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Solar updraft power plant system: A brief review and a case study on a new system with radial partition walls in its collector

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A R T I C L E I N F O

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Abstract: The solar updraft power plant system (SUPPS) is a low-temperature solar thermal system which utilizes both the buoyancy effect of hot air generated inside a greenhouse by solar radiation and the chimney effect to generate electricity without producing either greenhouse gases or hazardous waste. In this work, a brief review is presented concerning new developments in experimental setups, thermodynamic analyses, turbine, chimney, energy storage, mathematical models and CFD simulations, as well as special applications, and the effects of the ambient cross wind (ACW) on SUPPS. Then as a case study, we show the developments of three SUPPS numerical models to explore the impact of ambient cross wind on large-scale SUPPSs. Three large-scale SUPPSs with similar configurations are investigated: one with a conventional horizontal canopy; one with a familiar sloped canopy design; and one with eight radial partition walls (RPWs) uniformly distributed under the collector canopy. The models are used to evaluate the effects of ACW on the fluid flow and heat transfer processes under various environmental conditions. The velocity, pressure, and temperature contours in and out of the three plants along with the power output of the turbine are analyzed and compared. The results indicate that both the sloped canopy with a lower collector inlet and the RPWs designs are effective in improving the performance of a SUPPS by reducing the amount of heated air escaping from the collector under ACW. An added benefit is that some wind energy is partly harnessed thanks to the design of the RPWs.

1. Introduction

Several problems have recently captured worldwide attention: energy shortage, environmental pollution, and water scarcity. Currently, about 90% of Chinese cities suffer from the severe haze phenomenon [1] which is mainly caused by the emissions of fossil-fired power stations, the exhaust of vehicles, the dust from numerous construction sites, and even household fuels [2]. Further, the basic state policy of urbanization in China is leading to an increasing number of people from the rural population moving to cities, where they can gain access to better working and living conditions. However, a significant increase of energy consumption during this urbanization process also places a great pressure on the government. In addition, water scarcity, a global problem, is even worse in China due to its large population. These three points are interrelated with one another as the energy issue plays a key role in each. Therefore appropriate solutions to the energy crisis will be helpful to solve many issues in China, and renewable energy technologies should be seriously considered.

Among the various solar energy technologies, the solar updraft power plant (SUPP) is a promising technology which can be widely used in countries with large arid and otherwise useless desert lands. A traditional solar updraft power plant system (SUPPS) consists of a solar collector, an energy storage layer, a chimney, and several pressure-based turbines [3].

This technology takes advantage of the buoyancy effect of heated air to generate electric power without greenhouse gas emissions. During the daytime, solar radiation passes through a transparent canopy, heating the energy storage layer beneath the cover, which in turn heats air inside the canopy. The collector canopy can be designed to increase the collection efficiency by giving it higher transmissivity for short wavelengths and lower transmissivity for long wavelengths. The buoyancy effect induced by air of a higher temperature in the chimney leads

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to a large pressure drop under the center of the canopy. Thus a strong airflow is developed through the chimney, which can be used to drive turbines installed within the solar chimney stack to generate electricity. At night, the energy storage layer releases thermal energy absorbed during the day in order to heat the air under the canopy maintaining system operation [4].

Since the concept was first developed and a prototype was put in operation during the 1980s by Schlaich [3,5], the SUPPS attracted extensive attention due to several advantages including: cheap building materials, negligible hazardous waste generation, good use of desert land, a long working life span, and low operating costs. The technology is attractive, especially for countries with vast deserts, because it can give additional benefits such as the improvement of desert environments [6], and the production of clean water for residential use [7–11], air filtration [12], and drying agricultural products [13,14]. To reduce the cost of SUPPSs and address the safety issues met in the chimney building, some other types of SUPPS concepts were developed in the past decade [15,16]. Recently, several review papers presented both historical and existing research on SUPPS [15,17–21].

In this paper, a brief review on recent SUPPS developments will be presented, and some key issues with the technology will be raised. These will be followed by a case study of a SUPPS with radial partition walls under its collector to avoid the negative effect of ambient crosswind.

2. Literature review

2.1. Experimental setup

Due to the good characteristics of the technology, relevant theoretical research, numerical simulations, and experiments of the SUPPS have greatly promoted practical applications for the technology [21]. The first SUPPS prototype, built in Manzanares, Spain by Schlaich [3] during 1981-82, had a peak output power of 50 kW with a chimney height of 195 m. This prototype successfully operated for seven years (1982–1989), validating the solar chimney concept. Performance data of the Manzanares prototype is of great significance, providing reference for the research that followed [5,22]. Since then, no large SUPPS has been built, partly due to problems improving both the power generation and structural design aspects of the system. Several groups around the world tested smaller prototypes in various environments such as in America, Northwest China, and North Africa. A research group led by Sherif [23–28] developed comprehensive mathematical models to study the fluid flow and heat transfer processes for various SUPPS scales. Three different geometric designs taking the chimney shape, collector geometry and energy storage layers into consideration were established in Florida to evaluate the various factors affecting the power output of a SUPPS. Maia et al. [13,29–31] built and tested a solar chimney in Belo Horizonte (Brazil), with a tower height of 12.3 m and a collector diameter of 25 m. Zhou et al. [32] reported a pilot experimental solar chimney power setup in Wuhan, China. In their setup, the collector was 10 m in diameter and the chimney was 8 m in height. According to their measurement results, the temperature difference between their collector outlet and the ambient air was 24.1 °C. They noticed a phenomenon of air temperature inversion which appeared after sunrise on both cool and warm days. Kasaeian et al. [33] presented a very similar solar chimney pilot power plant with a 10 m collector diameter and 12 m chimney height; they also measured the temperatures and air velocities, and observed an air temperature inversion at the bottom of the chimney after sunrise on both cold and hot days. A similar phenomenon was also verified by Ghalamchi et al. [34,35]. Kalash et al. [36] built and examined the performance of a small-size sloped SUPPS in Syria. Bugutekin [37] established a solar chimney system near the Adiyaman University campus and analyzed the effect of environmental temperature, chimney height, the collector diameter, and solar radiation on its performance.

Shahreza and Imani [38] experimentally investigated a new small scale model of a solar chimney in which two intensifiers were installed around the solar chimney to intensify the heat flux radiated by the sun, and an air tank was located at the bottom of the system to increase the solar radiation reflected by the intensifiers. They found that the utilization of intensifiers caused an increase in velocity magnitude in the chimney.

2.2. Thermodynamics analysis

Gannon and von Backström [39] conducted thermodynamic analysis on a SUPPS, presenting an ideal air standard cycle analysis for the system with performance limitations, ideal efficiencies, and relationships among main variables. Later, they also considered the actual cycle by including: the chimney friction along with the kinetic energy losses in the turbine and chimney exit.

Petela [40] performed energy and exergy balances and analyzed the thermodynamic interpretation of processes occurring in these SUPPS components. Taking a SUPPS receiving 36.81 MW energy of solar radiation as an example, the energy and exergy flow diagrams were distributed between the SUPPS components. This was the first work to advance a new concept of mechanical exergy of air which could quantitatively determine the effect of the terrestrial gravity field on the component processes of the SUPPS. Ming et al. [41] presented a simple thermodynamic analysis on the SUPPS and considered the ideal and actual thermodynamic processes of each SUPPS components. The results indicated that the ideal cycle and actual efficiencies of a standard Brayton cycle corresponding to a medium scale SUPPS (chimney height 400 m) were 1.33% and 0.3%, respectively, while the same parameters for a large scale SUPPS (chimney height 1000 m) were 3.33% and 0.9%, respectively. Based on the second law of thermodynamics, Koonsrisuk [42] made a comparison between a conventional SUPPS and a sloped SUPPS. An appropriate entropy generation number and second-law efficiency for solar chimney power plants were also proposed. Results indicated that there is an optimum collector size that provides the minimum entropy generation and maximum second-law efficiency, and that a sloped SUPPS is thermodynamically better than a conventional SUPPS for certain configurations. Recently, Guo et al. [43] developed an unsteady theoretical model that considers soil heat storage in order to investigate the thermodynamic behavior of a SUPPS throughout a daily operation cycle. They also considered the system performance under different working conditions: steady without heat storage and unsteady with heat storage; different heat storage materials were used during the unsteady analysis. Hamdan [44] performed a simplified thermodynamic analysisfor steady airflow inside a solar chimney used in the Arabian Gulf region. Chen et al. [45] proposed a SUPPS to re-utilize the low-temperature waste heat and presented a mathematical model of the system based on the first and second laws of thermodynamics.

2.3. Turbine

Gannon and von Backström [46] presented an interesting design of the turbine system used in SUPPSs and an experimental investigation was conducted to assess the performance of a SUPPS turbine. In that design, the chimney supports served as inlet guide vanes (IGVs) to introduce pre-whirl which could reduce the turbine exit kinetic energy at the diffuser inlet and assists the flow turning in the IGV-to-rotor duct. In addition, a novel single rotor was utilized which would allow the supports to be placed directly under the chimney walls. In their scale model experimental measurement, the total-to-total efficiencies were 85–90% and the total-to-static efficiencies were 77–80% over the design range. Later, von Backström and Gannon [47] presented an analytical model to express the influences of turbine flow, load coefficient, and degree of reaction on turbine efficiency. The optimum degree of reaction, maximum turbine efficiency for required power, and maximum efficiency for constrained turbine size could be found from the analytical solutions. Experimental results of a 720 mm diameter turbine scale model agreed very well with the analytical model, and a peak turbine total-to-total efficiency could reach up to 90%. Later, Fluri and von Backström [48] conducted an analysis on the performance of the power conversion unit (PCU, consisting of one or more turbogenerators, power electronics, a grid interface, and the flow passage from collector exit-to-chimney inlet), explored the interaction between the PCU and the SUPPS, and compared the efficiency and output power of three PCU configurations.

Pastohr et al. [49] carried out a two-dimensional numerical analysis on a SUPPS by coupling all the parts including the collector, turbine, chimney, and energy storage layer. The pressure drop at the turbine was also considered. Numerical results were compared with a SIMPLE code model to verify the feasibility of the CFD method. Serag-Eldin [50] constructed a CFD model to predict the detailed internal flow inside an axisymmetric boundary-fitted coordinate SUPPS for various turbine characteristics. The mathematical model, within which the turbine characteristics were embedded implicitly, included the mass, momentum, and energy conservation equations, along with the transport equations for the kinetic energy of turbulence and its rate of dissipation. Results indicated that turbine characteristics have significant influence on the flow field and the overall plant performance of a SUPPS. Recently, Denantes and Bilgen [51] developed an efficiency model to predict the performance of counter-rotating turbines with and without inlet guide vanes. Ming et al. [52] conducted a 3-dimensional numerical analysis on a SUPPS coupled with a turbine and analyzed the temperature, mass flow rate, output power, and efficiency with turbine rotation speed. Recently, the optimal ratio of pressure drop across the turbine in SUPPS was also considered [53–55].

2.4. Chimney

Close attention has been paid to the shape of chimney. Sherif's group was the first to build a SUPPS with a convergent chimney [26–28]. For a large scale SUPPS, Schlaich et al. mentioned a divergent chimney [3,56] and Krätzig introduced hyperbolic chimney structures [57]. Later, Ming et al. [58] and Koonsrisuk and Chitsomboon [59] analyzed the effect of chimney shape on a SUPPS overall performance. However, for large scale SUPPSs, the action of ambient crosswind on the chimney from the point of the structure should be the key issue. Many structural phenomena, like forced vibrations, static and dynamic instabilities, or damage-induced failure, will influence a SUPPS safety and reliability [60], which may be one of the most important reasons why a 200 MW SUPPS has not yet been built.

2.5. Energy storage

One outstanding advantage of SUPPS over other solar energy power generating technologies is that it can generate electricity smoothly and continuously even when the solar radiation fluctuates during cloudy days. This is because of the energy storage layer, which can significantly alleviate the fluctuation in output power of SUPPSs. This has been verified by early experimental studies [3,22,28], and theoretical analysis on the effect of an energy storage system on SUPPSs has been conducted by many researchers [61–65]. Similarly, Bernardes studied several soil thermal properties [66]. Recently, Ming et al. [67] were the first to define "fluctuation-factor" as the variation of output power by renewable energy power generation systems. They then presented a comprehensive mathematical model to calculate the overall performance of SUPPSs with water/soil energy storage layers, and they analyzed the variation of the fluctuation-factor and output power of SUPPSs for varying thicknesses and positions of the water storage layer. Larbi et al. [68] reported the performance of a SUPPS with a heat storage system in Adrar, the south western region of Algeria. In their study, the influence of the meteorological conditions, geometrical parameters of the SUPPS, thickness of the storage system, and the wind velocity on the generated electric power were analyzed. Thermodynamic analyses based on the first and second laws have been conducted by Guo et al. [43] and Karimi-Pour-Fard et al. [69], which further verified that the energy storage layer can remarkably smooth and increase the output power of SUPPSs, providing them with a unique advantage over other renewable energies.

2.6. Mathematical model and CFD analysis

Many mathematical models to assess the overall performance of SUPPSs have been reported in the last few decades. Before 2000, the most famous model was developed by Pasumarthi and Sherif [27], which incorporated the effects of many effects such as the single and double canopy, the ground storage materials, the ambient cross wind, the turbine, and the chimney. Later, Bernardes et al. [70] developed a mathematical model to describe the thermal behavior and output power performance of a large scale SUPPS which features variations in the thermal physical parameters of the atmosphere. Ming et al. [71] conducted further research into the influence of various geometric parameters on the driving force, power output, and efficiency performance of SUPPSs. Recently, the mathematical models conducted by Koonsrisuk and Chitsomboon [72], Akhtar and Rao [73], Maia et al. [31], and Zhou et al. [74,75] are note-worthy.

With the rapid development of computational prediction, research publications using CFD methods on SUPPSs occupy the mainstream in this field. Bernardes et al. [76] were the first to conduct a numerical simulation on SUPPSs, followed by Pastohr et al. [49] in 2004. Ming et al. [52,62,64,71,77,78] published a series of research publications from different angles to numerically analyze the SUPPS's performance. Koonsrisuk and Chitsomboon [42,59,72,79–83] used CFD methods to investigate the changes in flow characteristics caused by geometrical shape variations. They suggested that a solar chimney with a sloping collector and a divergent-top chimney performed better than a conventional system with a constant-height canopy and a constant-area chimney. Kasaeian et al. [84] and Lebbi et al. [85] developed numerical models to analyze the effects of geometrical parameters on a constructed solar chimney power plant. Fasel et al. [86] used ANSYS and an in-house developed CFD code to simulate the fluid dynamics and heat transfer mechanisms in SUPPSs. Their results indicated that the flow in the chimney was fully turbulent. Al-Kayiem et al. [87] presented a mathematical model and analyzed the thermal energy and fluid flow within a SUPPS with an inclined roof, which was further validated by experiments. Recently, CFD analysis can be found in the following research articles looking into various parameters [38,54,58,88–93].

2.7. Special application

Nearly 40 years have passed since the biggest solar updraft prototype was built in Manzanares, Spain, and a commercial SUPPS has not been built yet. The key reasons lie in the fact that: (1) the power generating cost of a SUPPS is not significantly lower than that of the other types of power generating technologies; (2) no technological innovations can be achieved in SUPPSs to greatly reduce their power generating cost as the main technologies (greenhouse effect, stack effect, energy storage, wind turbine generator) are conventional; and (3) the functions of electric generation and agricultural plants of SUPPSs have not attracted governments and/or investors' attention. Thereby, special applications and/or novel configurations for cost reduction of SUPPS have been reported by many researchers.

The chimney occupies a large part of the initial investment of SUPPS [3,28,94–100]. Currently there are two methods to reduce the construction cost of a tall chimney. One is the floating solar chimney advanced by Papageorgiou et al. [101–106], which was further verified by Zhou et al. [107] and Deodhe and Raut [108]. The other is the sloping chimney which is built along a high mountain [42,75,79,109–114] or existing buildings [115]. Experimental results indicate that a sloped solar chimney also has good overall performance [36].

The coupling of a solar chimney with food drying and desalination has attracted wide attention. Numerical analysis [10,13,29,116,117] and experimental results [11,118] have reported that solar chimneys can be a perfect system for this application.

Low temperature waste heat recovery can also benefit solar chimneys. Chen et al. [45] reported a detailed thermodynamics analysis on low temperature waste heat recovery based on a solar chimney. Zandian and Ashjaee [119] explored the possibility of combining a thermal steam power plant dry cooling tower with a solar chimney. The design eliminated the construction cost and made use of low-grade energy without additional greenhouse gas emissions. The applications of SUPPS for precipitation [7,8,120], air pollution reduction, and greenhouse gas removal [12,121–125] have recently been reported. The latter applications can help alleviate global warming as SUPPSs become negative emissions technologies.

2.8. The collector and the surrounding ambient air

Initially, the collector serves as a huge heat exchanger, converting solar energy to thermal energy, where the greenhouse effect occurs due to the temperature and density differences between the air within the collector and the surrounding ambient air. In the cold season, the temperature and humidity within the collector are favorable to green plants [3,5,56]. Generally, the collector canopy is close to the ground, and for the Spanish prototype, it is only 2–6 m high from the periphery to the center [5]. Some new designs of the collector, made to achieve better overall performance of SUPPSs can be found in recent review publications [15,17,18].

However, the connection between the collector and ambient air will cause some very complex phenomena as there can be various ambient crosswinds ACWs imparted from differing directions. Serag-Eldin [126] was the first to report a CFD simulation by coupling the SUPPS with the ambient air. Zhou et al. [127] developed a theoretical model to study the influence of ACW in the chimney outlet on the performance of SUPPSs with various heights. It was found that ACW across the chimney outlet had some positive effects on the output power of the system. In subsequent research, Ming et al. [93] carried out detailed numerical simulations to assess the impact of ACW on the performance of a SUPPS. Results demonstrated that ACW had adverse effects on the system, especially for large-scale plants, and a further investigation was needed to alleviate the phenomenon.

Large wind pressure and strong vibrations induced by crosswinds are serious structural challenges for such plants. Lupi et al. [128] found a new type of bi-stable flow around circular cylinders with span-wise stiffening rings by comparing with well-known bi-stable flows described in the literature. Vibration impact on the SUPPS structure was also investigated. Harte et al. [129] discussed the influence of ACW on the durability of SUPPSs by analyzing the impact of resonant frequency vibrations on the load carrying behavior of solar chimneys. Natural draft cooling towers and the chimneys of SUPPSs share many features: shell structures made of reinforced concrete, slender bodies, and similar operational principles. Experience in dry cooling tower design can be used to guide the structural design of SUPPSs. The research conducted by Harte et al. [130] and Krätzig [131] illustrated the structural design problems which these structures have in common. For example, for cooling towers Al-Waked et al. [132] found that an intake-wind under the tower stack would significantly reduce the cooling efficiency and a similar phenomenon was found in SUPPSs, as outlined in the research performed by Pretorius and Kröger [133] and Serag-Eldin [126]. A numerical simulation was conducted by Ming et al. [77] to study the influence of various ambient wind speed profiles on the flow field, temperature distribution, driving force, updraft velocity, and output power of a SUPPS with the same size as the Manzanares prototype. Results indicated that ACW has both negative and positive effects: at ground level, some amount ofwarmairispushed outof the collectorby the ACW before it reaches theturbines;andat the tower outlet, a wind suction effect can speed up the airflow within the chimney and slightly increase the output power. Another work by Tan [134] analyzed the influences of ambient air speed and internal heat load on the performance of a solar chimney in the tropics. They found that for their model, with a collector height of 2.5 m, the ACWs did not significantly influence the system performance until the wind speed was higher than 3.0 m/s due to the relatively low chimney height.

It is encouraging to see much research being done on the design of SUPPSs. Recently, together with other non-conventional renewable energies, a SUPPS has been proposed by Ming et al. [122] to be part of the global strategy to fight global warming. However, the influence of the ACW velocity profiles on the performance of large scale SUPPSs with different geometrical structures is still unknown.

Some studies reported that the output power of SUPPSs are heavily depended on the scale of the system and the height of the chimney [59,131]. In this paper, two large-scale three-dimensional SUPPS models are explored: first, a conventional SUPPS with constant canopy height and another with a sloped canopy design are compared to test the influence of the ACW on the performance of the two systems. Then a novel geometric structure with eight additional radial partition walls (RPWs) uniformly distributed over the circumference under the collector are employed to improve the system performance under ACW. The pressure, velocity, and temperature contours along with the output power of SUPPS are presented and analyzed.

3. A case study of SUPPS with radial partition walls

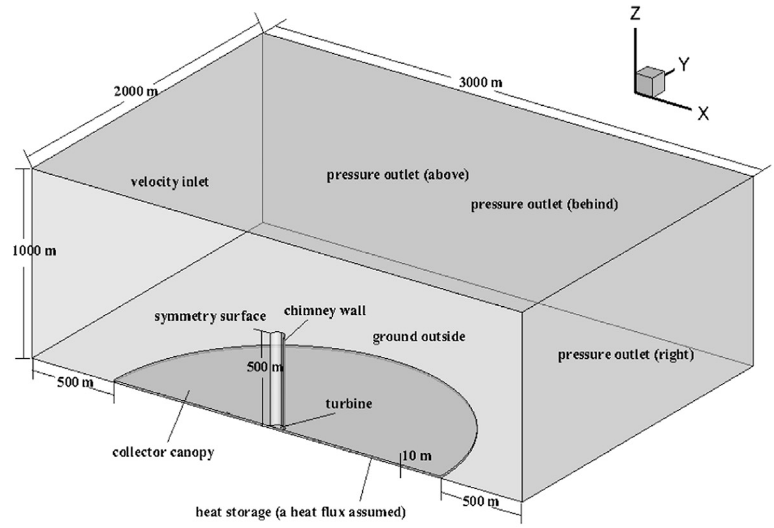
3.1. Computational model

3.1.1. Geometric model

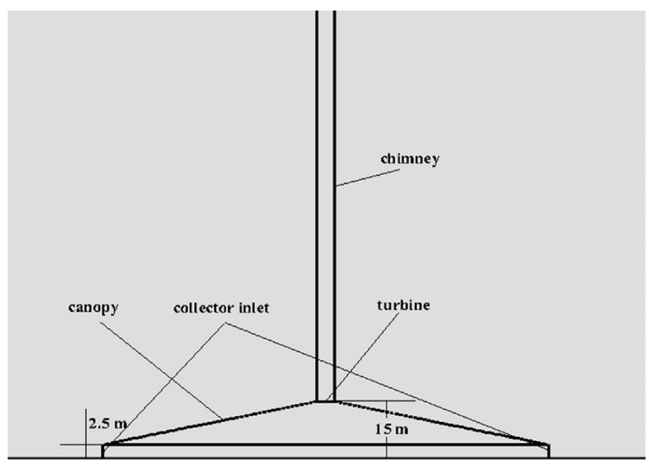
Three simplified large-scale models of the SUPPS are adopted for numerical simulations. All three models are larger than any SUPPS ever built. As shown in Fig. 1(a), Model 1 has a canopy with a constant height of 10 m and a radius of 1000 m, and a tubular cylindrical chimney up to 500 m high. Referring to previous work, the radius of the chimney is chosen to be 40 m [89]. Model 2, shown in Fig. 1(b) [89], is of the same size as Model 1 however its canopy height increases from 2.5 to 15 m linearly, sloping from the inlet to the center (later referred to in this manuscript as the sloped model). How the canopy sloped design is superior to the constant canopy design and how the height of the canopy influences the output of the SUPPS have been addressed in previous studies [135]. In this article we will mainly concentrate on ACW cold air slipping under the canopy. Model 3 (displayed in Fig. 1(c)), with all geometric parameters is identical to Model 1, has eight additional RPWs uniformly distributed over the circumference under the collector, stretching from the canopy edge to the chimney stack. Because the models are symmetric, only half of the system is calculated to save computing resources. All SUPPS models are enclosed in a cube, which is of a much larger scale (4 km in length, 3 km in width, and 1 km in height), to let the downstream flow fully develop. All models are tested with various ACWs acting on both the chimney outlet and the collector inlet.

3.1.2. Mathematical model

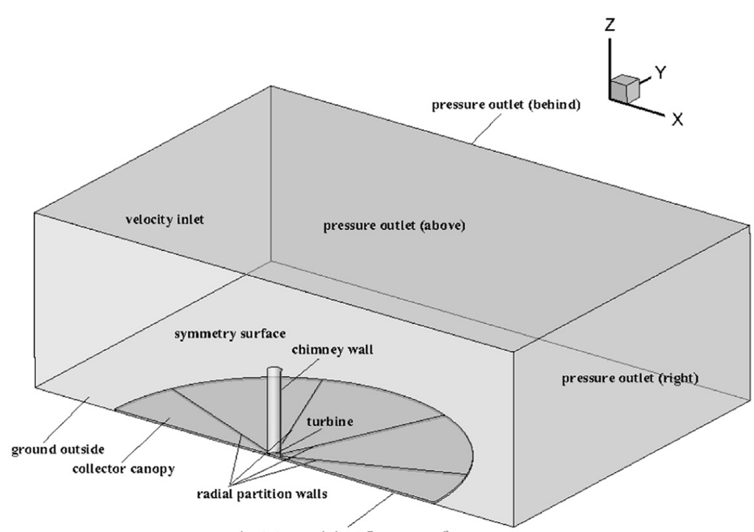
The flow and heat transfer characteristics within the SUPPS and its surroundings are quite complex. For the SUPPS, the flow within the collector, if the ACW velocity is zero, is considered to be purely natural convection induced by solar radiation which heats the ground under the collector and then results in increasing the temperature of the flowing air. However, the introduction of ACW in the environment causes the system to be in a combined natural and forced convection mode. This mixed convection is different from that of the assisting,



(a) Three-D geometrical model including SUPPS and surroundings for Model 1



(b) Front view of SUPPS Model 2 with sloped collector (not to scale)



(c) Three-D geometrical model of SUPPS and surroundings for Model 3

Fig. 1. Geometrical models of SUPPS. (a) Three-D geometrical model including SUPPS and surroundings for Model 1 (b) Front view of SUPPS Model 2 with sloped collector (not to scale) (c) Three-D geometrical model of SUPPS and surroundings for Model 3.

Table 1
Boundary conditions.

Faces	Boundary type	Set value
Inlet (x=0 m)	Velocity inlet	u=A·In(z/0.01)
outlet (x=3 km, z=1.5 km, y=2 km)	Pressure outlet	p=0 Pa
Turbine	Reversed fan	Δp=0–800 Pa
Ground under the canopy	Wall	q=600 W/m^2
Ground around the canopy	Wall	T=318 K
Canopy surface, RPWs and chimney surface	Wall	q=0 W/m^2
Symmetry surface (y=0)	Sym	

opposing, and transverse flows as defined by Bergman et al. [136]. The flow regimes can be classified according to the ratio of Gr and Re^2 as shown in Eq. (1) below,

$$\frac{Gr}{\mathrm{Re}^2} = \left(\frac{g\beta\Delta TL^3}{\nu^2}\right)/\left(\frac{U_eL}{\nu}\right)^2 = \frac{g\beta\Delta TL}{U_e^2} \tag{1}$$

where, Gr and Re are the Grashof number and the Reynolds number, respectively. β is the thermal coefficient of volume expansion; g is acceleration of gravity; ν is kinematic viscosity. Simple analysis from previous work [89] indicated that the flow within the chimney was strong turbulent flow even though without ACW. The existence of ACW will introduce more turbulence in the flow. Therefore, a turbulent mathematical model is selected to calculate the flow and heat transfer process in the SUPPS. The air density varies slightly and can be modeled using the Boussinesq approximation [77]. The conservation equations of mass, momentum, and energy along with the standard k-ε model are presented as follows:

Continuity Equation:

$$\frac{\partial\rho}{\partial t} + div(\rho\mathbf{V}) = 0 \tag{2}$$

Momentum equation (N-S equation):

$$\frac{\partial(\rho u_i)}{\partial t} + \frac{\partial(\rho u_i u_j)}{\partial x_j} = \rho g_j - \frac{\partial p}{\partial x_i} + \frac{\partial\tau_{ij}}{\partial x_j} \tag{3}$$

Energy equation:

$$\frac{\partial(\rho c_p T)}{\partial t} + \frac{\partial(\rho c_p u_j T)}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\lambda\frac{\partial T}{\partial x_j}\right) + \tau_{ij}\frac{\partial u_i}{\partial x_j} + \beta T\left(\frac{\partial p}{\partial t} + u_j\frac{\partial p}{\partial x_j}\right) \tag{4}$$

Equation for the turbulent kinetic energy k:

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j}\left(\alpha_k\mu_{eff}\frac{\partial k}{\partial x_j}\right) + G_k + G_b - \rho\varepsilon - Y_M + S_K \tag{5}$$

Equation for the energy dissipation ε:

$$\frac{\partial}{\partial t}(\rho\varepsilon) + \frac{\partial}{\partial x_i}(\rho\varepsilon u_i) = \frac{\partial}{\partial x_j}\left(\alpha_\varepsilon\mu_{eff}\frac{\partial\varepsilon}{\partial x_j}\right) + C_{1\varepsilon}\frac{\varepsilon}{k}(G_k + C_{3\varepsilon}G_b) - C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} - R_\varepsilon + S_\varepsilon \tag{6}$$

where σ_T, σ_k, and σ_ε are the turbulent Prandtl numbers for T, k, and ε, respectively: $\sigma_T=0.9$, $\sigma_k=1.0$, and $\sigma_\varepsilon=1.3$. Energy dissipation is $\varepsilon = C_D\frac{k^{3/2}}{l}$, where $C_D=1.0$. C_1 and C_2 are two constant coefficients for energy dissipation with $C_{1\varepsilon}=1.44$ and $C_{2\varepsilon}=1.92$. Coefficient of eddy viscosity: $\varepsilon_m = C_\mu\frac{k^2}{\varepsilon}$, where $C_\mu=0.09$. G_k denotes the generation of turbulent kinetic energy induced by the mean velocity gradients, given by $G_k = -\rho\overline{u_i' u_j'}\frac{\partial u_j}{\partial x_i}$.

The temperature varies little in the system, thus the variation in density is neglected except in the buoyancy term. So the Boussinesq approximation is adopted to calculate the buoyancy force.

$$\rho = \rho_0(1 - \beta(T - T_0)) \tag{7}$$

The RNG model, which is thought to be more accurate than the k-ε model to simulate flow with strong vortex, calls for more computing resources. What's more, some simplifying assumptions are made in the following Section 2.3, thus a more accurate model is unnecessary.

3.1.3. Boundary conditions

Taking into account the ACW and other uncertainties could make the boundary conditions complex. Some reasonable assumptions are therefore made to simplify the boundary conditions without significantly impacting the validity of the results. These are summarized below:

(a) Neglect the pressure difference due to gravity in the vertical direction.
(b) The flow field is assumed fully developed, and vibrations caused by wind are neglected, so the simulation can be seen as steady in time.
(c) The solar radiation is uniformly absorbed by the ground, and local thermal equilibrium is achieved between the ground and the air in its vicinity.
(d) Radiation heat exchange among the walls is neglected since the temperature rise in the system is relatively small.

The boundary conditions used in the numerical simulations are described in Table 1.

(1) Inlet boundary (x=0)

In order to simplify calculations, we do not compute the temperature decrease with height outside the SUPPS although it can vary by 3.5–5 °C. The temperature of the crosswind is assumed to be a constant value of 293 K (20 °C). The velocity profile can be simplified to $u = A\cdot\ln(z/0.01)$ since the coefficients are constant once the conditions of the environment are prescribed. A specific wind velocity profile in vertical direction can be obtained if an expected wind speed is determined at the chimney outlet (z=500 m).

(2) Outlet boundary (x=3000 m, y=2000 m, and z=1000 m)

There are three pressure outlet boundaries in Model 1, as shown in Fig. 1(a), all of which are set far enough to make sure that the flow field is fully developed and no reverse flow exists near the boundaries.

(3) Ground boundary (z=0 m)

The exposed ground outside the collector is assumed to be a wall boundary with a constant temperature of 318 K. The ground covered by the canopy is assumed to be a wall with constant heat flux of 600 W/m^2, a typical solar radiation intensity. A no-slip wall condition (the flow velocity contacted with the wall is zero) is used to describe the air flow near the ground surface.

(4) Turbine boundary (z=10 m at the chimney)

In this work, we used a two-dimensional reversed fan to simplify real three-dimensional turbines [52] which are not easy to implement considering the scale of the calculation region. The simplification, as described in previous research [49] is accurate enough to predict the performance of the solar updraft plants. Cases with different pressure drops across the turbine, ranging from 0 to 800 Pa, are examined to calculate the output power of the system, which is determined by the equation,

$$W_{eff} = \eta_{eff}\Delta pV \tag{8}$$

where W_{eff} stands for the electric output power of the turbine and η_{eff} is the overall energy conversion efficiency from thermal to electricity for the turbo-generator unit. In reality, the turbine efficiency is variable for different wind speeds and achieves a peak value at a relatively high rotational speed. Here we simplify the η_{eff} to be a function of V by fitting the data from a previous study [137], which can be expressed as

$$\eta_{eff} = 4.083\times10^{-15}V^3 - 6.167\times10^{-10}V^2 + 3.408\times10^{-5}V + 0.1403 \tag{9}$$

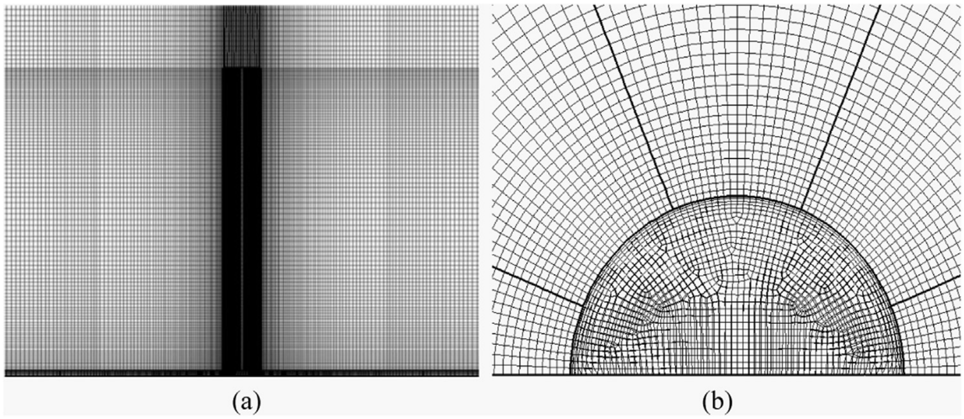


Fig. 2. Grid system of Model 3: (a) grid layout on the symmetric plane; (b) local grid pattern near the chimney.

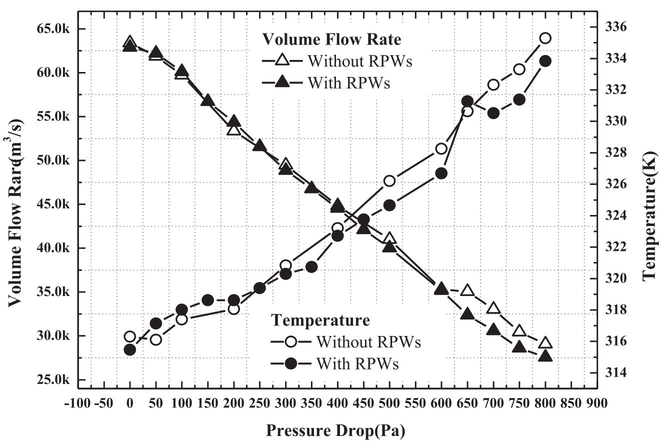


Fig. 3. Comparisons of volume flow rate and average temperature at chimney outlet between Models 1 and 3 for various turbine pressure drop when $u_{500\ m}$=0 m/s.

Then Eq. (8) can be rewritten as

$$W_{eff} = \Delta pV\,(4.083 \times 10^{-15}V^3 - 6.167 \times 10^{-10}V^2 + 3.408 \times 10^{-5}V + 0.1403)\quad (V \in (2000,\ 70000)) \tag{10}$$

A rough calculation showed that the peak efficiency for the turbine-generator unit is about 90% around V=70000 m^3/s, while the minimum efficiency is expected to be 35% around V=2000 m^3/s.

(5) Other wall boundary (canopy, chimney, and RPWs)

All the walls of the collector canopy, chimney, and RPWs are assumed to be non-slip, isotropic, and of no thickness. As the RPWs are assumed to have no thickness, Model 3 and Model 1 are expected to have the same performance when there is no ACW.

3.1.4. Grid system and simulation validation

As a structured grid system is thought to be more accurate than an un-structured one, a grid system (Fig. 2) with approximately 4.0×10^6 hexahedron is applied to discretize the computational region. Calculations have been performed by the general purpose CFD package FLUENT 14.0 nested in ANSYS 14.0. A third-order QUICK divergence scheme is used to discretize the convective term and a second-order divergence scheme for the diffusion terms. All the equations are solved coupled with a convergence tolerance of 10^{-7} for all the computed quantities.

As stated above, Model 3 with RPWs and Model 1 have the same performance when there is no ACW. Model 1 with 3489637 grids and Model 3 with 3634350 grids are tested to examine the validity of the calculations. Results (Fig. 3) indicate that the operating parameters of the two models are in good agreement for various conditions, with the

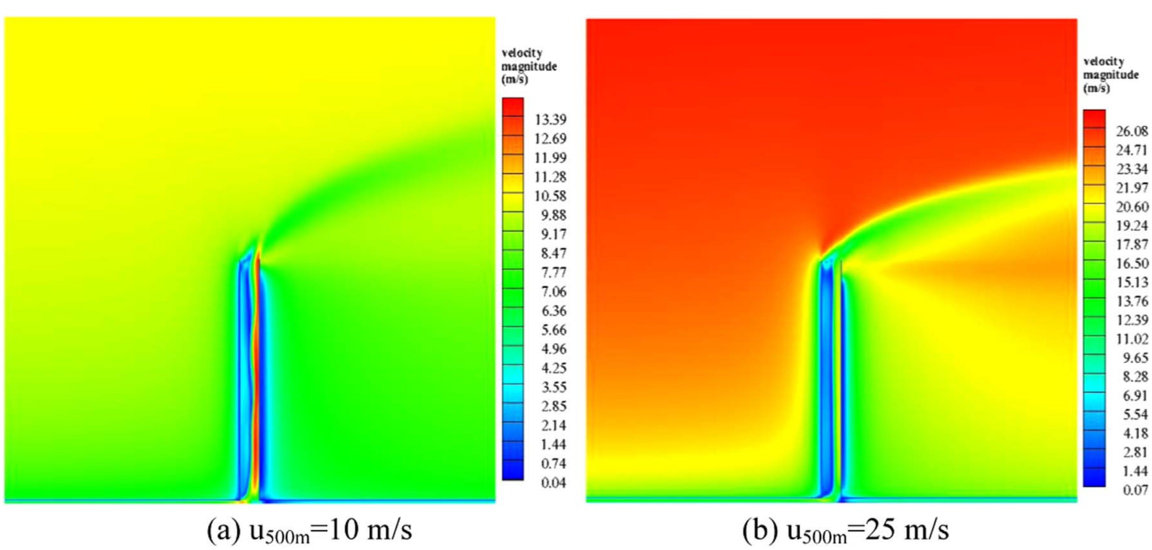


Fig. 4. Velocity magnitude distributions on the symmetry plane in Model 1 (without RPWs) with turbine pressure drop being set at 100 Pa for various ACWs (the $u_{500\ m}$ are calculated by Eq. (9)). (a) $u_{500\ m}$=10 m/s (b) $u_{500\ m}$=25 m/s.

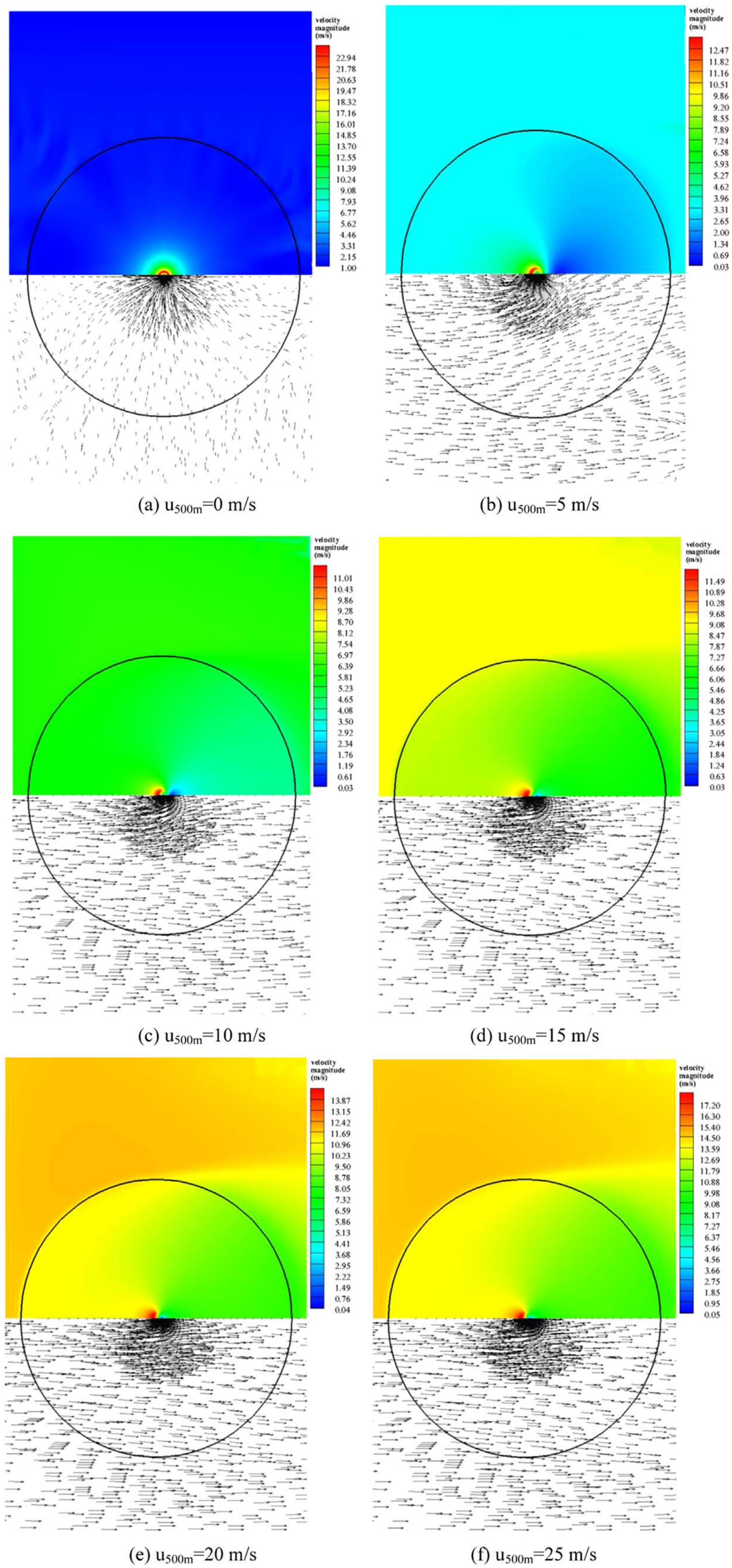


Fig. 5. Top view of velocity magnitude and vectors on the face (z=5 m) in Model 1 with turbine pressure drop being set at 100 Pa for various ACWs. (a) $u_{500\ m}$=0 m/s (b) $u_{500\ m}$=5 m/s (c) $u_{500\ m}$=10 m/s (d) $u_{500\ m}$=15 m/s (e) $u_{500\ m}$=20 m/s (f) $u_{500\ m}$=25 m/s.

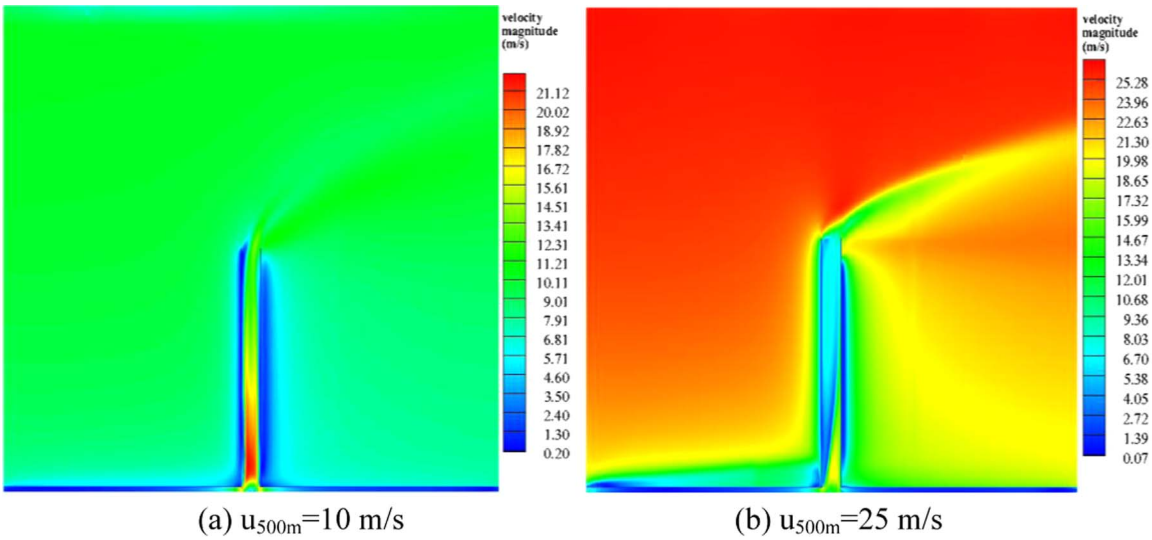


Fig. 6. Velocity magnitude distributions on the symmetry plane in Model 3 (with RPWs) with turbine pressure drop being set at 300 Pa for various ACWs. (a) $u_{500\ m}$=10 m/s (b) $u_{500\ m}$=25 m/s.

chimney outlet volume flow rate deviation smaller than 3% and an average temperature deviation smaller than 0.3% for all cases. As for Model 2, it has been tested in Shen's work [89], so the corresponding results will be directly obtained from that reference.

3.2. Results and discussion

The performance of the SUPPS is determined by factors, such as geometric structure of the system, solar radiation, heat storage layer, ACW, and turbine pressure drop. As demonstrated in previous research work [138], the ACW effected the velocity, temperature, pressure contours, and output power within the system as well as the environment around the plant. A wall heat flux of 600 W/m^2 (the corresponding solar radiation intensity is 875 W/m^2) is chosen for the calculations after considering energy loss through thermal radiation.

A series of ACW profiles with wind speeds at the height of the chimney outlet (500 m) ranging from 0 to 25 m/s by intervals of 5 m/s are calculated and compared. The corresponding wind velocities at the height of 10 m are 0, 3.19, 6.38, 9.58, 12.77, and 15.96 m/s. Results of previous research showed that a sloped canopy improved the performance of SUPPS when there is no ACW. However, how the varying ACW velocity profiles affect the SUPPS is unclear, especially for the large scale SUPPSs. Another work performed here is to check if, and how, the novel design of SUPPS with eight RPWs (Model 3) can improve the output power of the system in various ACW conditions.

3.2.1. Flow performances

Figs. 4–7 display a comparison of velocity distributions in the symmetry plane and the z=5 m plane of the SUPPS with/without RPWs. Comparing the flow contours in the previous work [89] for the sloped canopy design (Model 2), we can find distinctive differences among the air flow fields for the three models.

According to Figs. 4–5, the velocity magnitude in the chimney decreases quickly when there is an ACW, but the speed of the ACW ($u_{500\ m}$=5–25 m/s) seems to make little difference. The plant's performance deteriorates significantly due to ACW, and the system cannot sustain the ability to drive a turbine when the pressure drop is too small. Here we set the turbine pressure drop to be 100 Pa to demonstrate the performance of the plant (for this model, when the turbine pressure drop is set at 300 Pa, the system can't operate in a normal way when an ACW exists). A flat collector which is too high (10 m, model 1) may be responsible for severe degradation in the performance of SUPPS. The results compare well with the analysis performed by Serag-Eldin [126], who suggested that severe deterioration in system performance occurred from 10 m/s wind, and that even a weak 2 m/s wind could lead to a considerable degradation unless the collector inlet height is relatively low (7.5 m instead of 15 m). Though Serag-Eldin employed model dimensions suggested by Haaf [5,22] for a 5 MW plant, the suggestion could be instructive for construction of a commercial large-scale SUPPS built with kilometric high chimneys. Looking carefully at the airflow direction within the collector, in contrast with the phenomenon that the airflow sucked from the zone under the canopy for u=0 m/s, heated air is blown downstream of the collector instead of converging into the chimney.

Some of the enthalpy of the heated air is lost as seen in Fig. 4, which might be the main reason why ACW has negative effects on the performance of the SUPPS. As the ACW velocity increases from 0 m/s to 25 m/s at an interval of 5 m/s (Fig. 4), we find that the magnitudes of the corresponding airflow velocity with a fan pressure drop of 100 Pa are 12.0, 7.0, 5.3, 5.9, 6.8, and 8.4 m/s, beyond our expectation of negative influence of ACW. An interesting phenomenon mentioned in previous work occurs here [89]. We can find two-side effects introduced by the ACW to the system, both positive and negative. On the one hand, at the collector level, cold ambient air enters under the canopy, displacing a part of the heated air, thus weakening the plant's capability to generate electricity by reducing buoyancy. On the other hand, at the chimney outlet, the mixture of the strong ACW outside and the hot buoyant air flowing out from the chimney create a strong suction effect which can be explained using the Bernoulli Equation. The low pressure zone generated by the ACW suction restores slightly the strengthof the driving force within the chimney.

Since a large part of the heated air is blown away, the flat canopy design (model 1) is not an ideal design to sustain a reasonably high energy collection efficiency considering that ACWs of such magnitudes are common in nature.

In the research of Shen et al. [89], a SUPPS (referred to here as Model 2) with a sloping collector increasing in height from 2.5 m at the inlet to 15 m at the center, was simulated to analyze the influence of ACW on the performance of the SUPPS. Since Model 2 has a stronger ability to sustain a larger turbine pressure drop, the pressure drop in the turbine is set to be 300 Pa where it has the maximum power output. With the ACW ranging from 0 m/s to 30 m/s, the maximum airflow velocities in the chimney are 11.3, 10.4, 9.5, 7.6, 5.2, and 5.3 m/s when the $u_{500\ m}$ is 0, 10, 15, 20, 25, and 30 m/s, respectively. Compared with the calculated results in Fig. 5, it is not surprising to see that a lower collector inlet (2.5 m) has some advantage over a higher collector inlet.

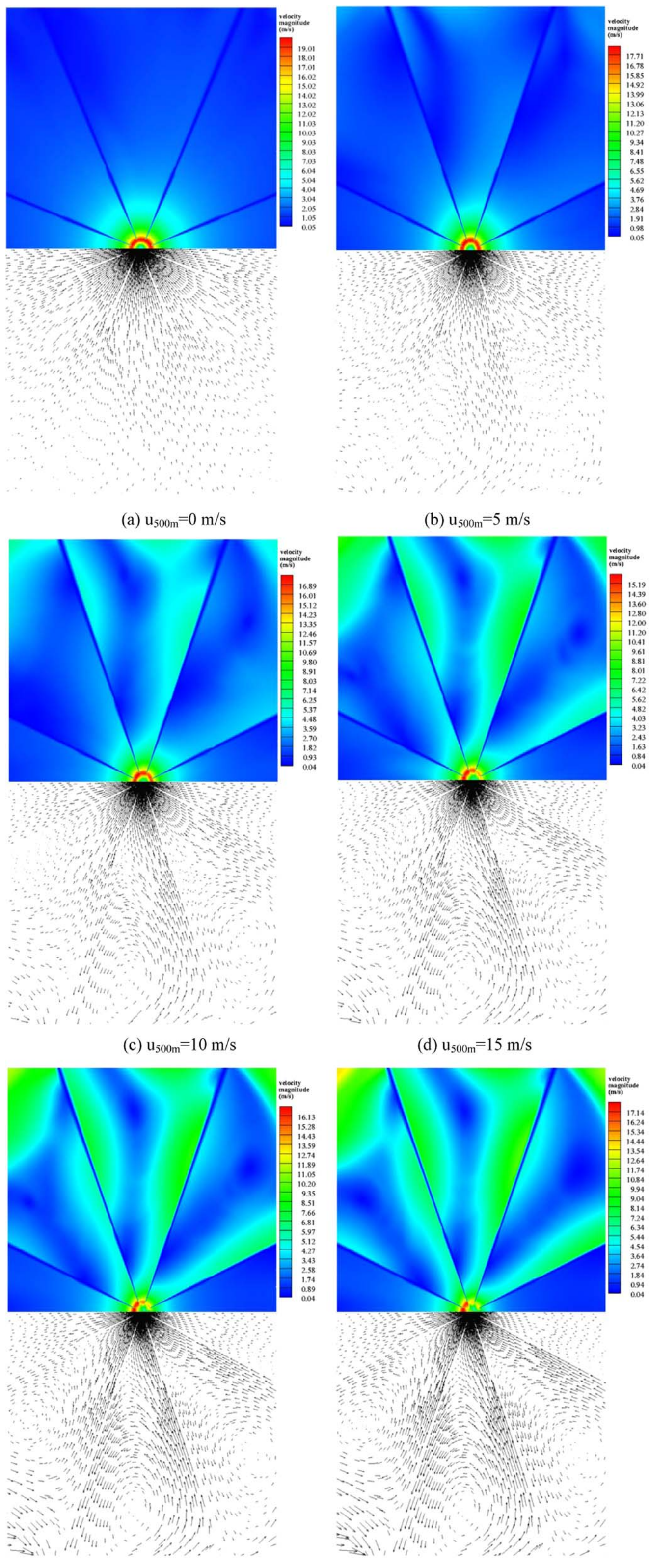


Fig. 7. Top view of velocity magnitude and vectors on the face (z=5 m) in Model 3 with turbine pressure drop being set at 300 Pa for various ACWs. (a) $u_{500\ m}$=0 m/s (b) $u_{500\ m}$=5 m/s (c) $u_{500\ m}$=10 m/s (d) $u_{500\ m}$=15 m/s (e) $u_{500\ m}$=20 m/s (f) $u_{500\ m}$=25 m/s.

The improvements are reflected both in the larger velocity magnitude at the chimney outlet with the same turbine pressure drop (for Model 1, it cannot work when the turbine pressure drop is 300 Pa) and the ability to sustain a considerable volume outflow rate under higher ACW velocities. A higher collector inlet means that a larger proportion of the heated air is blown downstream instead of being sucked into the chimney, thus the buoyancy effect is dramatically weakened, which is the main factor for plant performance deterioration.

Pretorius performed a thermo-economic plant optimization without considering ACW [139]. For a plant with a chimney height of 500 m, by varying the collector inlet height from 3 to 20 m and keeping the other parameters constant (chimney diameter and collector diameter), the power outputs of the systems were calculated. It was found that the higher the collector inlet was, the larger the power output would be. They interpreted this as a result of less friction losses under the collector. Later, Pretorius and Kröger [133] studied the effect of ambient wind on plant power output, and noticed that ACW significantly decreases the plant power output. They interpreted this as a result primarily due to the convective heat losses from the collector roof to the environment. There are surely some other factors that should be responsible for the deteriorating performance of SUPPS under an ACW environment.

A close look at Figs. 6–7 (Model 3), shows that, with the ACW ranging from 0 m/s to 25 m/s at 5 m/s intervals, the average air (?) velocities in the chimney are 10.4, 10.2, 9.3, 7.9, 8.4, and 8.6 m/s, respectively, with a turbine pressure drop of 300 Pa. RPWs appear to improve the performance of the SUPPS when ACW velocities lie between 15–25 m/s. There are at least four factors to explain the recovery of the average velocities. First, on the windward side of the canopy, as presented in Fig. 7, it is obvious that the RPWs prevent the heated air from escaping into the environment without driving the turbine, which is thought to be the prevailing effect that contributes to the performance improvement of the SUPPS. Second, the low pressure suction zone at the chimney outlet (Fig. 8), as mentioned above, also improves performance by increasing the driving force within the chimney. Third, an added benefit introduced by the RPWs design is that a part of the wind energy is being harnessed. Fourth, vortices developed in the compartments under the canopy dissipate a part of the potential energy, counteracting a small proportion of the benefits brought in by the novel design. Fig. 7 shows the velocity magnitudes and vectors on the plane z=5 m with RPWs: the higher the ACW velocity, the higher intensity the vortices in every compartment.

For an ACW velocity higher than 15 m/s, the performance of the RPWs design is better than the sloped-canopy design, it can be explained by the competition among the different factors that dominate the power output of the SUPPS.

3.2.2. Relative static pressure contours and driving force

Comparisons of relative static pressure contours on the symmetry plane of the SUPPS with/without RPWs are displayed in Figs. 8 and 9. Another comparison between the pressure fields of the model 1 (flat canopy design) and model 2 (sloped collector design) can be seen in previous research [89].

Fig. 8 shows the relative static pressure contours within the chimney without RPWs (Model 1) where G=600 W/m^2 and the turbine pressure drop is set to be 100 Pa. Because the collector inlet height is too large and there is no additional structure (like the radial walls) to prevent the heated air from being blown downstream, an increasing percentage of the cold flow enters the system through the collector inlet with increasing ACW, which is responsible for the performance deterioration of the SUPPS. A similar pattern reappears for the minimum relative static pressure in Model 2, but the transition point occurs at a lower ACW velocity (about $u_{500\ m}$=15 m/s), as the effects of ACW at the outlet of the chimney prevail over the buoyancy effects when the ACW is strong enough to disperse most of the heated air. As argued by Ming et al. [71], the system driving force can be a direct proportion of the minimum pressure, the driving force of the SUPPS will also first decrease, and then increase with increasing ACW velocity, further verifying the two-sided effects of ACWs.

Examining the relative static pressure contours in the previous

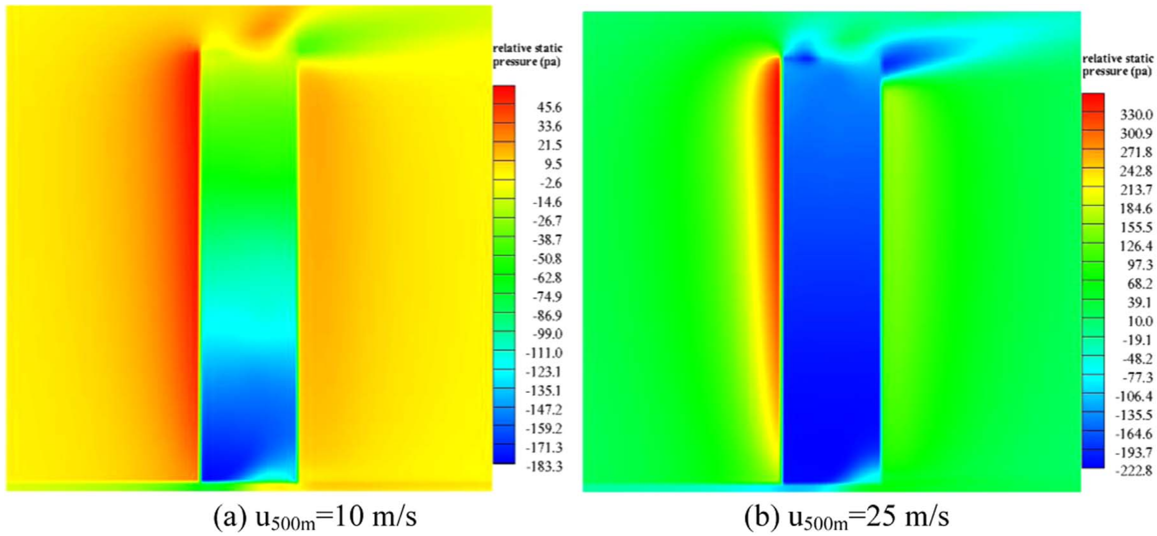


Fig. 8. Relative static pressure on the symmetry plane in Model 1 (without RPWs) with turbine pressure drop being set at 100 Pa for various ACW. (a) $u_{500\ m}$=10 m/s (b) $u_{500\ m}$=25 m/s.

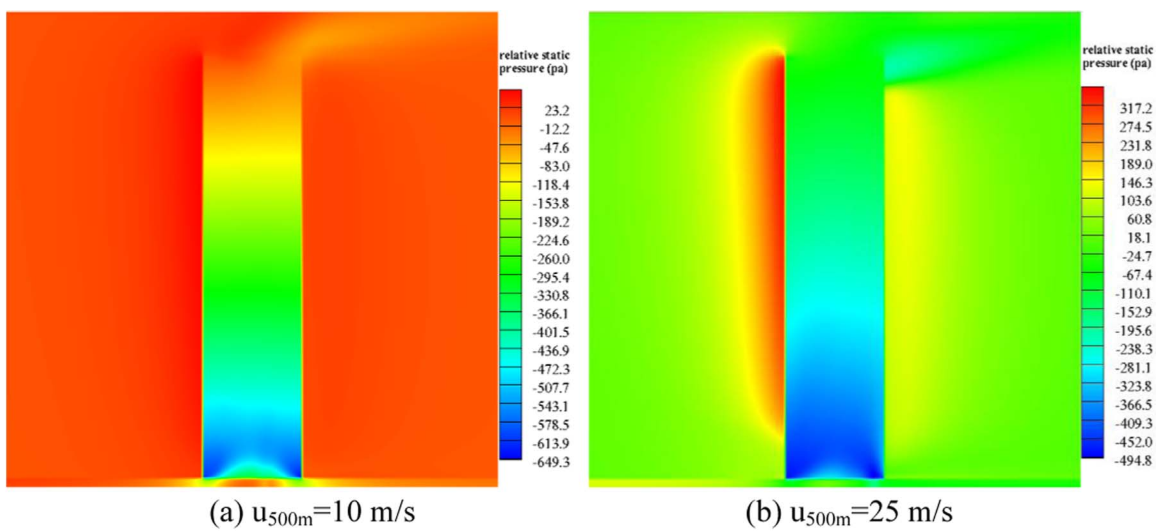


Fig. 9. Relative static pressure on the symmetry plane in Model 3 (with RPWs) when turbine pressure drop is set at 300 Pa for various ACWs. (a) $u_{500\ m}$=10 m/s (b) $u_{500\ m}$=25 m/s.

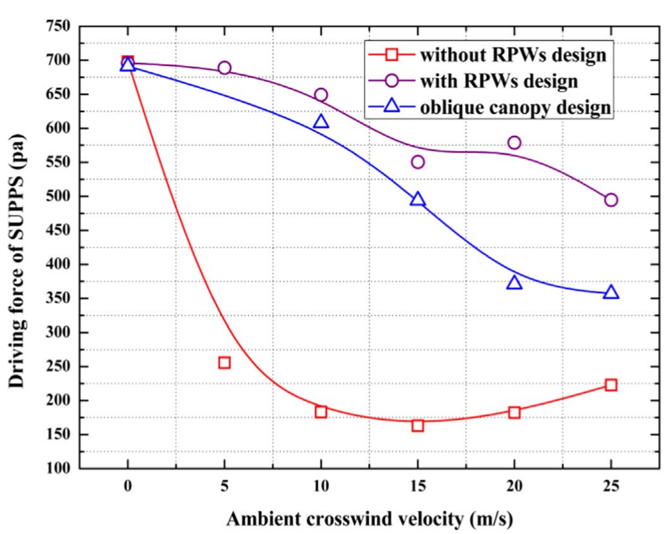


Fig. 10. Influence of ambient wind on the driving force of SUPPS models 1, 2 and 3..

work [89], we note that the sloped canopy design reduces the amount of cold air slipping under the canopy, maintaining the SUPPS's ability to operate decently in a stronger ACW environment. The development of a vortex at the chimney bottom leads to a negative pressure zone. A similar trend of the minimum relative static pressure is found for different ACWs, but the change in the contour line is more moderate since the ambient wind cannot affect the pressure distribution at the chimney bottom in a direct way.

Fig. 9 shows the relative static pressure contours within the chimney of model 3 with a turbine pressure drop of 300 Pa. Since this is the very place where airflow from the collector converges, the pressure undergoes the steepest gradient at the entrance of the chimney. It can be seen from Fig. 9 that the pressure reaches its minimum value near the turbine and then increases gradually through the chimney. The same phenomenon was observed by [140]. There is a vortex developed near the shell at the chimney entrance in the ACW's direction; the stronger the ACW, the more twisty the distribution of the contour lines will be. For an ACW ranging from 0 to 25 m/s at an interval of 5 m/s, the corresponding minimum relative static pressures are −695.9, −688.8, −649.3, −550.6, −578.7, and −494.8 Pa, respectively. With heated air being effectively protected by the radial walls, the driving force transition point mentioned above is shifted to a larger

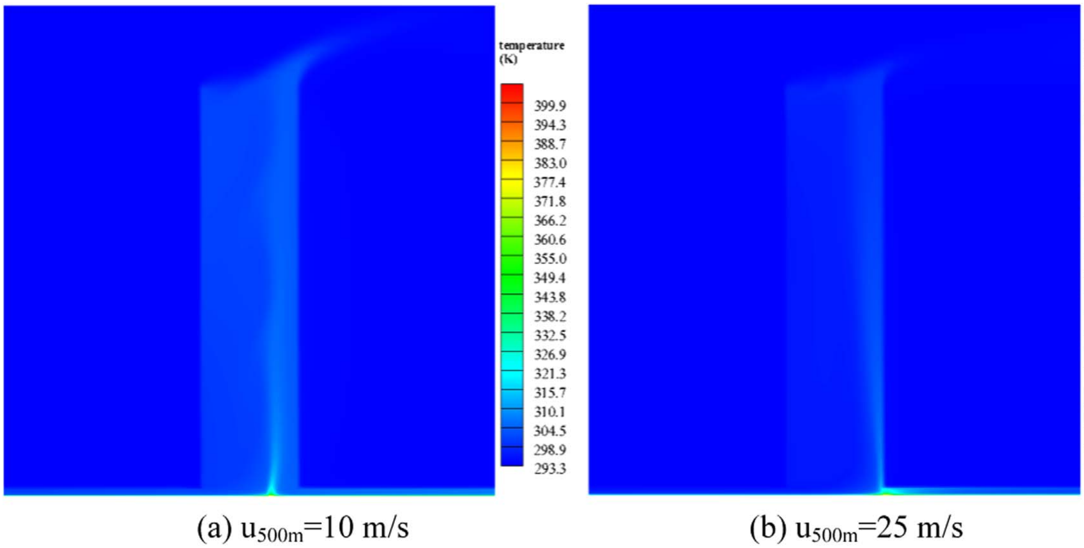


Fig. 11. Temperature contours on the symmetry plane in Model 1 (without RPWs) with turbine pressure drop being set at 100 Pa for various ACWs. (a) $u_{500\text{ m}}$=10 m/s (b) $u_{500\text{ m}}$=25 m/s.

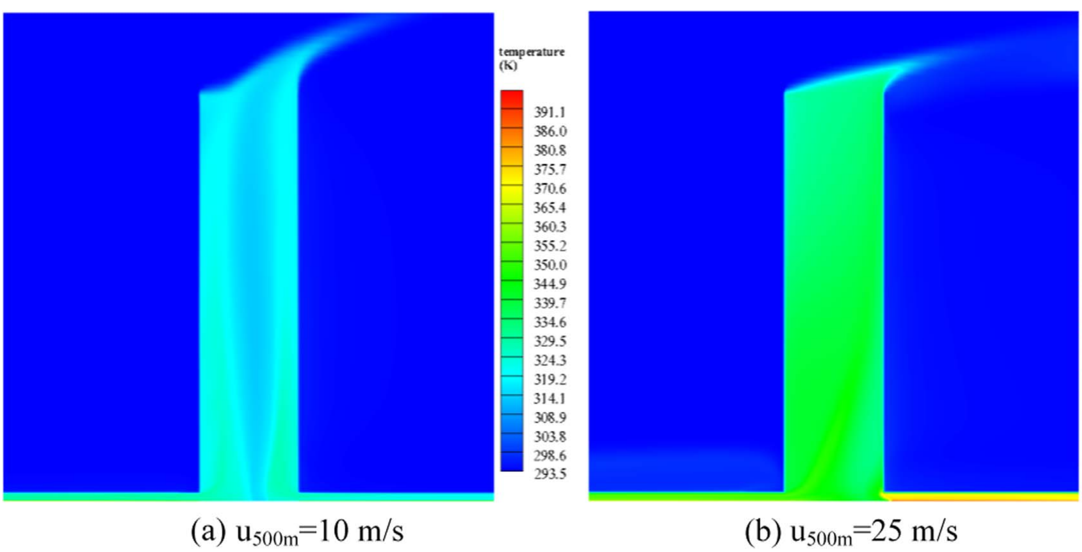


Fig. 12. Temperature contours on the symmetry plane in Model 3 (with RPWs) with turbine pressure drop being set at 300 Pa for various ACWs. (a) $u_{500\text{ m}}$=10 m/s (b) $u_{500\text{ m}}$=25 m/s.

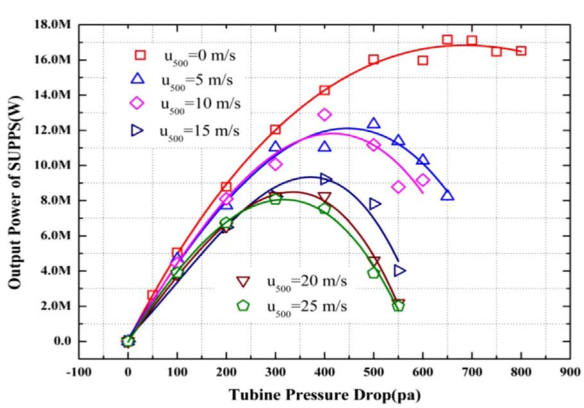


Fig. 13. Influence of pressure drop on turbine output power for SUPPS of Model 3.

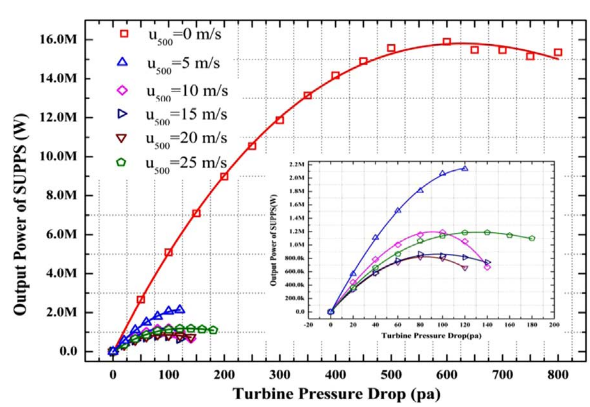


Fig. 14. Influence of pressure drop on turbine output power for SUPPS of Model 1.

ACW velocity.

Fig. 10 shows the influence of the ACW on the driving force of the three SUPPS models at G=600 W/m^2. It is obvious that SUPPS with RPWs is the best design to sustain the largest driving force in the chimney, with the sloped canopy design coming in second. The driving force of the SUPPS decreases to a minimum value and then gradually increases with increasing ACW velocity. The better the system is able to keep a high efficiency, the later the transition point occurs.

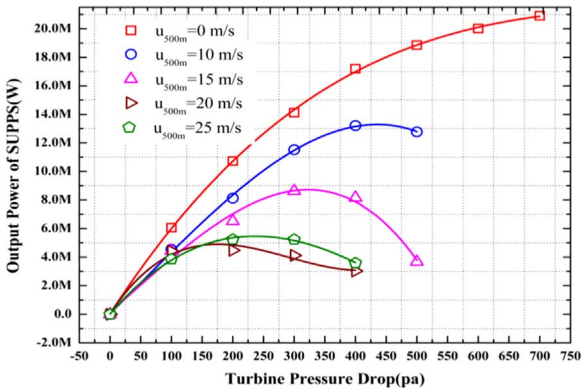


Fig. 15. Influence of pressure drop on turbine output power for SUPPS of Model 2 (Results re-processed with data from [89]).

3.2.3. Temperature contours

In this part, numerical simulation results of the temperature contours of the two geometrical models, the SUPPSs with/without RPWs, are quantitatively compared and analyzed, as shown in Figs. 11 and 12.

As seen from Fig. 11, the average updraft temperature magnitude decreases sharply with the increasing ACW velocity for flat canopy design without RPWs (model 1). When the turbine drop is set at 100 Pa and the ACW ranges from 0 to 25 m/s, the average temperature of the air flow in the outlet of the chimney is 318.62, 303.45, 300.60, 298.69, 297.52, and 296.97 K, respectively. Even a weak ACW ($u_{500\ m}$=5 m/s or $u_{10\ m}$=3.19 m/s) can result in more than 10 K average temperature drop within the system. With the increase of ACW velocities, the average temperature in the chimney tends to become steady (around 297 K), only marginally higher than ambient, as the strong ACW at chimney outlet gradually plays a dominant role in the SUPPS performance. Undoubtedly, the sharp drop of the average temperature within the system will seriously undermine the buoyancy effect, thus ultimately deteriorating the output power of SUPPS.

Whereas, the temperature decrease of the SUPPS with sloped canopy design [89] is much lower than that of the SUPPS with flat canopy under ACW conditions. Within a turbine working range of 0–150 Pa for both systems, Model 2 has an average temperature over 8 K higher than Model 1 for all cases. That's the very reason for the better performance of Model 2 comparatively to Model 1.

A careful observation of Fig. 12 concludes that when the pressure is set as 100 Pa, the corresponding average temperatures of the flow in the outlet of the chimney are 317.39, 312.44, 311.49, 310.59, 310.49, and 308.90 K, respectively, showing that the RPWs design (Model 3) sustains a higher average temperature in a slightly larger amount, around 10 K. It is obvious that the average temperature of the system will decrease no matter which design is adopted when ACW exists, because there is still cold ACW entering under the collector and a part of high enthalpy air escaping from the system. For all models, the temperature decrease cannot be offseted by either the relatively small benefit of a driving force increase aroused by the ACW at the chimney outlet, or a marginal increase of pressure and air speed in the windward side of the collector caused by the ACM. Model 2 is almost as efficient as model 3, as there is less hot air dilution by cold ACW entering under the canopy.

3.2.4. Output power

The detailed comparisons of power output for the three different systems are shown in Figs. 13–15. At the first glance of Fig. 13, it is surprising to find that the output power sharply declines when an ACW exists for Model 1. For the cases calculated, the output power of SUPPS reduces and hits the minimum between 15–20 m/s, then slightly increases with the ACW. And the difference of power output between any two ACW (5–25 m/s) is quite small compared with the magnitude of the power output with no ACW. The phenomenon can be reasoned as the dichotomous effects of ACW on SUPPS system, which have been mentioned in the previous work [89].

Comparing the output power of SUPPS with the flat canopy (Fig. 14) and the sloped one (Fig. 15), it can be seen that the sloped canopy will weaken the influence of the ACW significantly. What's more, when there is no ACW, for the same model scale, the output power of the sloped one is 10% higher than for the flat design. This means that the sloped design is beneficial to the energy collection efficiency of the system as demonstrated by Koonsrisuk and Chitsomboon [59].

An in-depth look at Figs. 13 and 14 shows that the RPWs design improves the output power of SUPPS system greatly. This phenomenon can be explained by the fact that the RPWs significantly reduce the hot air blown away by the ACW. When the ACW is 5 m/s ($u_{500\ m}$=5 m/s) and the turbine pressure drop is 0 Pa, the calculated volume flow at the chimney outlet is 64501 m^3/s, slightly larger than 63405 m^3/s for the case without an ACW. The results can be explained as follows: while the two-sided effects mentioned above still exist, an additive effect is that the wind energy is partly harnessed by the RPWs design, which slightly improves the plants performance. Unfortunately, the effect is relatively weak when compared with the impact of the hot air running out. Undoubtedly, the RPWs design partially counteracts the negative effects of the ACW on the performance of the SUPPS.

In addition, the comparisons among Figs. 13–15 further indicate that the ACW has an influence on the SUPPS performance both though the collector inlet and the chimney outlet. The utilization of a sloped canopy, as well as the adoption of RPWs, cannot eliminate the negative effects of the ACW but can sustain a reasonably high system efficiency in the ACW environment. In addition, the use of RPWs creates a more efficient SUPPS in most cases.

Further research might examine structural modifications of the chimney top and also examine a mixed model design with a sloped collector and RPWs, as well as outside blockage wall which interest was shown by a previous work [93].

4. Conclusions

A brief review of the SUPPS has been presented, followed by a case study of three SUPPS models with chimney heights up to 500 m. The influence of various ACWs on the performance of the fluid flow, heat transfer, driving force, and power output of these different structures is analyzed.

From the numerical simulation results, we found that:

(a) The RPWs design improves the performance of the SUPPS in three ways. First, on the windward side, the RPWs prevent the heated air in the compartments from escaping into the environment without driving the turbine. Second, an added benefit is that some wind energy is partly harnessed due to the RPWs' design. Third, one drawback is that several vortexes are formed in the compartments, and disperse considerable potential energy, which partly counteracts the benefits bought by the RPWs design. The vortex formation can be explained by a possible Bernoulli Effect caused by the air velocity difference between the air inside and outside the canopy. Although the RPWs prevent air exchange between compartments of the canopy, the outside ACW seems to have a significant effect at the collector level.

(b) When comparing the output power of the different designs, the RPWs design is slightly better than the sloped canopy design under most conditions. A combination of these two designs should further improve the system performance.

(c) No matter which structure is adopted in this work (Model 2 or 3) to alleviate the negative effects of the crosswind, there is still an obvious reduction in the performance of the SUPPS when compared with that of SUPPS without ACW. The loss of enthalpy of the heated air overwhelms the slight benefits bought by the ACW at the chimney outlet.

Acknowledgements

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