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A moist air condensing device for sustainable energy production and water generation

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ABSTRACT

A solar chimney power plant (SCPP) is not only a solar thermal application system to achieve output power, but also a device extracting freshwater from the humid air. In this article, we proposed a SCPP with collector being replaced by black tubes around the chimney to warm water and air. The overall performance of SCPP was analyzed by using a one-dimensional compressible fluid transfer model to calculate the system characteristic parameters, such as chimney inlet air velocity, the condensation level, amount of condensed water, output power, and efficiency. It was found that increasing the chimney inlet air temperature is an efficient way to increase chimney inlet air velocity and wind turbine output power. The operating conditions, such as air temperature and air relative humidity, have significant influence on the condensation level. For water generation, chimney height is the most decisive factor, the mass flow rate of condensed water decreases with increasing wind turbine pressure drop. To achieve the optimum peak output power by wind turbine, we should set the pressure drop factor as about 0.7. In addition, increasing chimney height is also an efficient way to improve the SCPP efficiency. Under ideal conditions, the system total efficiency of a SCPP with a height of 3000 m can be up to nearly 7%.

1. Introduction

1.1. Background

Energy and water are two essential items in our lives. As the population increases and living standard improves, the global energy demand will increase continuously. A report shows that total world energy consumption rises from 549 quadrillion British thermal units (Btu) in 2012 to 815 quadrillion Btu in 2040, with an increase of 48%. Particularly in China and India, account for more than half of the world's total increase in energy consumption over the 2012 to 2040 projection period [1]. Fossil fuels continue to provide most of the world's energy, which have arisen about the corresponding environmental cost, especially for greenhouse gas (GHG) emissions, exacting a heavy toll on human health [2]. On the other hand, the freshwater shortage is emerging as one of the most critical global issues. In China, large areas, especially in North and West China, are experiencing a severe dryness, and the total national water shortage in 2030 is predicted to be nearly 200 billion m^3 with more than 25% for domestic needs [3]. In addition, due to global warming and other extreme climatic phenomena, like the El Nino Phenomena, the droughts are getting more and more serious. The demand for providing sustainable freshwater is increasing.

Given the depletion of resources and increasingly growing environmental problems, people and governments would turn their attention to clean and renewable solar energy. As it is well known that China is rich in solar energy resource, the annual average sunshine time in most areas is more than 2000 h and the total annual radiation is nearly 1500–1800 kWh/m^2, providing favorable conditions for the full development of solar technologies [4].

The idea of solar chimney power generating technology was first put forward by Schlaich et al. [5] in 1978. Shortly after that, in 1983, the German government and a Spanish electricity company jointly built the world's first solar chimney power plant (SCPP) in Manzanares, Spain. The experimental SCPP had a chimney 194.6 m in height and 5.08 m in radius, a collector 122.0 m in radius, and a peak output power of 50 kW. This prototype was fully tested and validated till 1989. Haaf et al. [6,7] gave some experimental results and a scientific description of this SCPP proto-

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Nomenclature

A	chimney cross-section area [m^2]
c_p	specific heat capacity [J/(K kg)]
d	chimney diameter [m]
d_s	moisture content in per kilogram air [kg/kg (dry air)]
f	friction factor
g	gravitational acceleration, 9.8 [m s^{-2}]
H	chimney height [m]
$\dot{m}$	condensed water in per kilogram air [kg/kg]
$\dot{m}_{total}$	mass flow rate [m^3/s]
n	wind turbine pressure drop factor
p_v	water vapor partial pressure [Pa]
p_s	saturated water vapor partial pressure [Pa]
p_z	pressure at some height [Pa]
s	water content in per cubic meter [kg/m^3]
t	Celsius temperature [°C]
T_0	heated air temperature at the chimney entrance [K]
T_z	temperature at height being z m [K]
v	specific volume [m^3/kg]
V_z	vertical velocity [m/s]
V_0	velocity at the inlet [m/s]
V_l	condensed water velocity [m/s]
Z	vertical height [m]
P_e	system total output power [W]
P_{e1}	wind turbine output power [W]
P_{e2}	hydraulic turbine output power [W]
V	the inlet volume flow rate of airflow [m^3/s]
Q_{air}	thermal energy absorbed by airflow inside the tubes [W]

Greek symbols

Δ	difference or increase
κ	specific heat ratio
ρ	density [kg/m^3]
ρ_H	air density at the exit of the chimney [kg/m^3]
γ	latent heat [J/kg]
ε	the entrance and exit losses factor
η_1	the efficiency of wind turbine
η_2	the efficiency of hydraulic turbine
η_{sys}	system efficiency

Subscripts

0	chimney inlet
H	chimney outlet
l	water liquid
s	saturated state
v	water vapor

type. A comprehensive review of scientific literature on SCPP was also provided by Zhou et al. [8].

Ming et al. [9] proposed several types of engineering structures that were able to transfer heat from the Earth's surface to the upper layers of the troposphere, thus could cool down the Earth by increasing atmospheric convection, enhancing outgoing long wave radiation to the outer space. The solar updraft chimney, one of the devices proposed to transfer surface hot air several kilometers higher was introduced. A SCPP is comprised of three main components, the chimney (for stack effect), the solar collector (the greenhouse), and turbines (power conversion unit, driven by airflow to produce CO_2-free electricity). Moreover, the performance of a SCPP [10], such as the effect of the energy storage layer [11], turbines [12], ambient crosswind [13], and chimney shape [14] on thermo-fluid dynamics and power output were also studied via numerical method for the purpose of theoretical analysis.

The research group led by Sherif [15,16] developed comprehensive mathematical models to analyze the influence of miscellaneous parameters of a SCPP, such as ambient conditions and structural dimensions, on the temperature and output power of the solar chimney. They concluded that the output power of a solar chimney was directly proportional to the air temperature difference attained in the collector and the mass flow rate of air, appropriate enhancements could help to increase the overall chimney output power. Besides, three types of experimental prototype were built by them in Florida, with the chimney shape, collector construction, and an energy storage layer performance being taken into consideration.

Koonsrisuk and Chitsomboon [17] proposed a dynamic similarity variable between a SCPP prototype and its scaled models, thus could simplify the experimental study of SCPP and cut expense. Maia et al. [18,19] developed a numerical model of the turbulent flow inside a solar chimney to evaluate the influence of geometric configurations and operational variables on the flow behavior. It showed that the height and diameter of the chimney were the most significant variations in the flow behavior. The energy and exergy analysis of the airflow inside a solar chimney were also carried out. Patel et al. [20] studied the effect of geometric parameters to optimize the configuration of SCPP. Krätzig [21] developed a mathematical model to analyze the thermo-fluid mechanical processes of SCPPs and to evaluate their power/energy harvest performance. Nia and Ghazikhani [22] studied the heat transfer characteristics of a SCPP numerically using passive flow control approach. Fasel et al. [23] developed a numerical model using CFD method to investigate the fluid dynamics and heat transfer of SCPPs. Cao et al. [24] suggested that the TRNSYS can also be used as a convenient tool to simulate the performance of SCPPs.

In order to evaluate the performance of SCPP, researchers found that the ratio of the pressure drop across the turbine to the total driving pressure is much significant. Most investigators have assumed that the optimum ratio is 2/3 [7,25–27]. Koonsrisuk and Chitsomboon [28] found that with a constant driving pressure, the optimum ratio of the turbine extraction pressure to the driving pressure was 2/3 and it was a function of the plant size and solar heat flux. Bernardes and Backström [29] and Hedderwick [30] indicated that the optimum ratio was not constant during the day and it is dependent of the heat transfer coefficients in the collector. Nizetic and Klarin [31] concluded that the turbine pressure drop factors were in the range of 0.8–0.9 by using a simplified analytical approach. Guo et al. [32] indicated that the solar radiation and ambient temperature had obvious effect on the optimum turbine pressure drop ratio by an analytical approach and numerical simulations, and the optimum ratio of the Spanish prototype varies from 0.90 to 0.94 under normal climate conditions.

Since Schlaich et al. [33] introduced the SCPP, with a good overview of the technology, many researchers tried to find conceptual devices more efficient. Koonsrisuk et al. [34,35] proposed a solar chimney system with a sloped collector. When comparing the conventional SCPP with the sloped solar chimney power plant (SSCPP) based on the Second Law of Thermodynamic analysis, results showed that SSCPP was thermodynamically better than conventional SCPP in some configurations. Meanwhile, they developed a model to evaluate the performance of conventional SCPP and SSCPP with varying flow area. It suggested that the SCPP with sloping collector or divergent-top chimney performs better than that of a conventional SCPP. Fei et al. [36] designed a SSCPP for Lanzhou, China, which was able to produce 5 MW electric power on a monthly average all year. A pilot SSCPP also built in Damascus University by Kalash et al. [37]. Pretorius and von Backström [38,39] put forward the idea of constructing a SCPP with the chimney height of 1500 m, which also provided detailed calculations and structural designs. These prototypes have played a very important role in promoting innovative researches of SCPP, and they also provide us with a broad perspective and inspiration.

Shariatzadeh et al. [40] proposed a new SCPP with solid oxide fuel cells and solid oxide electrolysis cells, which could work continuously at night. Shahreza and Imani [41] conducted an experimental and numerical study on a small scale solar chimney prototype. de_Richter et al. [42] proposed to combine TiO_2-photocatalysis with solar chimney power plants (SCPPs) to cleanse the atmosphere of non-CO_2 greenhouse gases, by which would help to limit global temperature rise. Zheng et al. [43] proposed the hybrid cooling-tower-solar-chimney system, which could generate electricity and dissipate waste heat simultaneously. Ninic and Nizetic [44] developed a gravitational vortex column model to study the possibility of making use of the warm, humid air in the atmosphere. Ferreira et al. [45] studied the possibility of a solar chimney to dry agricultural products. A device called "Solar Cyclone" was introduced to separate water from surface air by Kashiwa and Kashiwa [27]. An expansion cyclone separator was used for condensing water and removing atmospheric humidity inside the chimney, where the temperature was below the dew point. If it worked, this cycle was sustainable, but the efficiency was unclear and should be determined in further studies.

As the air rises in the chimney, the air temperature decreases with chimney height, the induced buoyancy effect is then used to drive the turbine to generate electricity. One of the SCPP's advantages is its relatively lower unit electricity price. Zhou et al. [46] investigated a solar chimney system to achieve both power generation and seawater desalination. One-dimensional compressible flow model was carried out to study the performance of the SCPP. In this system a large amount of heat was wasted as latent heat released during the process of water evaporation, causing the system power output to be lower than that of a classical SCPP.

Starr and Anati [47,48] proposed an artificial construction within a vertical tube with a height of 3 km and a radius of 50 m, which they named aerological accelerator (AeAc). The system is generally much higher than the lifting condensation level (The lifting condensation level is defined as the height at which the relative humidity of an air parcel reaches 100% when it is cooled by dry adiabatic lifting.). So freshwater could be extracted from hot moist air with the condensation. The recovery of water is a partial duplication of natural atmospheric convection process. Thus it needs no external drive, in fact, no need of a driving energy source is better than the automatic release of latent heat of condensing water vapor in ideal situations. Starr and Anati [49] examined the probable success of the procedure and were encouraged by the results. Furthermore, they studied the effectiveness of controlled atmospheric convection by comparing to natural precipitation at five different locations. They examined whether a period of low precipitation is a period of favorable or unfavorable condition for producing water by the AeAc. They computed the ratio of the AeAc production to natural precipitation and deduced that the effectiveness of AeAc in arid regions was higher than in rainy regions.

Recently, Ming et al. [50] re-analyzed the AeAc device and found that the system can supply freshwater for residential and agricultural use with a proper collecting method, as well as the output power. They suggested that the electricity produced by this device could be remarkable, but the performance of this device was still unclear. In this study, we proposed a novel AeAc device base upon a SCPP system. This system has no collector but black tubes around the chimney. There are two kinds of turbines installed in the system: wind turbine(s) to achieve output power from the upwind to the upper air and hydraulic turbine(s) to capture the energy from the downward freshwater. We established a one-dimensional compressible flow and heat transfer mathematical model to investigate the performance of this sustainable AeAc device. In addition, the influences of operating conditions and chimney height on the system performance were studied.

2. System mechanism

As the moist air rises through and out of the solar chimney, Kroger and Blaine [51] showed that water vapor could condense to form clouds, and the impact on SCPP's performance was not negligible. Hence, VanReken and Nenes [52] studied a cloud parcel model initialized to simulate the range of expected operating conditions for a proposed SCPP in southwestern Australia. They found that for high relative humidity of water vapor, cloud could probably form inside the chimney. At some moderate levels of water vapor enhancement, it is sensitive to the assumed entrainment rate. The cloud (excess water vapor) once formed could react upon the performance of power generation facility, no matter formed within the chimney or out of the chimney.

When small convective cells in the atmosphere grow into fully developed thunderstorms, the entrainment of air from adjacent columns into the otherwise buoyant column of air will cause the damaging effects, as Squires and Turner showed [53], the entrainment constant varies inversely with cloud radius.

As a matter of fact, the tube (chimney) functions as an artificial stimulator of condensation and precipitation. Fig. 1 shows the similar device, hot and humid air flow is induced through a warm seawater shower. Because of the density difference between the inside and outside, the air flows upward guided by convection. As air parcel rises, its temperature decreases as the reduced internal energy is converted to gravitational potential energy, which causes the relative humidity to increase. As the chimney is high enough, the adiabatically ascending moist air within the chimney should reach the lifting condensation level, where the temperature drops under the dew point or reach the saturation temperature inside the tube, and the water vapor in the moist air will begin to condense onto any available solid surfaces: this is the same process by which clouds form. During this condensation process, the released latent heat of the water vapor will heat the moist air flowing upward and cause a decrease in density, and this will increase the buoyant force of the system and ultimately accelerate the air flow.

In this process, an important point is that the temperature of the moist air entering the chimney should be higher than that of the ambience. As a result, the caused buoyant will drive the moist air to upward the chimney. An effective technical method is to increase the humidity of moist air before entering the chimney. The moist air flowing through exposed seawater; the seawater and the flowing moist air are both preheated by solar energy to enhance the evaporation process, which increase the humidity and temperature of the moist air. This evaporation process from the seawater is the so called distillation. When compared with conventional desalination technology, the device has higher cost. Fortunately, however, this can be compensated by installing both wind turbines and hydraulic wind turbines at the bottom of chimney where the upwind air flow and the downward freshwater are separated by different flow channels. As a result, the process of extracting water from the air through the phase change process of hot moist air inside the chimney and obtaining electricity from

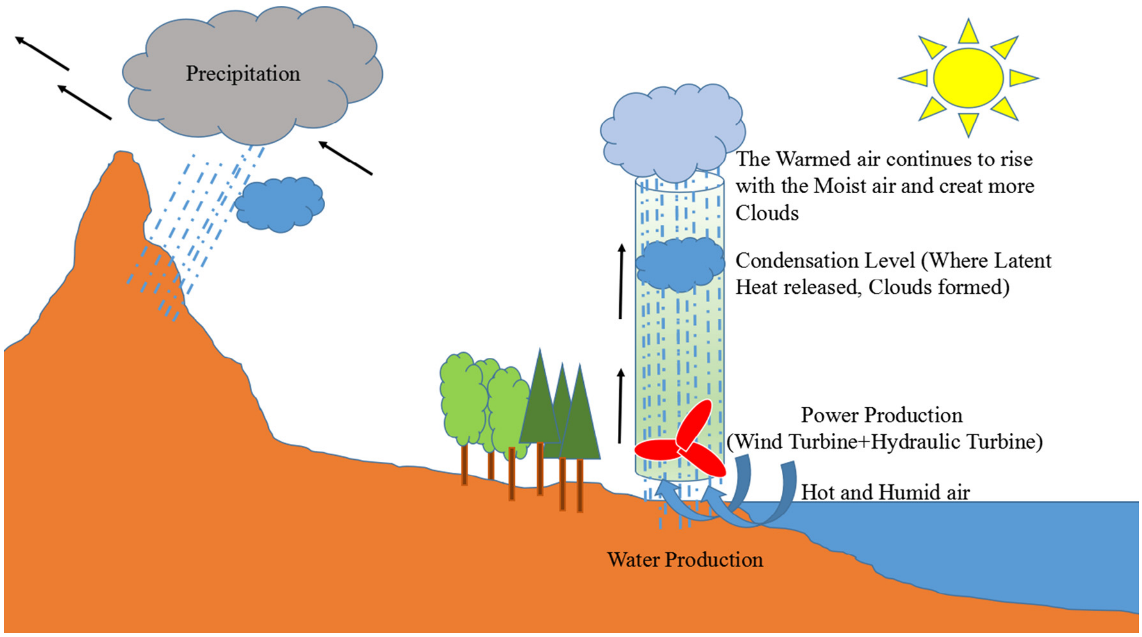

Fig. 1. The process of a SCPP with water vapor condensation on the sea surface.

the upward air flow and the downward water flow may improve the overall performance of SCPP.

3. Model description

3.1. Physical model

The construction costs budget of a traditional SCPP are more or less the following [54]: 25% for the chimney, 5% for the turbines, and 70% for the collector. Thus in order to cut down the total expense, Bonnelle [55] proposed a variant SCPP with no collector, similar to the energy tower. In addition, Papageorgiou [56] studied a SCPP without solar collector. As the solar collectors received thermal energy by the solar irradiation to create warm air, it is evident that the heat is necessary for solar chimney operation, but they found the released latent heat from the water vapor of moist air during condensation process could be the air up-drafting generator, thus the solar collectors could be omitted. In addition, they suggested that the SCPP be placed in humid areas, near the sea, in which more power output would be possible.

In this study, the proposed device shown in Fig. 2 was similar to the SCPP advanced by Schlaich et al. [5], thus we still call it SCPP. In this device, some black tubes are used to replace the collector, which are much less expensive. In fact, these black tubes not only act as a collector with the greenhouse effect, but also for heat storage. The water-filled black tubes exposed to the sun absorb energy from the solar radiation. At night, when the ambient air starts to cool down, the water inside the tubes releases the heat which is stored during the day. In addition, heat storage with water is higher (per kg) than the heat capacity of air, sand, and gravel. In Fig. 2, another substantial improvement is the separate channels in the tower: the inside channel is the same as the traditional chimney for the hot moist air to flow upward where a wind turbine is installed at the base; the outside channel is used for the generated freshwater to flow downward where a hydraulic turbine is installed near the exit. In the chimney a condensation system with solid porous surfaces is installed at the height above the condensation level, and the condensed liquid water particles adhere to these solid porous surfaces. These gathered liquid water drops form a water flow and ultimately enter the inlet of the water channel. Considering the gravitational potential energy of the liquid water, a hydraulic turbine is installed at the base to generate electricity, which will increase the total energy efficiency of the SCPP.

As recommended, the best choice of selecting a site might be the seaside near the equator because of such factors as the prevailing wind region, humidity, insolation, and environmental lapse rate, etc. For the purpose of studying the overall performance of this novel SCPP, a wind turbine is installed at the bottom of the chimney for generating electricity, moreover, we assumed that the condensed water once formed can all be collected, the means or methods for collection will be considered in future studies. Besides, if the amount of condensed water is considerable, it will have a large potential energy, therefore we assumed that the condensed water will fall down: thus we consider a hydraulic turbine installed at the bottom of the chimney to evaluate this part of the possible power output. These turbines both coupled with generators could generate electricity. The process of air flow through a shower at the end of the water-filled black tubes is not considered, it is assumed the black tubes heat the inlet air and hot water shower also humidifies the inlet air within a certain range.

3.2. Mathematical model

The performance of the SCPP greatly depends on the chimney dimensions and ambient conditions. The former mainly includes the chimney height and radius, while the latter includes the ambient temperature, ambient humidity, solar radiation, and wind velocity. In this study, because such time-varying factors as solar radiation and wind velocity are comparatively complex, we only give the inlet temperature and relative humidity (RH) for the hot moist air, and the ambient wind velocity is neglected (see Fig. 3).

Some assumptions are presented as follows to simplify the calculations:

(1) The pressure within the chimney at the chimney top P_H is the same as in the adjacent environment at the same altitude;

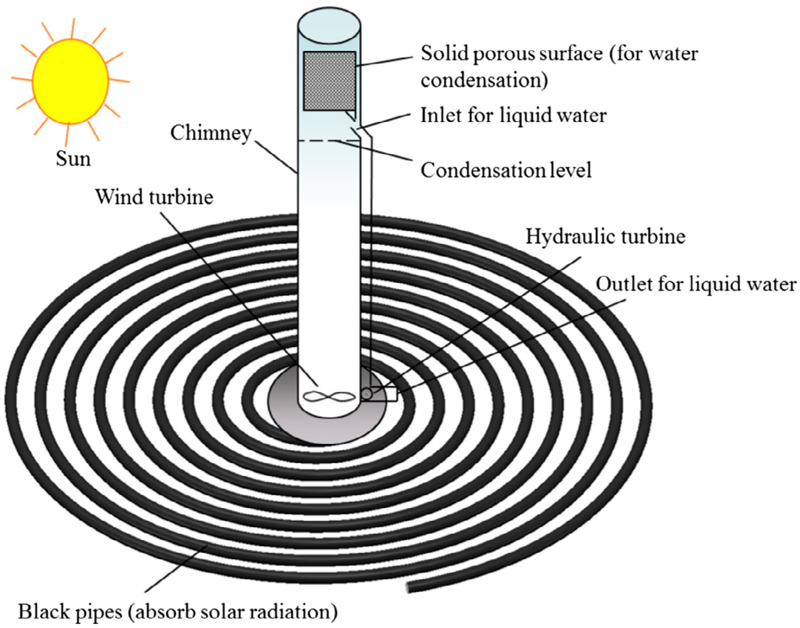

Fig. 2. A sketch of a new proposed SCPP.

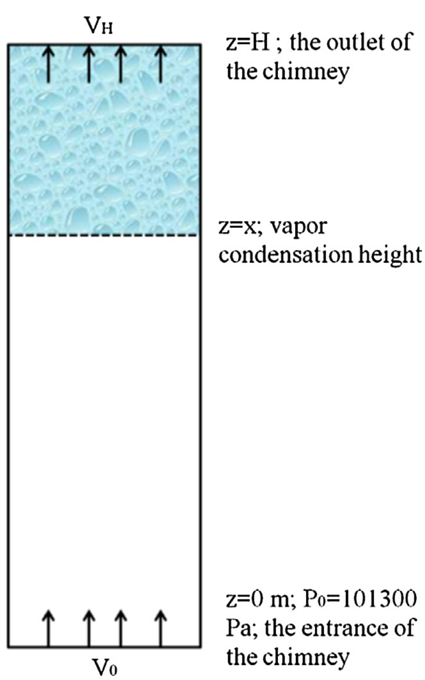

Fig. 3. The geometry of the chimney.

(2) The radius of the chimney is large enough, so that the parameters change only along the altitude;
(3) The environmental conditions are steady;
(4) The chimney is a circular cylinder;
(5) The walls of the chimney are thermally insulated;
(6) No super-saturation occurs;
(7) Once water droplets are formed, precipitate on the solid porous surfaces do not induce airflow perturbation.

As the ambient conditions such as the atmospheric temperature, pressure, and relative humidity (RH) vary with time and location, which will make the problem to become complex. In order to simplify the analysis without causing too much deviation, here we employ the standard atmosphere as the working condition.

The pressure, temperature, and density variations of the air outside the chimney can be calculated by [57],

$$T\infty(z) = T\infty(0)\left(1 - \frac{\kappa - 1}{\kappa}\frac{z}{H_0}\right) \quad (1)$$

$$p\infty(z) = p\infty(0)\left(1 - \frac{\kappa - 1}{\kappa}\frac{z}{H_0}\right)^{\kappa/(\kappa-1)} \quad (2)$$

$$\rho\infty(z) = \rho\infty(0)\left(1 - \frac{\kappa - 1}{\kappa}\frac{z}{H_0}\right)^{1/(\kappa-1)} \quad (3)$$

where $T\infty$ is the ambient temperature; $p\infty$ is the ambient air pressure; $\rho\infty$ is the ambient air density; z represents the height about the ground; R_g is the ideal gas constant, which is 287.05 J/(kg K); g is the gravitational acceleration, which is 9.8 m/s^2; κ is the specific heat ratio which is 1.235 for standard atmosphere.

In addition, H_0 in these equations is the atmospheric scale height. For planetary atmosphere, the atmospheric scale height is a distance in altitude for which the atmospheric pressure decreases. The atmospheric scale height remains constant at a particular temperature. It can be calculated by

$$H_0 = \frac{R_g T_\infty(0)}{g} \quad (4)$$

The driving potential, the buoyancy force, inside the chimney can be expressed as follows,

$$\Delta p = g\int_0^H (\rho_\infty(z) - \rho(z))dz \quad (5)$$

where g is the gravitational acceleration; H is chimney height; $\rho_\infty(z)$ and $\rho(z)$ are ambient air density and internal airflow density inside the chimney at any height z respectively.

The energy conservation equation can be written as

$$C_P(T_0 - T_z) + \dot{m}\gamma = gz + \frac{1}{2}(1-\dot{m})V_z^2 + \frac{1}{2}\dot{m}V_l^2 - \frac{1}{2}V_0^2 \quad (6)$$

where C_p is the air specific heat capacity, C_p = 1005 J/(kg K); T_z and V_z are air temperature and velocity at height z; V_l is the liquid velocity relative to air flow. The difference between V_z and V_0 is quite small because the shape of the chimney is cylindrical (the equation reminds us that a nozzle shape design at the top of the chimney will be effective to reduce the air flow temperature, helping to form clouds or precipitation), and $\dot{m}$ is relatively small, so we can rewrite Eq. (6) as

$$T_z = T_0 - \frac{(gz - \dot{m}\gamma)}{C_P} \tag{7}$$

In general, the total pressure of moist air is atmospheric pressure which is comparatively low, so the partial pressure of dry air and water vapor are lower, the moist air can be regarded as an ideal gas mixture, so the ideal gas state equation is

$$pv = R_g T \tag{8}$$

The temperature difference in the system is small (less than 50 K in most cases), so the latent heat for vapor condensation can be a constant (γ = 2,257,000 J/kg).

The partial pressure of water vapor is a function of the temperature t in °C and it can be calculated by the Arden Buck approximate equation,

$$p_s = 611.21 \cdot \exp\left(\frac{(18.678 - t/234.5)\cdot t}{257.14 + t}\right) \quad \text{for} - 80\,^{\circ}\text{C} < t < 50\,^{\circ}\text{C} \tag{9}$$

The RH for the air is defined as

$$RH = \frac{p_v}{p_s} \tag{10}$$

where P_s represents the partial pressure for the saturated moist air.

The water content per kilogram dry air is

$$d_s = 0.622 \cdot \frac{p_v}{p_z - p_v} \tag{11}$$

The water content per kilogram of moist air is

$$s = 0.622 \cdot \frac{p_v}{p_z - 0.378 p_v} \tag{12}$$

Inside the chimney, assuming a linear variation of air density with height, we can get

$$\rho(z) = \rho_0 - (\rho_0 - \rho_H) \cdot \frac{z}{H} \tag{13}$$

The updraft potential can be partly undermined by the wall friction, and other points losses along the chimney, the momentum conservation equation for the flow in the direction of chimney axis is given by Kashiwa and Kashiwa [27]:

$$\Delta p(1 - n) = \left[\varepsilon + e^{H/H_0} + \frac{f \cdot H}{d}\right] \cdot \frac{1}{2}\rho_0 V_0^2 \tag{14}$$

where n is the factor of pressure drop at the turbine (n will be 0 if there is no output power is generated); V_0 is the flow velocity in axial direction at the chimney inlet. The three terms in the bracket in the right side are the exit loss (with unit coefficient), other point losses, and wall friction. The factor ε accounts for the following energy losses: (1) the energy losses in the turbine; (2) energy losses at the location where the flow area changes; (3) the turbulent flow losses; (4) the vapor condensation at any location of the chimney. The wall is not too rough, so f = 0.01 for high Reynolds number flow in a pipe is adopted in the calculation.

The total moist air mass flow in the chimney is

$$m_f = \rho_0 V_0 A = \rho_H V_H A + m_f \cdot s \tag{15}$$

where ρ_0 and A are the moist air density and cross-sectional area of the chimney, m_f is the total mass flow through the chimney.

P_e represents the output power of the whole system. A portion of power is from the wind turbine installed in the bottom of the chimney thus the potential energy of hot air can be eventually converted into electricity, represented by P_{e1}. There is also a portion of power from the hydraulic turbine mounted near the outlet of the liquid water so that the potential energy of collected condensed water can be eventually converted into electricity, represented by P_{e2}. The output power P_e can be written as:

$$P_e = P_{e1} + P_{e2} \tag{16}$$

Here, P_{e1} and P_{e2} can be given by the following equation:

$$P_{e1} = \eta_1 n V \Delta p \tag{17}$$

$$P_{e2} = \eta_2 m_w g H \tag{18}$$

where η_1 represents the overall energy conversion efficiency from thermal to electricity which is preset as 0.72. It is the multiply of efficiency from thermal to wind turbine shaft output power and that from wind turbine shaft output power to electricity, the former being about 0.8 recommended by Schlaich et al. [5] and the latter being 0.9 which is available easily; V is the inlet volume flow rate of hot air in the bottom of the chimney; η_2 represents the efficiency of hydraulic turbine, which can reach 0.9 [46]; m_w stands for the mass of condensed water.

For a SCPP with water-filled black tubes acting as a collector, solar radiation into the system can be divided as three parts: (i) thermal energy absorbed by airflow above the tubes; (ii) energy stored by water during daytime with solar radiation; (iii) latent heat used by water evaporation. As mentioned before, water-filled tubes act as thermal storage thus the second part could heat air at night. Meanwhile, the release of condensation latent heat when the air rises up inside the chimney could almost offset the loss of latent heat of vaporization in the collector to some extent as the latent heat is assumed as constant. The system efficiency can be obtained as follows,

$$\eta_{sys} = \frac{P_e}{Q_{air}} \tag{19}$$

where η_{sys} is the system efficiency, and Q_{air} is the thermal energy absorbed by airflow inside the tubes, which can be calculated by

$$Q_{air} = c_p m_f \Delta T \tag{20}$$

where ΔT represents the air temperature rise between ambient and chimney inlet.

The iteration is listed in the chart as shown in Fig. 4.

4. Results and analysis

The performance of a hypothetical SCPP of 50 m radius extending vertically to several kilometers in height in different ambient conditions has been evaluated according to the mathematical model shown above. The primary parameters in calculation are shown in Table 1. Through input initial parameters, such as environmental parameters and operating parameters, the results can be obtained by iteratively solving the mathematic model in MATLAB. In this paper, thanks to the use of water-filled black tubes to absorb diffuse radiation and work as a thermal storage system, the chimney is able to operate 24 h on solar energy, it is crucial for those regions with abundant solar radiation. Accordingly, we assumed that the chimney operates 365 × 24 h and the water collecting mechanism inside the chimney is supposed to be 100% efficient. Pressure drop across the wind turbine is assumed as constant to theoretically analyze the effectiveness of this device for sustainable energy production, thus a set of wind turbine pressure drop factors are given.

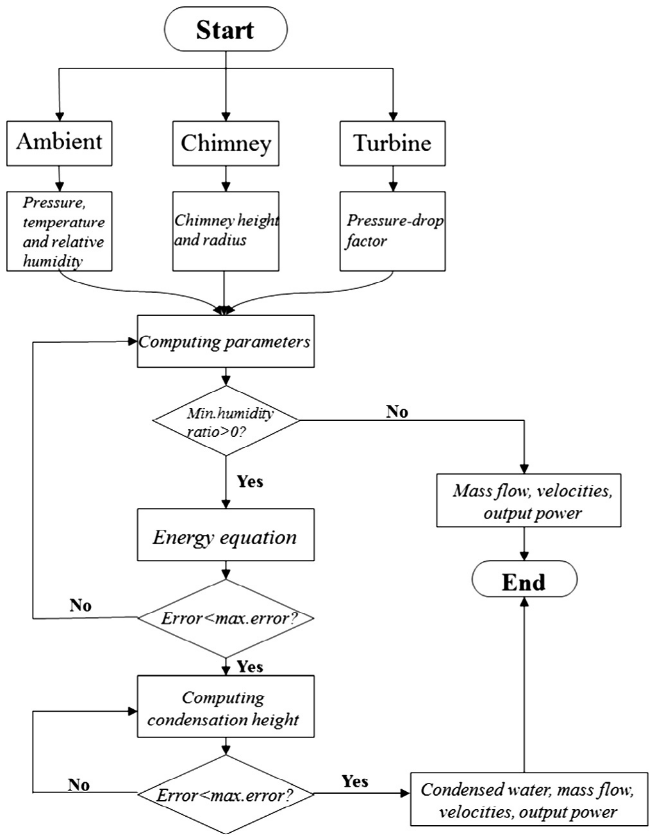

Fig. 4. The iteration flow chart for the mathematical model.

Table 1
Basic parameters of SCPP in calculation.

Coefficients	
The point loss coefficient	$\varepsilon = 0.1$
Wall friction factor	$f = 0.01$
Wind turbo-generator efficiency	$\eta_1 = 0.72$
Hydraulic turbo-generator efficiency	$\eta_2 = 0.9$
Calculating variable parameters	
Air temperature rise between chimney inlet and ambient	ΔT = 5 K, 10 K, 15 K, 20 K, 25 K
Chimney height	H = 1000 m, 1500 m, 2000 m, 2500 m, 3000 m
Chimney diameter	D = 100 m
Ambient air relative humidity	RH = 0.70, 0.75, 0.80, 0.85, 0.90
Wind turbine pressure drop factor	n = [0.1, 0.2…, 0.9]

4.1. Comparison on chimney inlet air velocity

Solar radiation could be absorbed water-filled black tubes in the daytime, thus raises the black tubes temperature. During the day, a fraction of the thermal energy of the black tubes will be transferred to the air flow above the tubes by convection and radiation. At night, when the air starts to cool down, the water inside the tubes releases the heat which is stored during the day, providing a stable air flow, thus driving the wind turbine to deliver output power steadily. It is obvious that the power generating capacity is mainly determined by the inlet volume flow rate of air flow and the wind turbine pressure drop.

Fig. 5 shows the chimney inlet air velocity varies with the wind turbine pressure drop factor under the circumstances of chimney inlet air temperature (ΔT = 5, 10, 15, 20, 25 K), chimney height (H = 1000, 1500, 2000, 2500, 3000 m), and ambient air relative humidity (RH = 0.70, 0.75, 0.80, 0.85, 0.90). It can be seen that with the increase of wind turbine pressure drop factor, the inlet air velocity decreases, as higher pressure drop lowers the air flow driving force and velocity. The driving force of the chimney will be reduced with the increase of pressure drop factor as Eq. (14). In general, the air flow into the chimney will drive the wind turbine blades installed at the bottom of the chimney and the corresponding shaft power will be converted into electricity. There will be a part of pressure loss of the potential energy in this pro-

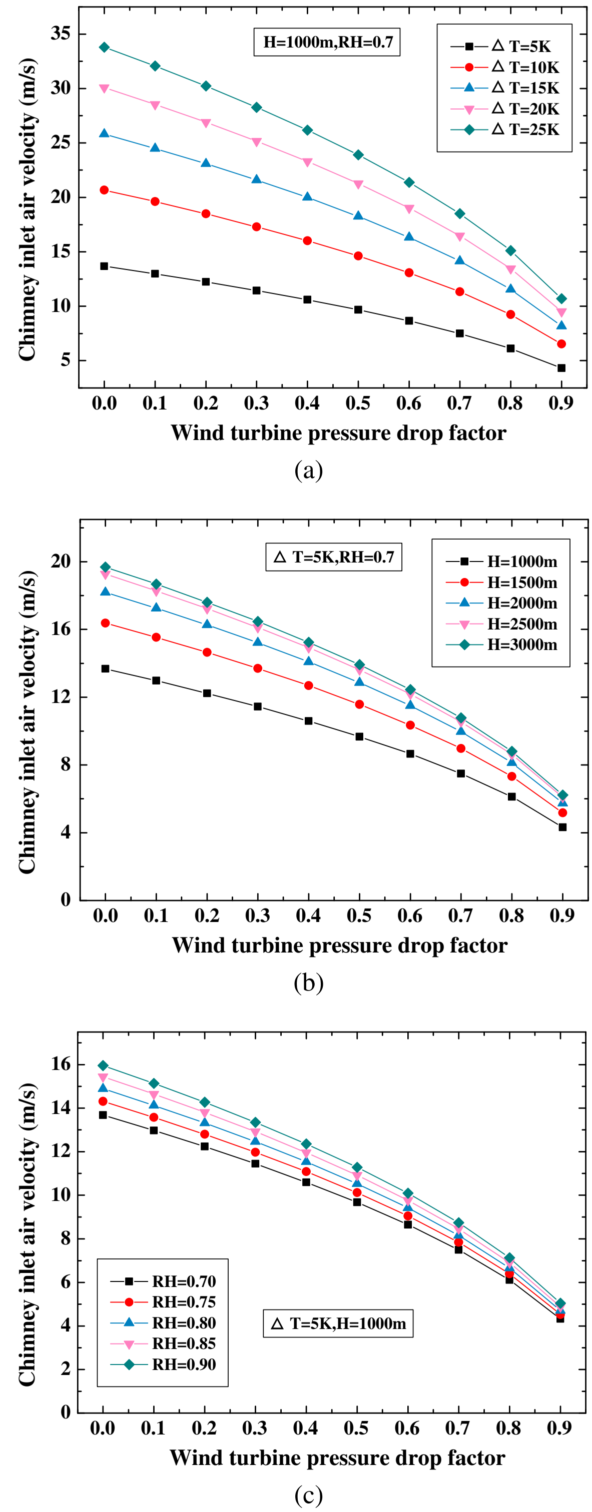

Fig. 5. The effect of chimney inlet air temperature, chimney height and ambient air relative humidity, on chimney inlet air velocity, with varying turbine pressure drop.

cess. When the driving force is reduced, lower velocity is inevitable. It also shows that the impact of inlet air temperature is most significant on inlet air velocity while the ambient air relative humidity does not affect it too much. It should be noted that, in Fig. 5(c), the inlet air velocity increases with increasing ambient air relative humidity. The reason is that when the inlet air is wetter, more water precipitation will occur in the chimney. The average density of the moist air in the chimney will become less. At the same time, more water precipitation means more condensation latent heat is released to heat the air inside the chimney. Due to these factors the difference in density becomes larger inside and outside the chimney. As a result, the driving force will increase. There is also a visible influence on inlet air velocity in different chimney heights, it can be contributed to the change of the driving force, but when the chimney is sufficiently high, this effect will gradually become weak. To sum up, when the temperature difference between the inlet air and the ambient air becomes larger, it will cause a stronger convective motion and an increase of the inlet air velocity. In this case there is also a significant increase in the driving force, by which then more potential energy is converted into electricity. The conclusion is that increasing the inlet air temperature is a more effective way to get a higher inlet air velocity.

4.2. Comparison on the condensation level

The condensation level can be defined as the exact height of relative humidity being 100% when the moist air flows upward in the chimney. For a given chimney, if the moist air with relative humidity being 100% enters the chimney, water precipitation will occur at the base of the chimney. However, if the moist air with lower relative humidity enters the chimney, sometimes the moist air does not become saturate when it leaves the chimney outlet. So the chimney height and the relative humidity of the ambient moist air should be matched to achieve a condensation level lower than the chimney height.

Fig. 6 denotes how the condensation level varies with the chimney inlet air temperature, chimney height, and ambient air relative humidity. The condensation level keeps constant with varying wind turbine pressure drop factor, and the wind turbine pressure drop is not a factor of influence on the condensation level. However, other factors including chimney inlet air temperature, chimney height, and ambient air relative humidity have different effects on the condensation level. With the chimney inlet air temperature

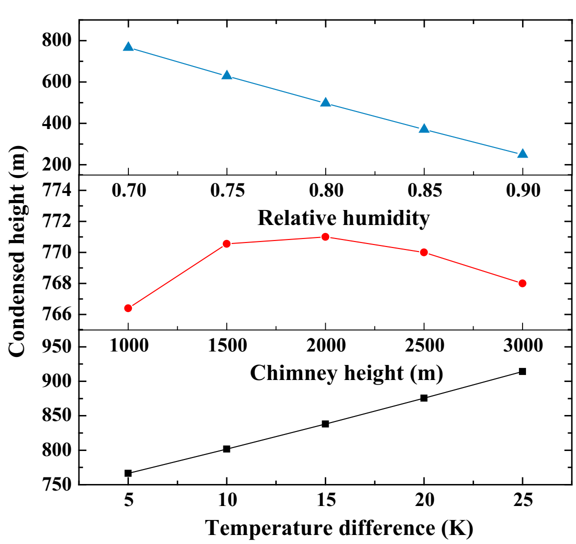

Fig. 6. The effect of chimney inlet air temperature, chimney height and ambient air relative humidity on condensed height.

ranging from 5 K to 25 K, the condensation level increases and the values are 766.4 m, 801.6 m, 838 m, 875.4 m, and 914.1 m for the five temperatures, respectively. Higher temperature means it would take longer distance to arrive at the height where the condensation occurs. From Fig. 6, we can see that the condensation level decreases with increasing ambient air relative humidity. It is apparent that the ambient air relative humidity is the most significant factor on the condensation level. The chimney height is a comparatively insignificant factor as it varies less than several meters. Known from the above, it is safe to draw the conclusion that the operating conditions includes ambient air relative humidity and chimney inlet air temperature have significant influences on the condensation level, while the effect of the geometric parameters such as chimney height could be neglected.

4.3. Comparison on condensed water

Fig. 7 illustrates how the chimney inlet air temperature, chimney height, and ambient air relative humidity affect the amount of condensed water. The condensed water continuously decreases with the pressure drop factor. As mentioned before, as wind turbine pressure drop factor increases, the inlet air velocity and the inlet air mass flow rate decrease, which means that there is less moist air condensed into water when the air flow climbs to the lifting condensation level. Beside, when the given turbine pressure drop factor increases, more potential energy of air flow is converted into electricity. But this also means that the air mass flow rate will be reduced, so it causes the decline curve of the amount of condensed water. In this view, a comprehensive consideration between water production and power generation should be carried out. In addition, a significant increase in condensed water caused by the increase of chimney height raised the production of the mass flow rate of air flow. However, there is a slight change in the amount of condensed water caused by increasing inlet air temperature. That is to say, for water generation, chimney height is the most decisive factor among the three conditions and the higher the *RH*, the better. In consideration of certain economic conditions, as far as possible increasing the chimney height allows to produce more water. At the same time, the increase of air relative humidity also is in favor of generating more water, while increasing the chimney inlet air temperature is not an efficient way to produce more water. It is worth noting that there is a change in Fig. 7(a). As inlet air temperature increases, the amount of condensed water increases until the temperature difference raise to 15 K, and then it decreases with increasing inlet air temperature. It is found that this abnormal phenomenon occurs only when the chimney height and the ambient air relative humidity are comparatively lower, such as chimney height is 1000 m and the relative humidity is 0.70. A relatively higher inlet air temperature means it takes longer journey for the air temperature to decrease to the dew point where the condensation occurs, so does the relative humidity. When the chimney is not high enough, less water precipitation occurs. Further simulation results indicated that, as the chimney height and the air relative humidity are high enough, the condensed water monotonously increases with the increasing inlet air temperature.

As a conclusion, to increase the water production, a *RH* of 90% and a tower height of 3000 m are the optimum parameters. This is logical as the higher the *RH*, the faster will the vapor reach the height of water condensation (*RH* = 100); when the chimney is high enough, and the lower the air temperature at a certain altitude, thus more water condensation can occur.

4.4. Comparison on output power by wind turbine

The influences of different conditions on output power by wind turbine are demonstrated in Fig. 8. It could be seen that, the output

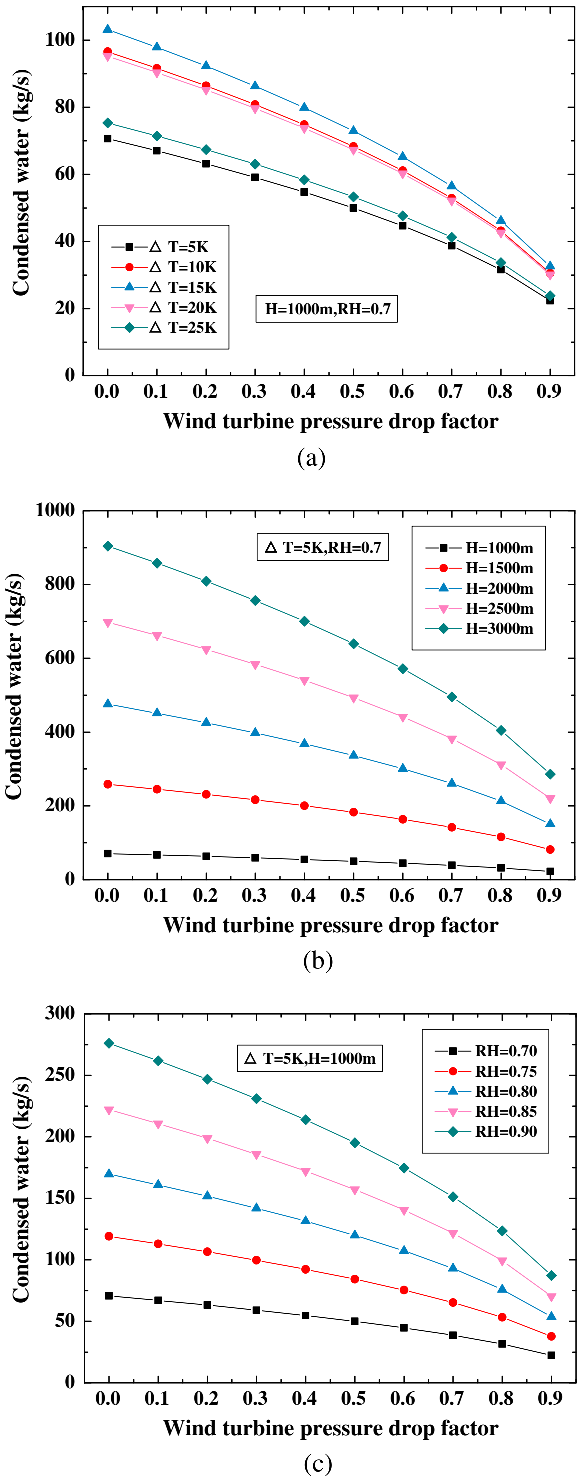

Fig. 7. The effect of chimney inlet air temperature, chimney height and ambient air relative humidity on chimney condensed water with varying turbine pressure drop.

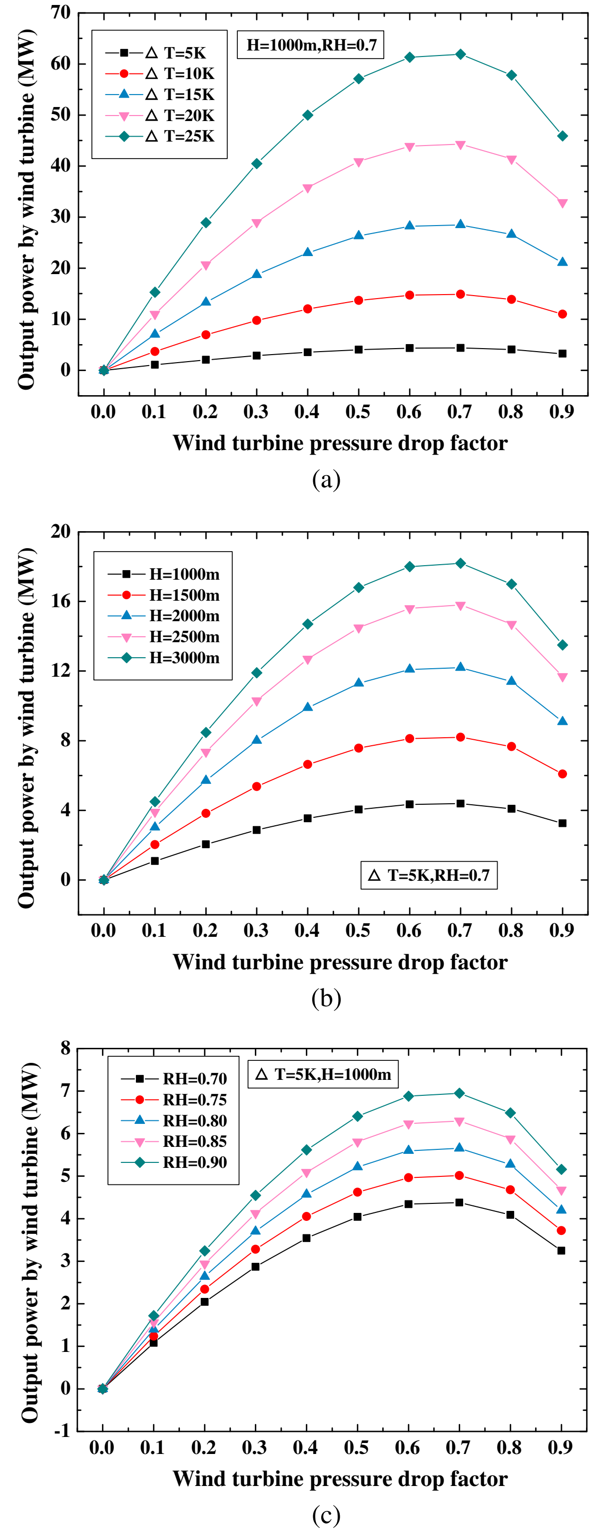

Fig. 8. The effect of chimney inlet air temperature, chimney height and ambient air relative humidity on output power by wind turbine with varying turbine pressure drop.

power raises first with the increasing turbine pressure drop factor until hits its peak value, where the pressure drop factor is set at about 0.7. Then a significant decrease in output power by the increase of the pressure drop factor due to reduced volume rate of air flow. It means that a higher turbine pressure drop would not increase the output power all the time. Refer to Eq. (17), there is a relationship of mutual restraint between the air volume flow rate and the airflow pressure drop factor: in order to obtain higher output power, the optimum point should be analyzed. We can see from these three graphs that it is easy to determine this critical point for output power. Therefore, to achieve the peak output power by wind turbine, we may set the pressure drop factor to be about 0.7.

Moreover, there are some differences on the influence of output power from these three graphs. As we can see, with the increase of the airflow temperature at the entrance of the chimney, the slope becomes steeper. That means that increasing the hot air inlet temperature difference could effectively increase the output power by the wind turbine. The influence of the inlet air temperature on output power by wind turbine is relatively large, but it is little affected by changing the air relative humidity. It is similar to the influence on inlet air velocity due to a direct relation between the air velocity and the wind turbine output power. Increasing the chimney height is also an effective method to improve output power. However, in comparison with increasing the inlet air temperature, it is not a good idea due to its sensitivity on output power. To conclude, it would be best to increase the air flow inlet temperature to improve the output power. The wind turbine and the pressure drop factor could be set at about 0.7. In Fig. 8, it can be seen that even a very tall chimney of 3000 m with a $\Delta T = 5$ K produces less power than a SCPP only 1000 m high with $\Delta T = 15$, 20 or 25 K.

4.5. Comparison on output power by hydraulic turbine

A hydraulic turbine is installed at the outlet of the condensed water channel as shown in Fig. 2. Remarkably, the more water precipitation from air condensation, the more output power achieved by hydraulic turbine. Fig. 9 shows the influence on various parameter conditions on the output power by hydraulic turbine. The output power continuously decreases with the increasing pressure drop factor. We can see that there is a positive relationship between the amount of condensed water and the hydraulic turbine output power. As the pressure drop increases, the reason for the falling curve can be attributed to the reduced air flow rate.

Within a certain pressure drop factor range, the wind turbine output power and the hydraulic turbine output power interact with each other. Hence, a comprehensive consideration of the system total output power need to be carried out.

In addition, it is found that the hydraulic turbine output power value is comparatively small especially in Fig. 9(a) and (c). As mentioned above, increasing the inlet air temperature is not always favorable to the condensed water especially when the chimney height is not too high, so does the hydraulic turbine output power. With a higher *RH*, the hydraulic turbine output power improved to a certain extent. So the chimney height is the most important factor on the hydraulic turbine output power. This is because the decisive factor in the hydraulic turbine output power is the potential energy of the condensed water. The height of the chimney determines the size of the potential energy or the driving force. The higher the altitude, the greater the potential energy is. More converted output power can be obtained. Therefore, when the chimney is not too high, such as 1000 m and 1500 m, the hydraulic turbine output power is much smaller than the wind turbine output power. In contrast, when the chimney is very high, the hydraulic turbine output power is considerable, we may make use of it as much as possible.

4.6. Comparison on system total output power

Fig. 10 indicates the influences of chimney inlet air temperature, chimney height, and ambient air relative humidity on the total output power of the SCPP, in which the wind turbine pressure drop factor is preset from 0 to 0.9. Known from this figure, if the pressure drop factor is constant, the system total output power increases with the inlet air temperature, chimney height, and ambient air relative humidity, though the degrees of increases are different. Like the impacts of those parameters on chimney inlet air velocity, they can lead to changes in the inlet volume flow rate of airflow. Moreover, we can see that there is a significant increase in changing chimney inlet air temperature. Improving the inlet air temperature is the best way among the three means to improve the overall system power output. The influence of wind turbine pressure drop factor on system total output power is rather complicated and looks similar to the influence of pressure drop factor on wind turbine output power. When the wind turbine pres-

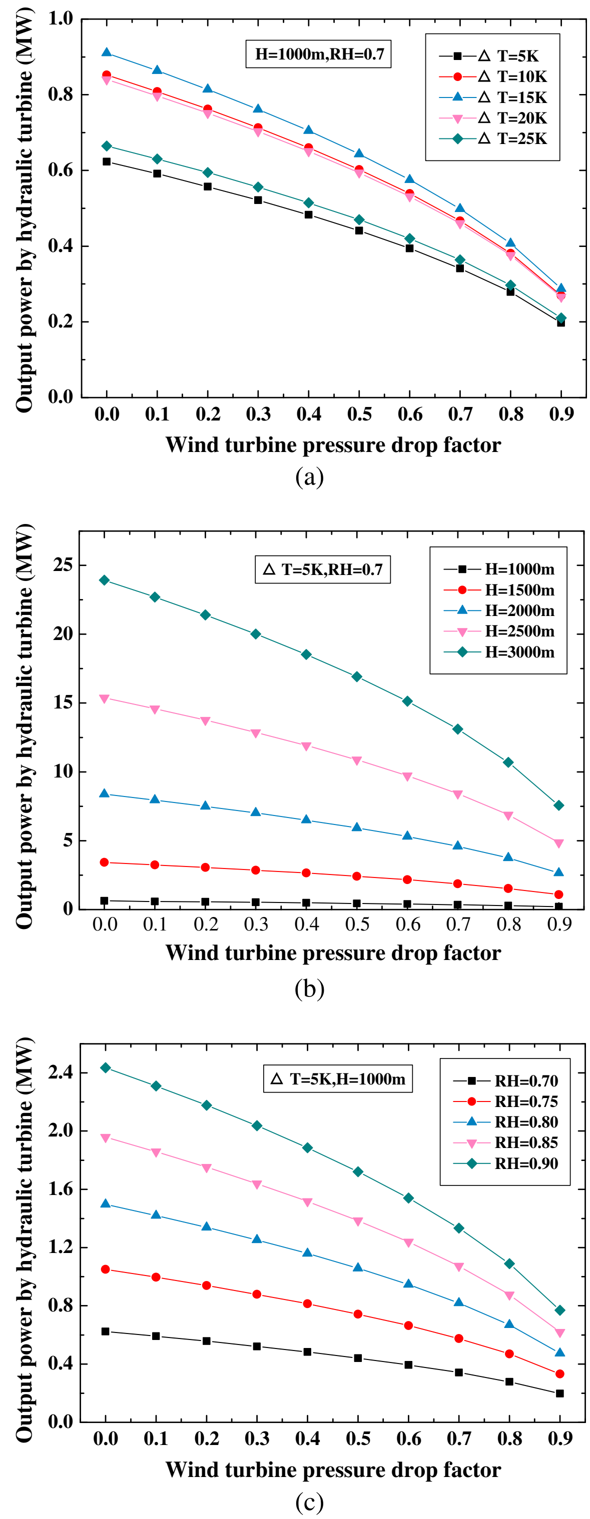

Fig. 9. The effect of chimney inlet air temperature, chimney height and ambient air relative humidity on output power by hydraulic turbine with varying turbine pressure drop.

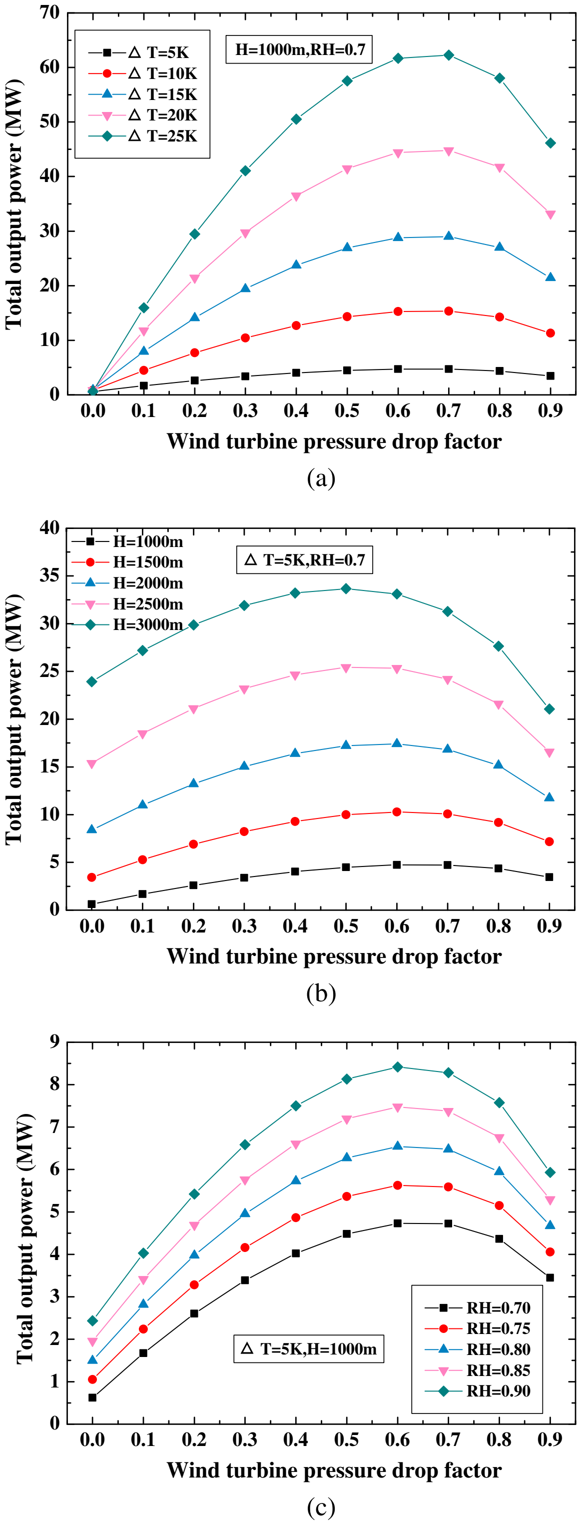

Fig. 10. The effect of chimney inlet air temperature, chimney height and ambient air relative humidity on system total output power with varying turbine pressure drop.

sure drop factor is small, the system total output power increases with the increase of pressure drop. The main reason is that the reduction of the inlet volume flow rate of airflow caused by the pressure drop factor is comparatively small; wind turbine pressure drop factor accounts for the main impact, making the output power present a rise trend. However, when the wind turbine pressure drop factor is very large, the inlet volume flow rate of airflow decreases more significantly up to act a dominant role in system, resulting in a reduction of the system total output power. Besides, there are some differences between peak values of the wind turbine output power and that of the system output power when taking into consideration the hydraulic turbine. We can see that these peaks also means the optimum wind turbine pressure drop factors for the system are moving to the left, this is because the reduction

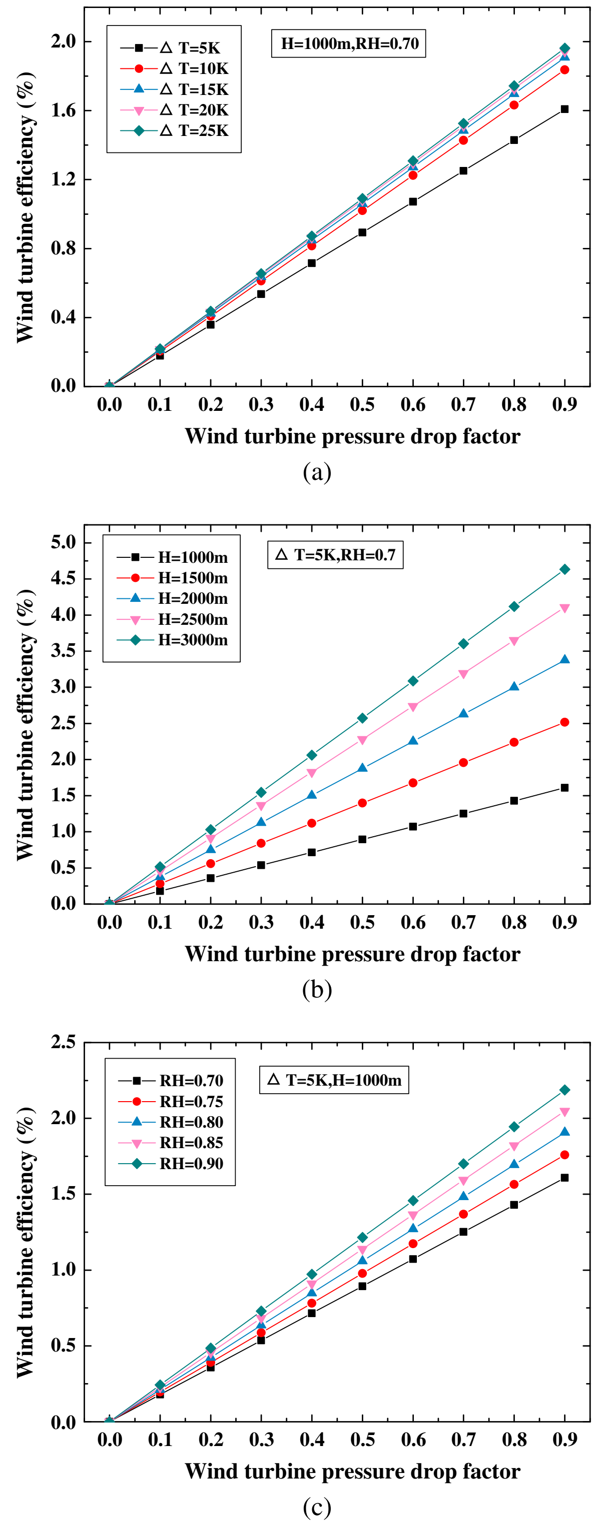

Fig. 11. The effect of chimney inlet air temperature, chimney height and ambient air relative humidity on wind power efficiency with varying turbine pressure drop.

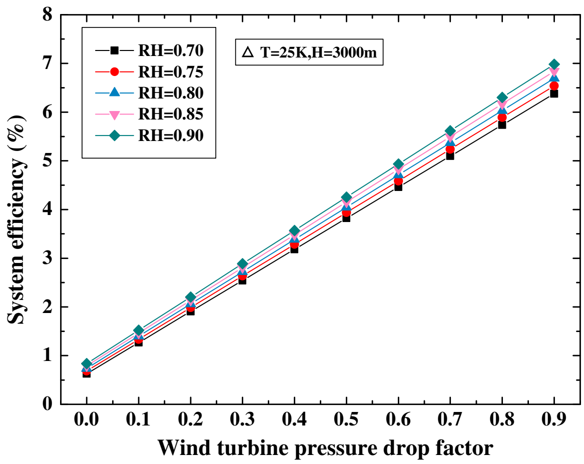

Fig. 12. The effect of ambient air relative humidity on system total efficiency.

of the hydraulic turbine output power with the increasing wind turbine pressure factor. On the other hand, it also suggests that the effect of the output power produced by the hydraulic turbine on the system total output power cannot be ignored. As shown in Fig. 10(b), when the chimney height is high enough, the impact is quite noticeable.

4.7. Comparison on SCPP efficiency

Fig. 11 describes how chimney inlet air temperature, chimney height, and ambient air relative humidity affect the wind power efficiency. The results indicate that the change of the above conditions bring about different degrees of change with the increase of wind turbine pressure drop factor. We can see that the wind power efficiency goes up with increasing pressure drop factor, that is, the energy conversion efficiency is getting higher. As shown in Fig. 11 (a), under the condition of the same turbine pressure drop, the higher the inlet air temperature, the higher the wind power efficiency. But when the temperature difference between the ambient and chimney inlet is very high, the increase is comparatively small. It indicates that improving chimney inlet air temperature is not always an efficient way to improve efficiency.

From Fig. 11(b), it is obvious that increasing chimney height is a quite efficient way to improve wind power efficiency, which achieves to an efficiency of 4.6%.

In Schlaich's design [33], he suggested that the chimney efficiency is fundamentally dependent on its height, but he ignored the change of parameters and phase change process when there is high humidity content. Besides, when the chimney is high enough, the hydraulic turbine output power is considerable, and that cannot be neglected, thus we can come to the conclusion that chimney height acts a decisive factor in SCPP efficiency. The influence of ambient air relative humidity on wind power efficiency is shown in Fig. 11(c). As we can see, the efficiency goes up with the increasing wind turbine pressure drop factor. Moreover, we also found that it is positively correlated with the relative humidity variation based on a given pressure drop factor. Ambient air relative humidity also acts an important role in efficiency which is not negligible.

As we discussed above, when the chimney is relatively high, the system output power includes the wind turbine output power and the hydraulic turbine output power are both considerable. In order to analyze the performance of this proposed device, e assumed a SCPP of 50 m radius with a height of 3000 m for the purpose of calculating the system total efficiency. The temperature rise of 25 K between ambient air and chimney inlet air is easy to achieve. As shown in Fig. 12, the system efficiency changes with the increasing wind turbine pressure drop factor in different ambient air relative humidity. With a relatively high ambient air relative humidity of 0.90, it is noticeable that the system total efficiency can go up to nearly 7%, meanwhile with only a $RH = 0.7$ the system total efficiency is already quite good with nearly of 6.2% which is normal for a tower 3000 m high.

5. Conclusion

As a solution to the shortage of energy and water in today's world, a solar chimney power plant has been proposed for sustainable energy and water generation. In this article, a mathematic model has been developed for a one-dimensional compressible flow and heat transfer. In order to study the overall performance of a SCPP variant, the system characteristic parameters such as chimney inlet air velocity, condensed water, output power and efficiency have been analyzed.

(1) The results indicate that increasing the chimney inlet air temperature is an efficient way to increase chimney inlet air velocity and wind turbine output power. The air properties such as air temperature and air relative humidity have significant influence on the condensation level;
(2) For water generation, chimney height is the most decisive factor, the mass flow rate of condensed water decreases with the increasing wind turbine pressure drop factor, thus a comprehensive consideration between water production and power generation should be carried out;
(3) To achieve the peak output power by wind turbine, we may set the pressure drop factor at about 0.7. There is a relationship of mutual restraint between the wind turbine output power and the hydraulic turbine output power. When the chimney is not high enough, the hydraulic turbine output power is much smaller than that of wind turbine. Increasing chimney height is also a quite efficient way to improve wind power efficiency which leads to an efficiency of 4.6% by calculation. Under favorable conditions, the system total efficiency can go up to nearly 7%.

Author contributions

T. Ming and T. Gong contributed equally to this work. T. Ming, T. Gong, and W. Liu raised the idea which was completed by R. de Richter and Y. Wu. T. Ming and T. Gong prepared the paper and the figures with contributions from all coauthors. Y. Wu and W. Liu also contributed to structuring the paper, bibliographical entries, and English corrections.

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