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Computational and experimental studies on solar chimney power plants for power generation in Pacific Island countries

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ABSTRACT

Computational and experimental studies were performed on solar chimney power plants (SCPP). The first part of the work was optimization of the geometry of the major components of an SCPP of 10 m height and 8 m collector diameter using a computational fluid dynamics (CFD) code ANSYS-CFX to study and improve the flow characteristics inside the SCPP. The collector inlet opening, the collector outlet height, the collector outlet diameter, the chimney divergence angle, chimney inlet opening and the diameter of the chimney were varied and optimum values that give the highest power were obtained. Based on the best configuration achieved for the 10 m high SCPP, a scaled down model of 1:2.5 was modeled and simulated. The 4 m tall SCPP had a collector diameter of 3.2 m. The collector outlet height was kept constant while the collector outlet diameter and the chimney throat diameter were varied in the second part. The collector inlet opening was also varied. The best configuration was then fabricated and extensive experiments were carried out on days of different solar insolations with and without water bags including the effect of atmospheric wind as the third and main part of this work. Detailed measurements of temperature variations along the collector and along the chimney height were performed. The air velocity at the location of turbine was measured and the power available to the turbine was estimated. It was found that, at higher wind speeds, the temperatures along the collector and along the chimney height drop a little; however, the air velocity and available power increase. Water bags were placed under the collector to obtain round-the-clock power. A 100 m SCPP was later modeled and simulated to predict the power available for bigger sized towers at different solar insolations. Such SCPP plants will be very appropriate for Pacific Island Countries; most of these countries have islands with populations of only a few hundred people. Also, the solar insolation is very high in these countries.

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1. Introduction

The increasing energy consumption all over the world and the harmful environmental effects of fossil fuels have forced the global energy community to look for renewable sources of power. The demand for electricity is continuously rising especially in developing countries [1]. Unfortunately, fossil fuels are still the primary fuel source and are widely used in most of the countries. For many developing countries, especially the small island developing states (SIDS), a considerable portion of GDP goes towards the cost of fossil fuels. Inadequate energy supplies can not only lead to higher energy costs, but are also a hindrance to the development of a country. With the greenhouse effect and air pollution becoming more severe, utilization of renewable energy sources is increasingly gaining greater importance and playing a major role in solving the above problems [2].

Renewable energy based technologies hold a great promise for the future as they are less harmful to the environment and their resources are available in abundance. Although there are many sources of renewable energy, solar energy is one of the more promising ones since the sun is the ultimate source of most renewable energy supplies. Although solar energy has the highest available energy, only a little fraction of the available energy is used. Solar energy is only available in the day, but technical advancements have made it possible to harness this energy at night by storing the solar energy available in the day [3,4].

A variety of devices have been built to harness solar energy; however most of them are expensive to build and maintain. This is one of the major issues in developing countries. The solar energy device must be simple, reliable and cheap to build and maintain. The Pacific Island Countries (PICs) have limited raw material resources and it is very expensive to import specialized materials.

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So, the preference is for technologies that require cheaper and easily available resources. The solar chimney power plant (SCPP) meets these conditions very well. The SCPP is simple and reliable since it has fewer rotating parts compared to other thermal power plants and it is cheap since the raw materials needed to build an SCPP are readily available in most of the developing countries. The SCPP can also produce power at night by using water bags to store the heat in day time and release this heat slowly at night to provide round the clock power supply [4].

Solar chimney power plants, also called, low temperature power plants, have their working fluid open to the atmosphere. A solar chimney power plant, in its simplest form, consists of three main components [4,5]: the solar air collector, the chimney or the tower and the power conversion unit which include turbines.

The collector is a transparent glass or plastic film close to the ground and is open at the periphery with its height constant, increasing or decreasing towards the center where the chimney is located. Solar radiation enters the collector and gets absorbed by the ground. The chimney is a long cylindrical structure placed at the center of the circular greenhouse collector [6,7]. It is required to ensure an air-tight joint between the collector and the chimney. The air below the collector gets heated up and rises towards the chimney. At the base of the chimney, one or more turbines are placed to extract energy from the rising air which possesses good amount of kinetic energy. Suction from the chimney draws more hot buoyant air from the collector and cold air from free atmosphere replaces the hot air due to natural convection. Water-filled tubes or bags are placed under the collector to make the SCPP work at night. Thus, the solar energy is first converted into thermal energy by the ground, which is then converted into kinetic energy of the hot air and later converted into mechanical energy by the turbine(s) [4,8].

Some of the main advantages of SCPPs compared to other solar thermal power plants include: (a) both direct and diffuse radiation are used for generating power, which is an important factor for PICs where the sky is often overcast, (b) SCPPs are very reliable and are not likely to break down since they have very few moving parts (mainly turbine); the robust structure ensures that very little maintenance is needed, (c) no cooling water is needed which is one of the primary requirements of many power plants [4,9]. This is a major advantage in PICs where the availability of fresh water is an issue, and (d) less developed countries such as PICs can easily build SCPPs as the building materials which are mainly concrete and glass or plastic sheets, are easily available. Also, SCPPs are easy to manufacture and do not require advanced technologies [4,9]. One major drawback of SCPPs is low energy conversion efficiency which means a much larger collector area is required.

2. Background

The concept of an SCPP was conceived as early as 1931 (in [4]). However, the first real concept of an SCPP was proposed by Jorg Schlaich in 1978. In the year 1982, the first (50 kW) SCPP was built and tested for performance in Manzanares, Spain. Haaf et al. [10] presented the principle and construction details of this SCPP while Haaf [11] presented the preliminary test results from this pilot plant. The tower had a height of 194.6 m and a radius of 5.08 m; the mean collector radius was 122 m and the mean roof height was 1.85 m. This plant worked on a regular basis from 1986 to early 1989. It used to start up automatically when the air speed in the tower exceeded about 2.5 m/s. In the year 1987, the mean annual solar insolation was over 150 W/m^2 at the site. Detailed performance of this system, its characteristics, the technical issues and basic economic data for future commercial SCPPs are discussed by Schlaich et al. [4]. Schlaich [12] also provided an overview of SCPPs. During the last decade, there is a tremendous increase in the research works in the area of SCPPs. One of the initial attempts to simulate an SCPP using CFD was made by Bernades et al. [13]. They performed numerical analysis of natural convection in a radial solar heater operating in steady state to predict the thermo-hydrodynamic behaviour of the device. A finite volume method was used to solve the Navier-Stokes and energy equations which gave a detailed picture of the effects of geometric and operational characteristics. The results obtained by Bernades et al. [13] showed that curved junctions initiate well distributed temperature fields and resulted in flow which is free from recirculation as well as a higher mass flow rate compared to straight junctions at the center of the collector. Padki and Sherif [14,15] investigated the viability of SCPPs for medium to large scale power generation and also their viability for rural areas. Detailed theoretical and experimental studies were performed by Pasumarthi and Sherif [7,16] to investigate the performance characteristics of an SCPP. With their mathematical model, they studied the effect of various geometric parameters on the air temperature, velocity and power output of the plant. They then did experimental modifications on the collector: extending the collector base, and introducing an intermediate canvas absorber. The second modification showed more benefits as it increased the air temperature as well as increased the mass flow rate. Their demonstration model had a collector radius of 9.15 m and a chimney height of 7.92 m.

The driving potential of an SCPP was analyzed and the results were presented by Kroger and Blaine [17]. They assessed a number of theoretical models and studied the influence of prevailing ambient conditions. It was found by them that humidified air can enhance the driving potential and at certain conditions condensation may occur. Bernades et al. [5] developed a comprehensive analytical and numerical model to describe the performance of SCPPs. The model was used to estimate the power output of SCPPs and also to study the effect of several ambient conditions and structural dimensions on the power output. They validated the results of their mathematical model against the experimental results and then predicted the performance of large-scale SCPPs. The main conclusions were that the chimney height, the pressure drop across turbine, the size and the optical properties of the collector are the major parameters for a good design of an SCPP.

Ming et al. [18] developed a comprehensive model to evaluate the performance of SCPPs by investigating various parameters like the relative static pressure, driving force, power output and efficiency. They also performed numerical studies to explore the geometric modifications on the system performance based on the Manzanares plant; a good agreement was found with the analytical model. From their work on thermo-economic optimization, Pretorius and Kroger [19] concluded that round-the-clock power generation is possible and the power generation is a function of the collector roof shape and collector inlet height. Pastohr et al. [20] carried out numerical work to study the temperature and flow field in an SCPP. A detailed analysis of the effects of solar radiation on the flow inside the solar chimney plant was performed by Huang et al. [21]. They employed the Boussinesq model and the Discrete Ordinate model for their simulations. They found the pressure throughout the system to be negative; it was also concluded that the temperature difference between the collector inlet and outlet and the pressure difference in the collector-chimney transition section is higher for higher radiation. Ming et al. [22] studied the effect of solar radiation on the heat storage characteristics of the energy storage layer with the help of different mathematical models for different components. Studies were conducted by Koonsrisuk and Chitsomboon [23] based on dimensional analysis together with engineering intuition to combine eight variables into a single dimensionless variable to establish dynamic similarity between a prototype and scaled models of an SCPP. Three plant

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