for flows, which separate from smooth surfaces (aerodynamic bodies, diffusers, etc.). The k-ε model is therefore not widely used in external aerodynamics**Error! Reference source not found.**. Applying a wall function helps the accuracy of the standard k-ε model.

The standard k-ε model includes two extra transport equations: one for turbulence kinetic energy (k) and the other for dissipation rate (ε). The model transport equation for k was adjusted from the exact equation based on experimental data. However, the model transport equation for ε bears little resemblance to its mathematically exact counterpart. The standard k-ε is suitable for high Reynolds-number flows far away from walls. The equations for turbulence kinetic energy, k, and dissipation rate, ε, are as follows:

$$\frac{\partial}{\partial t}(\rho k)+\frac{\partial}{\partial x_i}(\rho k u_i)=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right]+G_k+G_b-\rho\varepsilon-Y_M+S_k \tag{2}$$

$$\frac{\partial}{\partial t}(\rho\varepsilon)+\frac{\partial}{\partial x_i}(\rho\varepsilon u_i)=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial\varepsilon}{\partial x_j}\right]+C_{1\varepsilon}\frac{\varepsilon}{k}(G_k+C_{3\varepsilon}G_b)-C_{2\varepsilon}\rho\frac{\varepsilon^2}{k}+S_\varepsilon \tag{3}$$

Here G_k and G_b denote the generation of turbulence kinetic energy due to the mean velocity gradients and buoyancy, respectively. Y_M represents the contribution of the fluctuating dilation in compressible turbulence to the overall dissipation rate. σ_k and σ_ε are turbulent Prandtl numbers for k and ε, respectively. $C_{1\varepsilon}, C_{2\varepsilon}$ and $C_{3\varepsilon}$ are constants. S_k and S_ε are user-defined source terms.

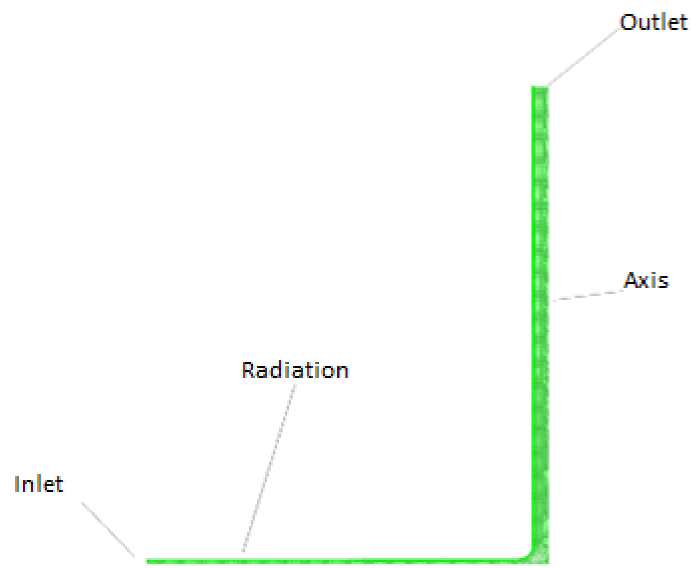
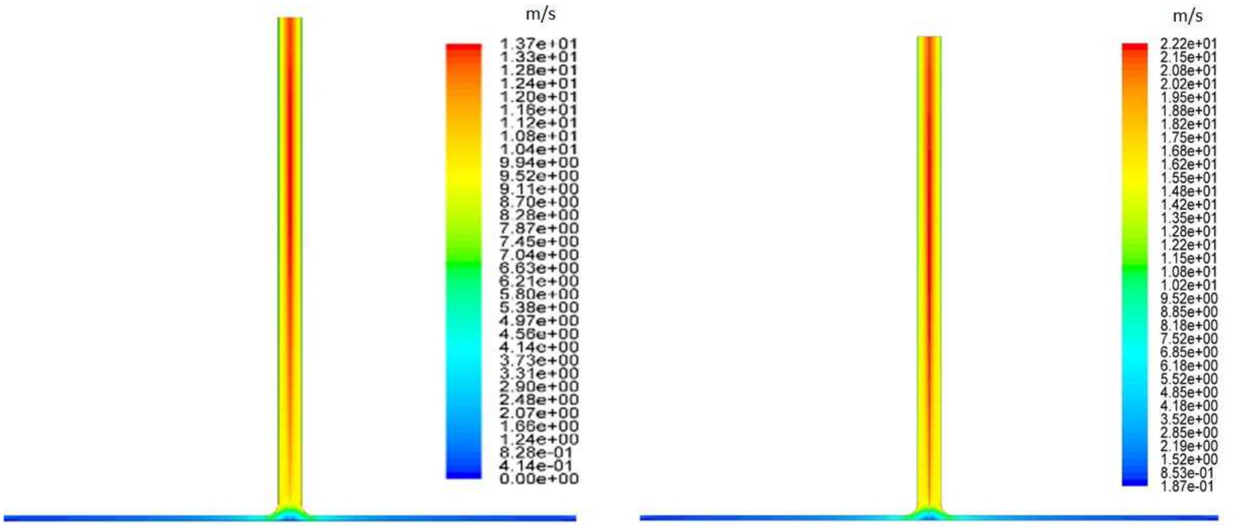


Figure 5 Zoom of model mesh.

Figure 6 (left) shows the velocity contour plot of a traditional design with a mass flow rate of 830 kg/s and an average inlet velocity of 8.5 m/s for the turbine for the winter case (minimum irradiation). Figure 6 (right) shows the velocity contour plot for a test case in which additional electricity was extracted from the waste heat. The calculated mass flow is 1200 kg/s, which represents a 45% increase in the mass flow rate. By considering different cases we see the range from 25 to 140% increase in the output electricity of the turbine of the solar chimney power plant. By building a bigger prototype on the order of 1 km height, power generation from the turbine can be raised to 100 to 200 MW. These numbers are based on the similarity analysis between the Manzanares power plant and larger conceptual solar power plants that have been investigated previously (Schlaich, 1995). By applying our idea of coupling the solar cycle with a nuclear power plant cycle, or any power plant cycle with a sufficiently warm, high mass flow rate, we can increase the power generation by at least 20-40 MW. Let say for 1000 MW nuclear power plant, with the thermal efficiency of .33 by adding the turbine work of a large scale SCPP (1 km), we can increase the thermal efficiency from 0.36 to 0.39. The output power of SCCP in 1km scale has been estimated to 100 to 200 MW (Schlaich 1995).



Left: Velocity (m/s). Contour plots of a Manzanares prototype, for winter case, zero radiation, and 400 W waste heat. The mass flow rate is 825 kg/s. Mean updraft velocity is 8.7 m/s. Right: Velocity (m/s). Contour plot of our patent design for a solar chimney tower system. Summer case, 1500 W heat flux, mass flow of 1,200 kg/s, and mean updraft velocity of 14.5 m/s. This system has a 150% increase of available-harvestable kinetic energy.

4. CONCLUSIONS

We performed and modeled a novel idea to use the available heat (waste heat) from power plants for a solar chimney power plant to enhance its efficiency compared to the traditional case. The harvestable power can increase by at least 25 to 140% in the winter and summer cases, using the new method. A side advantage of this method is decreasing the thermal pollution for nuclear power (and other thermal) plants. There also exists a possibility of reducing the capital cost of combined cycles for power plants, such as nuclear power plants plus solar power plants. The total thermal efficiency of the combined thermal system can increase by up to 6%, which is considerable for the nuclear power industry, and should have a significant effect on capital cost and development of new generations of nuclear power plants.

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