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The experimental appraisement of the effect of energy storage on the performance of solar chimney using phase change material

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ABSTRACT

This research aims at investigating the performance of a laboratory solar chimney using thermal phase change material. The geometric properties of this prototype consist of a chimney 0.3 m in diameter and the length of 12 m and an air collector with the diameter and height of 11 m and 0.65 m, respectively. Some measuring instruments including air speed meter, temperature sensors, and a processor are employed so as to record changes in temperature of intake air, ground, and air trapped within the collector in addition to speed alterations of intake air in three modes of utilizing soil, water and paraffin as a thermal storage material. It can be clearly seen from the results that using water and paraffin as thermal storage materials have increased the time productivity by 9% and 20%, and electric energy production by 6.2% and 22%, respectively in comparison to no absorber state in this solar power plant.

1. Introduction

In today's world, due to current economic reforms and the rapid pace of technological progress, energy consumption is rising. Many sectors experience exponential growth in energy consumption. Aman et al. believe that the rate of this increase is 2.4% (Aman et al. 2015). Renewable energy systems consist of solar, wind, geothermal energy, ocean energy, hydropower, biomass and fuel cell resources in which solar energy plays a pivotal role among these clean energy resources so that should only one percent of the world's deserts were exploited as solar power plants, this would supply the total annual electricity energy of the world. On the other hand, if all fossil fuels were gathered and burned, the obtained energy would be equivalent to only 4 days of sun radiation. One type of human energy sources is solar energy. It produces the least harm to the environment and therefore solar energy can be considered as a green energy source. Low carbon emissions, no fossil fuel requirement, long-term solar resources, less payback time, and etc are some of the benefits brought by utilizing solar energy.

Nowadays correct policies implementations along with planning in the field of energy efficiency are assumed as top priorities. Although abundant and unlimited solar energy without massive, costly and risky distribution networks is accessible from any location, it should be noted that unlike the energy provided by fossil fuels, solar energy is not available at all times. Cooling loads which mainly is caused due to the time lag between solar energy absorption and release of energy by objects, are present after sunset and hence this indicates the significance of solar energy storage to improve efficiency during these hours. Fossil fuel power plants will be soon replaced with solar power plants having very low cost, free from harmful gas emissions, and without occupying space (Raoufirad, 2006). Thermal Energy Storage (TES) can compensate this mismatch between availability and demand. Paraffin can be utilized as a thermal energy storage substance.

A two-phase energy transformation that is the conversion of solar energy into electrical energy is done at solar power plants. The first step is to heat the air with a low circular glass roof open at the environs; so that a hot air collector arises between it and the ground, and then the vertical chimney installed in the middle of the ceiling transmits air from itself to convert thermal energy it becomes kinetic energy. Since the hot air is lighter in comparison to the cold one, so it rises from the chimney; then chimney absorbs this hot air and suction it in the cooler collector out of the environment as much as possible (Schlaich, 2000). Finally, the inlet air volume is converted into electrical energy by a wind turbine and an electrical generator (Gebhart, 1993). Solar chimney power plants do not require direct sunlight and the collectors can be used for all solar sunlight, both direct and indirect, especially in cloudy weather, but it is worth to note that the efficiency of converting solar energy into electrical energy in these power plants is very low (Hajgholami, 2005). To deal with low efficiency of the solar chimney power plant,

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appropriate materials can be used to store the sun's energy during day and night.

The specifications of heat transfer and air flow with an energy storage layer in the solar chimney power plant system had been analyzed by Ming et al. (2008). They applied a numerical simulation for this analysis and results show that if the solar radiation raises, the chimney outlet and the energy storage layer will increase substantially. This increase in radiation raises the storage temperature leading a rise in energy loss at the bottom of the energy storage layer. To investigate the influence of thermal diffusivity and effectiveness of some ground thermal attributes, Bernardes (2013) performed a mathematical model. These studies demonstrate that when the physical actuation of the soil is lower but more permeable, then the output waves for periods with increasing heat will be markedly reduced referred to as a complex terrestrial thermal behavior. A visionary model based on the energy equations has been expanded. The thermal behavior and operation of a solar latent heat storage unit (LHSU) which consists of a series of specific tubes imbedded in the (PCM) were predicted (Qarnia 2009). He concluded that the output level would never be more than 28 °C, therefore the use of n-octadecane is not suitable as a PCM. On the other hand, if paraffin wax (P116) is used, part of the PCM will remain liquid and the water outlet temperature will increase. A Fortran computer code was developed by Anica et al. (2006) to predict the effects of operational conditions on heat transfer process as related to the heat transfer fluid (HTF) and geometrical parameters of water and paraffin shell and tube exchanger of latent thermal energy storage unit. Paraffin Rubitherm RT 30 was considered as a phase change material and water was used as a heat transfer fluid. The results illustrate that while total energy stored in form of latent heat remains constant, total stored energy goes up and temperature difference among HTF inlet and PCM melting point increases linearly.

Numerical predictions correspond slightly with the experimental outcomes. Thus, the defined CFD method could be implemented to indicate thermal behavior of LTES unit efficiently during charge and discharge process. Halawa and Saman (2011)) In a comprehensive numerical study on thermal function of the TSU concluded if the mass and PCM level are kept constant, the output and heat transfer rate will not change with the alterations in PMC dimensions. The phase change behavior of capric-acid and lauric-acid with the purity of sixty-five - mole% and thirty-five mole% respectively, calcium chloride hexahydrate, n-octadecane, n-hexadecane, and n-eicosane inside spherical enclosures were studied by Veerappan et al. (2009) to introduce a proper heat storage material. Comparing with the previous studies, the results represent a deviation of 15% for solidification and 20% for melting and also prove that the temperature below the initial one has no effect on the solidified mass fraction of PCM. The melting properties of 65 mol% C10H20O2 and 35 mol% lauric acid are superior to the other PCMs, although this PCM has the worst solidifying properties. Calcium Chloride Hexa-hydrate has supreme solidifying properties, whereas melting properties are almost satisfying. Due to having rapid rates of charge and discharge, this material is identified as the best phase change of the chosen PCMs. Beside that, the aforementioned PCM could be utilized in energy storage systems with low temperature. In 2014, Li and Liu (2014) tested PCM on a solar chimney. In this research, the thermal flux of different PMCs was calculated so as to compare the energy storage capacity of the laboratory. Finally, it was found that in all testing conditions, the PCM usage time could be longer than 13 h and 50 min. Shuli and Yongcai (2015) also examined the thermal performance of a solar chimney. They conducted this assessment with and without phase change material (PCM). The results indicate that entering PCM into solar chimney along with the airflow reduces the length of the charge, but it also increases that during the drainage period with a solar cell without PCM. In 2016, Iten et al. (2016) conducted an experimental analysis on the effect of thermal conductivity enhancers (TCEs) upon heat transfer function in the PCM during the melting and solidification operations to use it in solar chimney. The experiment shows that the VF, HF, HCS and SCS decreases the duration of melting by 8%, 12%, 14.5% and 16%, severally in comparison to the pure PCM sample. By adding phase change materials (PCMs) to the passive solar collector-storage wall system, Sun and Wang (2016) in their study concluded that the technology with PCM could be used to heat the interior of the building and the temperature fluctuations in the digital storage system enhance the new solar power.

In the present paper, the experimental thermal analysis of a solar chimney power plant has been conducted for three kinds of PCM:

- Covering the collector’s ground with natural soil (without absorber)
- Using water-filled black tubes as thermal absorber
- Using paraffin-filled black tubes as thermal absorber

2. Experimental setup

In the present work, experimental investigations are carried on a solar chimney power plant experimental setup. The setup consists of a 0.3-meter-diameter and 12-meter-tall chimney and an air collector with 11 m and 0.65 m in diameter and length respectively. Dimensions and geometrical properties of this prototype have been selected from Bernardes et al. (1999) research results. The cone-shaped input of the chimney is one of its unique characteristics which provides the best condition for airflow and the temperature diversity between inlet and outlet air flow. The dimensions of the conical structure are 80 cm diameter at inlet, 32 cm diameter at outlet, a 34 cm edge and 20 cm slant height. The setup location is a land area of 92 m^2, located at 36°34′30.06″ North latitude and 59°11′58.458″ East longitude. The ground was levelled and aligned as well as determining the center. As an important main part of the experimental solar power plant, the tower is made of two PVC tubes 315 mm in diameter, thickness of 6.2 mm, and 6 m tall. The collector surface is made of glass and polycarbonate sheets with 12.3° slope and an average height of 65 cm (Fig. 1). Dimension of chimney is shown in Table 1.

The experimental procedure is divided into two steps. An infrared thermometer with a temperature range from −20 °C to 537 °C, tolerance of about ± 2 °C, and emissivity of 0.95, along with a speedometer to measure air velocity with a the range from 0.4 m/s to 25 m/s and temperature range from 0 °C to 50 °C were used for primary measurement. The measurement tools specifications are listed in Table 2.

A data logger recorded the information every minute during 24 h. The data logger has a counter that was connected to anemometer sensors so as to record wind flow velocity with a time constant (ts) on

Fig. 1. Experimental solar power plant.