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# Sloped-collector solar updraft tower power plant performance

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ABSTRACT

A mathematical model describing fluid flow, heat transfer and pressure distribution inside a sloped-collector solar updraft tower power plant (SCSUTPP) is presented by assuming a steady compressible flow. Compared to conventional horizontal-collector solar updraft tower power plants (HCSUTPPs), the performance of SCSUTPP is comprehensively studied based on the mathematical model. The power outputs for SCSUTPP and HCSUTPP using the essential expression of driving force are respectively compared with those using the driving force expressions containing no integral, as proposed in literature. Results show that the expression containing no integral is accurate for HCSUCPP based on a compressible fluid model. The expression containing no integral is not accurate for predicting the driving force of SCSUTPP based on an incompressible fluid model when no variation of the atmospheric density with heights and no variation of difference of the atmospheric density and the density of the current inside the short SUT with heights are assumed. The gravitational effect has to be considered for predicting the SCSUTPP performance. The results show that the pressure potential and the power production of an SCSUCPP with a collector of 848 m height and a vertical SUT 123 m high lies between those for two HCSUCPPs respectively with vertical SUTs 547 m and 971 m high. This work lays a good foundation for accurate predication of potential power produced from SCSUTPP.



## 1. Introduction

A conventional solar updraft tower power plant (SUTPP) consists of a circular solar collector constructed on horizontal ground, a vertical solid solar updraft tower (SUT), also known as solar chimney, situated at the center of the solar collector, and turbine generators installed between the collector outlet and SUT inlet. In the solar collector covered by transparent roof, solar radiation is received and the indoor air is heated. In the SUT, the difference between the densities of warm air inside a tall SUT and the ambient air produces a buoyancy (Fig. 1), which drives the air to flow in the collector toward the SUT. Finally, the air current powers the turbine generators [1,2]. The SUTPP energy conversion can be divided into four phases as follows [2]: (i) the collector converts solar energy to thermal energy of the air, (ii) the SUT converts the thermal energy to kinetic energy of airflow, (iii) the turbine generators convert the kinetic energy of the airflow to electric power, and (iv) the remaining kinetic energy and the thermal energy of the warm air current are mainly converted to gravitational potential energy under the effects of the initial momentum and the buoyancy force after the air ejects from the SUT outlet [3].

The feasibility of the SUTPP technology has been demonstrated by the 50 kW pilot Manzanares plant prototype which was constructed and operated successfully in 1980s. The plant prototype had a solar collector 122 m in radius and a tower 194.6 m high with a radius of 5.08 m [1,4]. Multiple phase energy conversions occur in the SUTPP system that belongs to a low-temperature thermal power generation system. This results in low energy conversion efficiency, which increases with the increase in system size. In order to produce electric power economically, a large collector and a huge SUT are needed [1,2]. A guyed corrugated metal sheet flue and a brick tower were built for the Manzanares prototype SUT and for the pilot Wuhai prototype SUT, respectively, just for experimental measurements. Nonetheless, the best structure for high SUT is considered to be thin-walled reinforced concrete shell structure because of the longest life-span at the most favorable costs among the many possible construction methods and the materials of building SUT [1,2,5]. There exist disadvantages for commercial conventional SUTPP, including high construction cost and limited height because of the technological constraints and restrictions on the construction materials. In order to solve these problems, some novel SUTPP concepts have been proposed. Günther [6] presented a sloped-tower SUTPP concept with its SUT supported by a mountain. Zhou et al. [7] proposed a novel concept for producing energy integrating a man made mountain hollow used as "SUT" and a giant solar collector constructed by surrounding

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**Nomenclature**

| | |
|---|---|
| $A$ | cross-sectional area ($m^2$) |
| $A_r$ | collector area from outlet to position with a distance $r$ ($m^2$) |
| $b$ | roof shape exponent |
| $B$ | upright distance from the roof to the mountain side (m) |
| $c_p$ | specific heat capacity, 1005 (J/kg K) |
| $D$ | diameter (m) |
| $g$ | gravitational acceleration, 9.81 ($m/s^2$) |
| $h$ | any height (m) |
| $H$ | SUT or collector height (m) |
| $I$ | solar radiation intensity ($W/m^2$) |
| $L$ | cross width of collector passage (m) |
| $\dot{m}$ | mass flow rate (kg/s) |
| $p$ | pressure (Pa) |
| $P$ | power (W) |
| $r$ | distance along the mountainside from the collector outlet to a random position (m) |
| $R$ | specific gas constant for air, 287 (J/kg K) |
| $R_{coll}$ | total length of collector (m) |
| $T$ | temperature (°C) |
| $v$ | velocity (m/s) |

*Greek symbols*

| | |
|---|---|
| $\alpha$ | mountainside slope (°) |
| $\varepsilon$ | pressure loss coefficient |
| $\gamma$ | specific heat ratio, 1.4 |
| $\eta$ | energy conversion efficiency (%) |
| $\rho$ | density ($kg/m^3$) |
| $\tau$ | shear stress (Pa) |
| $\Delta$ | difference |
| $\Delta T$ | collector temperature rise (°C) |

*Subscripts*

| | |
|---|---|
| *acc* | accelerating axial airflow |
| *avg* | average between Points 2 and 3 |
| *br* | internal bracing |
| *coll* | collector |
| *eff* | effective |
| *f* | wall friction |
| *gro* | ground |
| *i* | inlet |
| *k* | kinetic energy |
| *load* | turbine load condition |
| *loss* | loss |
| *no load* | no load condition |
| *poten* | potential |
| *roof* | collector roof |
| *sup* | support |
| *sut* | solar updraft tower |
| *tg* | turbine generators |
| *turb* | turbine |
| $\infty$ | atmosphere |
| 1 | collector inlet |
| 2 | collector outlet |
| 3 | SUT inlet |
| 4 | SUT outlet |

the hollow space excavated. Kashiwa and Kashiwa [8] proposed a novel concept 'solar cyclone' by using an SUT and an expansion cyclone separator for harnessing solar power and extracting fresh water from the atmosphere. Wang et al. [9,10] proposed two hybrid SUT systems for both power generation and seawater desalination suitably at a site adjacent to the sea by installing a high-efficiency condenser at the SUT outlet or the inlet, respectively. Papageorgiou [11] proposed a soft SUT concept called floating solar chimney (FSC) instead of reinforced concrete SUT to be used for power generation. Without doubt, FSC will avoid external limitations such as possible earthquakes. The cost of FSC is much lower as pointed out by the inventor, but unfortunately its lifespan is far shorter than the conventional reinforced concrete SUT. Zhou and Yang [12] proposed a novel solar thermal power plant with FSC stiffened onto a mountain-side, segment by segment. Bilgen and Rheault [13] proposed a novel sloped-collector SUTPP (SCSUTPP) with a sloped collector constructed on a suitable mountainside and a short vertical SUT built on the collector top. The solar collector also acts as an "SUT" due to its gradual ascent along the mountainside. Compared to the solar collector constructed on the horizontal ground, the collector on an appropriate slope at mid and high latitudes will reduce the incidence angle, increase insolation received by the collector, and show higher thermal performance, thus effectively improving the power output of the SCSUTPP. Recently, some researchers [13–18] have performed some studies of the performances of the SCSUTPPs by analyzing the air flow and heat transfer in the systems. Cao et al. [14] established the mathematical model for SCSUTPP, and took a 5 MW SCSUTPP designed in Lanzhou, China as an example to study the SCSUTPP performance based on their model. Later, they [15] compared the performance of conventional horizontal-collector solar updraft tower power plants (HCSUTPPs) and SCSUTPPs proposed in China based on simulation. Panse et al. [16] developed a model to investigate the performance of the SCSUTPP without a short SUT at the collector top. A mathematical model was developed by Koonsrisuk for the SCSUTPP, and based on this model he studied the effects of a near-unity ratio of the collector inlet flow area and the collector exit flow area, the assumption that the density differences in the collector and that in the chimney are approximately equal, the chimney height and the collector area on the plant performance [17]. Kalash et al. [18] designed an SCSUTPP setup, and performed experimental investigation of the temperature field in the solar collector. However, the comprehensive studies on the

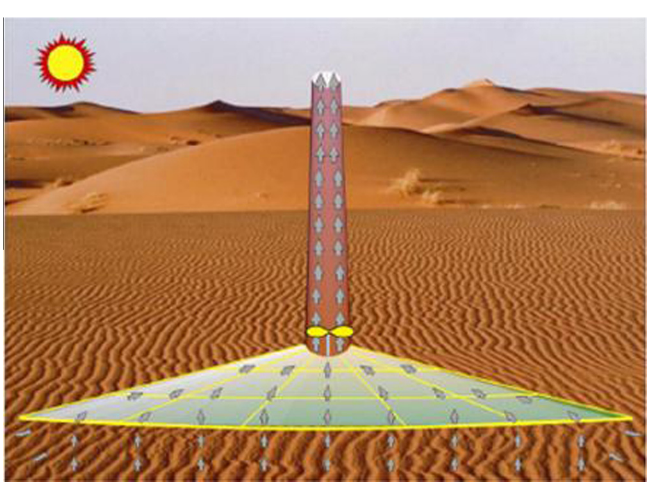

**Fig. 1.** Perspective of an HCSUTPP.