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Large-scale freshwater generation from the humid air using the modified solar chimney

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A B S T R A C T

Global Warming will probably modify air circulation patterns and increase the severity of droughts, heat waves, heavy precipitation, and floods across the world. A device called *'aerological accelerator' (AeAc)* is proposed in this paper to harvest water from the air using a very high tower where the warm and humid air enters from the bottom and rises till the top driven by buoyancy force. This *AeAc* device is similar in operation principle to a solar chimney power plant (SCPP) with additional features. A mathematical model was developed to calculate the potential energy and water that can be generated in various environments. The calculation results show that clouds are generated within and out of the chimney and the latent heat released by the vapor can noticeably increase the power output of the modified SCPP. With a proper water collecting method, the system can supply water and carbon-free renewable energy for residential and agricultural use. The present study opens the perspective that with minor improvements, significant energy and freshwater production might be possible using these tall engineering structures, whose high chimney can be built thanks to fabric balloons filled with gases lighter than air.

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1. Introduction

In the last decade, the serious extreme weather events, like Super Typhoon Hagupit (Ruby) over Philippine in 2014, occurred more than in any other period in human civilization history [1]. The destructions by hurricanes cost billions, like Sandy in New York (US $71.4 billion in 2012), or Katrina in New Orleans and the Gulf Coast (US $108 billion in 2005) [2]. The extreme weather is thought to be closely related to the GW effect. Due to hysteresis effects, the global temperature will continue to increase even if human beings stop discharging carbon dioxide immediately. IPCC scenarios predicted that GW would become more severe in the future, which would reduce crop yields and exacerbate food insecurity.

A device called *'aerological accelerator' (AeAc)* was proposed back in the 1970s by Starr and Anita [3] to gain water out of the air using a very high tower where warm and humid air entered from the bottom and rises till the top by buoyancy. This device operates similarly to solar chimney power plants (SCPP). In a recent paper, Ming et al. [4] suggested several devices cool the Earth by atmospheric convection enhancement and thus to fight global warming. Among these atmospheric convection devices, several variants of solar updraft chimneys were mentioned. Generally, a MW scaled SCPP consisted of three main components: a chimney with a height of hundreds of meters, a solar energy collector covering an area of several km^2, and a turbine installed on the bottom of the chimney. The air underneath the collector was heated by the solar irradiation and created a strong airflow in the chimney. Then the turbine was driven by the airflow to produce carbon-free renewable electricity [5–8]. Thermal inertia of the materials under the greenhouse (GH) allows sensible heat release during the night. Thus the system can produce electricity 24 h/day with no-intermittency [9]. A comprehensive review of SCPP system was given by Ref. [10]. Furthermore, the possible use of the device for other purposes, such as removal of

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polluted air and heat from the surface of a water basin, were discussed by Starr [11].

Although a 200 m high SCPP prototype was built and tested by Schlaich [12] in the 1980s, no industrial scale SCPP system was built since then. This was because the initial investment for a 200 MW commercially scaled SCPP was too high, in the order of $ 1.0 billion [13,14]. With this in mind, to achieve substantial construction cost reductions, Bonnelle [15] proposed other variants of SCPPs with no GH collectors, like the tropical energy tower [16,17]. Tropical energy towers, floating over warm oceans or seas where water surface temperature is quite hot (>25 °C) all year long, had great potential for electricity generation. The driving force of these tropical solar chimneys is the latent heat of water vapor. Thus these devices without collector are “updraft condensation latent heat towers”. To circumvent the drawbacks of relatively low sea surface temperature, the SCPP variants proposed in this article might take profit of low-grade waste heat from thermal power plants. The idea of using waste heat from thermal power plants to drive SCPPs has been proposed and studied by several authors like Chen [18].

Recently, we discovered that similar devices were proposed much earlier in the 1970s by Starr and Anati [3], not for producing energy but for collecting drinkable water and increasing the amount of rainfall in the local area [19]. Bonnelle's devices are very similar to the devices proposed back in the 1970s by Starr and Anati, named *'aerological accelerators'* (*AeAc*) by the authors. Starr's devices took advantage of the temperature gradients existing in the atmosphere for energy conversion. Given the proper condition, the thermal energy could be converted into kinetic energy because of the buoyancy effect. Furthermore, such vertical motion of air would cause condensation of water vapor by adiabatic cooling during air expansion associated with updraft in the chimney. Consequently, the process is self-sustained and requires no external energy. The proposed device harvested the energy of the low atmosphere due to the unstable temperature gradient in the vertical direction, similar to natural convective processes (Fig. 1). It was expected that the *AeAc* could produce considerable freshwater because the humidity was naturally high on the sea surface.

Similar to the natural moist convection process, *AeAc* device can be used to harvest water from the air using a tall tube without consumption of exterior energy other than the automatic release of latent heat of water vapor. The air density inside the tube is less than the air density outside. Thus an upward draft will be generated in the chimney. The ascending moist air within the tall tube is cooled down by the atmosphere through the chimney wall, like cumulus convection. But the guided convection within the tube differs from the outdoor natural convection because inside the tube there is no dilution or entrainment of ambient air with small moisture content and relatively low temperature. The amounts of water extraction calculated by Starr [3] were in the range of 2000 metric tons per hour during humid months. These quantities compared well with the amount of water production by modern desalinization plants, which construction costs are in the range of US $1billion [20]. In the previous studies, the researchers did not take into account the heat convection processes between the chimney wall and air flow. As some heat is lost, previous results might underestimate the water production rate and slightly overestimate the electricity generation capacity of the real system.

The *AeAc* is a variant of a solar chimney power plant (SCPP) which is different from high temperature solar thermal power generation systems [21,22] and solar thermoelectric system [23–26]. The characteristics of SCPP were widely studied in the past two decades [27–33] by many researchers from parametric optimization [34–36] to various applications [37–39]. Some recent research explored the possibility to use the solar chimney effect to produce water for residential use [40,41]. Pretorius [42], and Kröger and Blaine [43] demonstrated that the water vapor in the air could increase the power output of the SCPP under certain thermal conditions in the atmosphere due to the latent heat released during the condensation process in the chimney. If the water vapor enters the air before it goes through the system as a working fluid, the latent heat released by the condensed water will surely help to improve the system performance. However, if the water is evaporated under the GH canopy, the power output of the SCPP will be reduced because the average temperature of the air will decrease due to the heat absorbed by the phase change process. Agriculture under the GH canopy of a SCPP [44] will weaken the system's capacity to generate power. How the vapor condensation might affect the system and how to take advantage of the condensed water in the chimney are important issues in SCPP research. There was also some interesting research these years combining the solar chimney effect and water evaporation process to cool the systems [45].

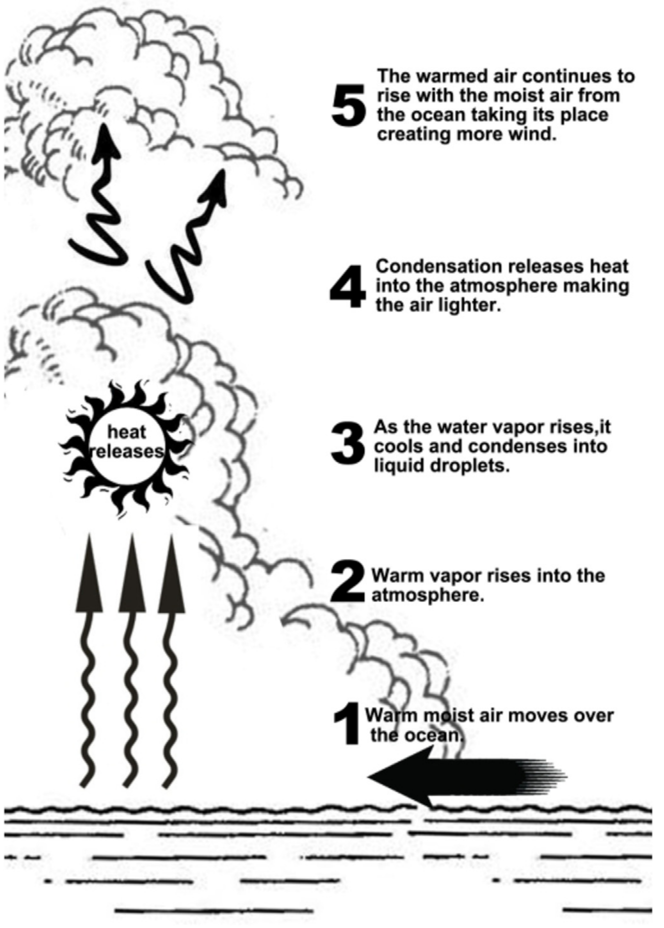

Fig. 1. The process of natural convection and water vapor condensation.

Zhou et al. [46] performed computer simulations on SCPPs located in the hot desert and found that rain might be generated. They explored the possibility to generate clouds and even precipitation around the SCPP using a 3D physical model. The results indicated that because of the plume jet into the colder surroundings, the relative humidity of the airflow coming out from the chimney increased significantly. This might change the microclimate around the SCPP, like precipitation, but with the risk of cloud shadows on the SCPP collector. In another work, Zhou et al. [47] developed a physical model to calculate the efficiency of the SCPP where the heat released by the vapor condensation was considered. They found that the vapor condensation helped to increase the power output of the system because of the latent heat released. It was the evaporation process under the canopy that led to a decrease in the power output of the system. Kashiwa and Kashiwa [48] calculated the water production in the SCPP, and they designed an expansion cyclone separator to remove the condensed vapor from the gas stream. However, their model can be improved as it employed Poisson's adiabatic equation to approximate the thermodynamic processes in the chimney, which didn't consider the gravitational potential energy. Ming et al. [49,50] studied the effectiveness of a modified SCPP which was able to extract freshwater from the air. In the novel engineering structure, the GH canopy was replaced by a collector made of black tubes which were used to warm the air and water. They analyzed it in comparison to natural precipitation at nine cities in China. Gong et al. [48] did a thermal and hydronic analysis of a novel SCPP design with an inverted U-type cooling chimney. They found that water injection can effectively strengthen the convection process and increase electricity generation. Ming et al. [48] developed a three-dimensional physical model to study the air cooling process associated with water evaporation and condensation in the chimney. It was found that the evaporation of the water droplets enhanced the relative humidity of the airflow in the chimney and the condensation level was significantly reduced. Recently, Ming [51] et al. established a three-dimensional CFD model to study the compressible flow characteristics and heat transfer process in the SCPP system. Their model described the air cooling phenomenon in the chimney and the associated condensation. Asayesh et al. [52] developed a physical model to analyze a solar chimney with a 250 m collector and 200 m height chimney for desalination and power generation. Zuo et al. [53] developed a numerical model to study the wind supercharged SCPP system combined with seawater desalination. It was found that the wind pressure ventilator significantly increased the power generation and the freshwater production by providing a negative pressure at the chimney outlet. Rahbar and Riasi [54] proposed two novel configurations of SCPP integrated with transparent PV cells and saline water desalination to improve utilization of solar energy and land resource. They claimed that the implementation of PV cells or water desalination could enhance solar energy utilization efficiency. Maia et al. [55] reviewed the main technologies used for solar desalination using SCPP. They thought that the hybrid solar chimney-desalination system had high potential but remained a research phase. More numerical and experimental research was necessary to make this technology competitive for water desalination.

Richter et al. [48] reviewed a unique hybrid device through the integration of the photo-catalysis with carbon-free electricity generation based on the SCPP technology. They claimed that solar chimney power plants integrated with TiO_2-photocatalysis could remove the greenhouse gases and generate electricity at the same time. Several other research work has been carried out to use the SCPP for seawater desalinization [56,57], but often significant amounts of energy are consumed for condensation of the water vapor, for instance by using cross-flow vertical tubes with large amounts of cold brine water passing through them [58], or by using a compressor-refrigeration system for cooling a condensation surface [59].

Papageorgiou [60] carried out a quantitative analysis to evaluate the influence of the latent heat released by the water vapor on the overall performance of the system. His research showed that a gram of vapor condensed per kilogram of air would lead to 2.25 K temperature rise of the airflow, which would significantly increase the power output of the system. In Bonnelle's Ph.D. dissertation [15], a mixing device was designed to ensure good thermal contact between the air and warm water. This device, equipped with sails, floated on the sea surface and was driven by the wind. A SCPP made of balloons was inspired by Papageorgiou's floating solar chimney [61]. VanReken and Nenes [62] also explored the cloud formation in the chimney. For an airflow with high relative humidity, clouds would form quickly in the chimney at a relatively low height. The authors concluded that clouds would slightly reduce the power output of the system. Several chimney shapes were studied, for instance, by Kashiwa and Kashiwa [48] and Ming et al. [63]. Implementing a convergent nozzle at the chimney top helped to improve the performance of the system. On one side, air velocity acceleration helps to increase the power output of the system. On the other hand, lower air temperature can be achieved because of the conversion between thermal and kinetic energy, making way for more vapor condensation.

As illustrated above, the *AeAc* appears to be a profitable venture to obtain freshwater and electricity. In light of new construction technologies and of increasing needs of drinkable water and droughts risks, in this paper, we built a new physical model to analyze the *AeAc* proposed by Starrl [64]. Different from other work, this model can accurately quantify the flow speed, condensation level, and water generation capacity for the *AeAc*.

2. Mathematical modeling

2.1. Construction of the AeAc system

The initial proposal by Starr and Anati [3] consisted of a tube of large diameter (100 m) to reduce frictions losses inside and reach the condensation point with variable initial moist content in the air. As a possible location, a mountain with a slope as straight as possible was proposed by Starr to reduce the construction problems, which were already envisioned in 1970. An experimental model would have to be anchored to a steep mountain slope. At its foot, there should be a water surface, possibly artificial, to provide moist intake air. A favorable location within the United States, where cliffs rise from a moisture-supplying body of water, locates on the northern coast of the island of Molokai in the Hawaiian Islands. At that location, there are places at which 1000 m elevation occurs within only a 600 m horizontal distance. The similar location also exists in other countries like in Oman on the Arabian Peninsula. Locations with no mountain or cliffs will also be considered as significant progress has been made in building very tall structures. For example, a skyscraper over 1.0 km high is under construction in Jeddah in Saudi Arabia, and structural engineers studied building chimneys 1.5 km high [65,66].

To reduce construction costs, several ways to decrease the size of *AeAcs* were considered. The height and diameter of the tube could be reduced considerably if:

1) The intake air is near humidity saturation when it enters the chimney inlet, which can be achieved by a specially designed apparatus.
2) The air inside the tube can be accelerated, like funneling the sea breeze.

The research carried out in the present article proposes both increasing RH at the entrance and increasing air temperature to intensify the stack effect. Such an “optimization” seems easy to be implemented.

A similar device has been proposed by Prueitt [67], but his patent was not fully considered by the research community until now. As shown in Fig. 2, the local air is sucked-in by a naturally induced airflow through a warm sea water shower, with the air flow moving upwards and the water flow dripping downwards. The heat and mass exchange between the air and water result in the humidification of the air and heating of air.

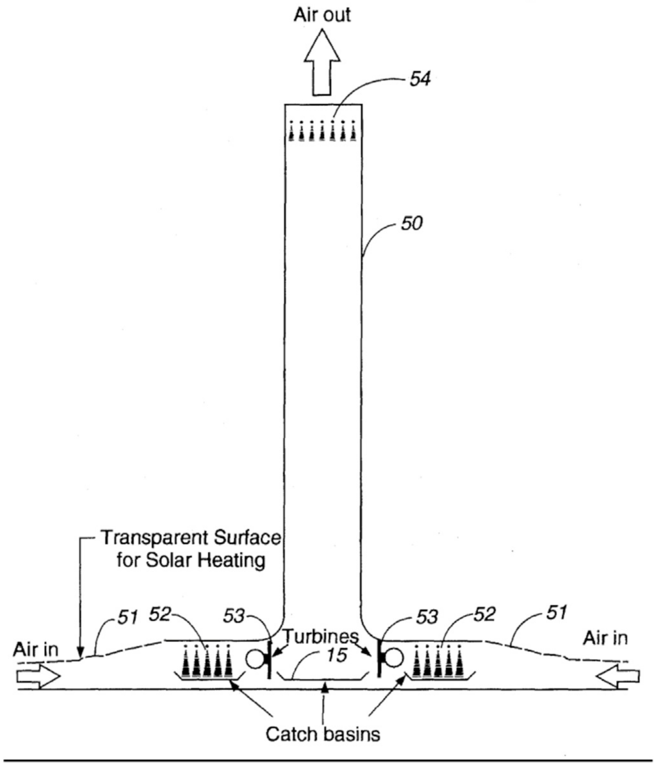

Fig. 2. Convection chimney proposed by Prueitt in his patent [67].

Prueitt [67] proposed a small GH collector to warm the air before humidification. If the hot sea water is much warmer, the air flow will be quickly warmed and humidified close to water vapor saturation. So, if installing a long black plastic tubing is less expensive than building a canopy, and the water pumps (from the sea to the shower) do not experience too much pressure drop by friction inside the long tube, the GH canopy can be replaced by the black tube. As shown in Fig. 3, which illustrates the device studied in this article, the seawater can be warmed in a black tube exposed to the sun in its way from the sea till the shower spray [49].

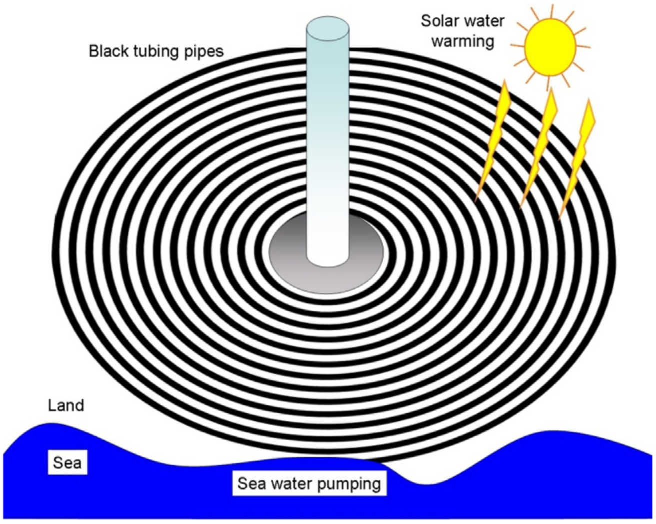

Fig. 3. Proposed AcAe in this article with no collector, only black tubing to warm the sea water, before the showers at the entrance.

2.2. Potential environmental impacts

Although mine shafts were built for a different function, the condensation water at upward convection does show that this method indeed has the potential to extract water from the air. We shall face now the reverse process: can a large number of *AeAcs* distributed over the globe have the damaging effect of reducing natural rainfall?

People had noticed the damages caused to natural water reservoirs by irrigation, an artificial process that started some thousands of years ago. However, for artificial optimization purposes, if the intake air is nearly saturated when it enters the tower, the *AeAc* does not anymore extract water from the ambient air, but from human-made saturated air.

This *AeAc* might also be used as a hurricane prevention tool, as suggested by Bonnelle [15] and Hagg [68] who proposed to build them as light floating structures. Hurricanes arise from warm water at the ocean's surface. Here, the *AeAc* creates a competing system which uses thermal energy of the hot surface water to produce electricity. The *AeAcs* might help to weaken and even eliminate the destructive power of hurricanes. So, states facing the “hurricane risk” could be interested in such a principle, taking into consideration the US $ billion destruction costs of hurricanes [69] sometimes exceeding more than US $50 billion. Thus the *AeAc* was worth being studied. However, its possible hurricane prevention use and possible locations are out of the scope of this article. The social impacts of this type of high structures that might disrupt the landscape aren't addressed here, as they will be the object of further work together with its economic and ecological impacts by helping agriculture, generating clean water and cheap electricity.

When looking into the ocean's surface average temperature distribution at the Red Sea in July, August, and September [70], the average sea surface temperature is always higher than 30 °C. Taking advantage of the energetic potential to generate power and freshwater (or clouds) by constructing *AeAcs* near the coast, these devices can cool down the local ocean surface temperature effectively, improving the local climate (cooler environment and more precipitation), alleviating the GW effects, and generating electricity and freshwater.

In the natural world, seawater is evaporated and adds moisture into the air constantly. A quick decrease of the air temperature leads to condensing vapor, forming of clouds and precipitation. Recently, Lo and Famiglietti [71] concluded that irrigation in California's Central Valley strengthened the Southwest U.S. water cycle. *AeAcs* might help to do the same by using sea water. Lo and Famiglietti [71] stated that irrigation in the Central Valley initiates a previously unknown, anthropogenic loop in the regional hydrological cycle, in which summer precipitation is increased by 15%, causing a corresponding 30% increase in Colorado River stream flow. According to the studies of Yeh [72], DeAngelis [73], Puma and Cook [74], the evapotranspiration led to two-level effects on the atmospheric circulation. The first-order effect results in a net land surface cooling and a local increase of atmospheric water evaporation, and the second-order effect results in higher precipitation rates locally or in neighbored regions. All these facts remind us that increasing the evapotranspiration rate of the ocean may help to increase the precipitation rate in the vicinity. More precipitation allows for more irrigation, a land cooling effect, and enhanced atmospheric water content. A favorable water circle may follow. But more studies should be done to analyze the possible consequences such as the concern that more precipitation in one region might induce a drier climate in a near region. However, the potential impacts of the local atmospheric circulation change on the global water cycle and climate change is still unclear.

The use of *AeAcs* over the warm ocean waters along the coast can help to sustain the rainfall and strengthening the regional water cycle. The SCPP plant proposed in this article can help to supply the moisture into the local air and even can form clouds directly. In such a different manner, using seawater, a SCPP can accelerate the water cycle without consuming the existing freshwater as described by Lo and Famiglietti [71]. Using underground water to irrigate the crops may help to add precipitation and increase the rivers' runoff. But that is not a sustainable way because it will deplete underground water and bring other problems, such as soil salinization and ground settlements [71,75,76]. The proposed SCPP, which can be seen as an automatic seawater desalination system, works more sustainably.

Environmentally speaking, the *AeAcs* might help to fight against GW as they might allow the earth environment to evacuate more solar energy, by cooling the surface and forming low altitude clouds. Clouds with high emissivity are an effective method to cool down the earth by reflecting sunlight. Also, by enhancing a heat evacuation mechanism (infrared radiation) from the atmosphere's lower layers and the sea's surface, to the high atmosphere and the outer space is another way to cool the earth [4].

2.3. Mathematical model

The performance of the *AeAc* heavily depends on the temperature of the inlet air, the chimney height, and ambient temperature [77,78]. In our model (Fig. 4), some assumptions are introduced to simplify the model:

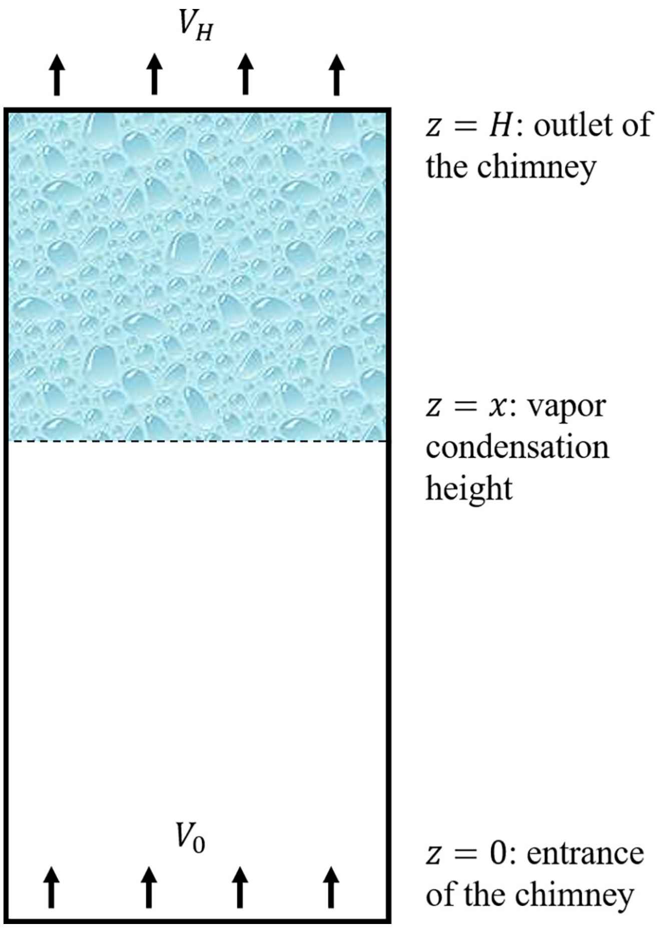

Fig. 4. The geometry of the chimney.

1) The pressure at the outlet of the chimney is the same as the atmosphere at the same altitude.
2) The radius of the chimney is large enough that the temperature and flow speed are assumed to be uniform at the same altitude.
3) The wall of the chimney provides ideal thermal isolation.
4) The atmosphere temperature, pressure, and density change with the altitude. And the standard atmosphere is employed for the calculation.

The air temperature, pressure, and density variation with the altitude in the atmosphere were given by Ref. [48]:

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

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

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

with

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

In Eqs. (1)–(4), $T_\infty(0)$, $p_\infty(0)$, and $\rho_\infty(0)$ are the air temperature, pressure, and density on the ground, respectively. z represents the altitude height, g represents the gravitational acceleration, and κ is the specific heat ratio, and R_g is the ideal gas constant.

The motive potential inside the chimney can be described as [79].

$$\Delta p = g\int_0^H (\rho_\infty(h) - \rho(h))dh \tag{5}$$

where h is chimney height, $\rho_\infty(h)$ and $\rho(h)$ are the air density in the atmosphere and the air density in the chimney at a specific height, respectively.

The energy conservation equation for per kilogram of moist air in the chimney is given by

$$C_p(T_0 - T_z) + \dot{m}L = gz + \frac{1}{2}(1 - \dot{m})V_z^2 + \frac{1}{2}\dot{m}V_l^2 - \frac{1}{2}V_0^2 \tag{6}$$

where C_p is the specific heat capacity of air, T_z and V_z are the air temperature and velocity at an altitude of z; V_l is the water droplet velocity which is slower than the air flow. V_z does not change much along with the chimney because the cross-sectional area of the chimney is constant for this design. $\dot{m}$ is very small when compared with the air flow rate. Eq. (6) can be rearranged as:

$$T_z = T_0 - \frac{(gh - \dot{m}L)}{C_p} \tag{7}$$

The well-known ideal gas state equation is expressed as

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

Since the temperature difference is less than 50 K for most of the cases in this study, the latent heat of water vapor condensation is assumed to be a constant ($L = 2,257,000$ J/kg). Because the vapor partial pressure only takes a small proportion of the total pressure, the variation of R_g is neglectable in this study.

The partial pressure of water vapor in the saturated moist air varies significantly with the temperature. The Arden Buck approximate equation [60] is commonly used to calculate the partial pressure of water vapor in the saturated moist air.

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

The RH is defined as the ratio between the partial pressure of water vapor in the air and that in the saturated moist air.

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

The water vapor content per kilogram dry air is given by

$$d_v = \frac{m_v}{m_a} = \frac{n_v}{n_a}\frac{M_v}{M_a} = 0.622\frac{n_v}{n_a} = 0.622\frac{p_v}{p_a} = 0.622\frac{p_v}{p - p_v} \tag{11}$$

The water vapor content per kilogram moist air can be calculated by

$$s = \frac{d_v}{1 + d_v} = \left[0.622\frac{p_v}{p - p_v}\right] \Big/ \left[1 + 0.622\frac{p_v}{p - p_v}\right] = \frac{0.622 p_v}{p - 0.378 p_v} \tag{12}$$

The air density in the chimney is assumed to linearly correlated with the altitude. Thus

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

The updraft force can be partly canceled by the pressure loss along with the chimney, such as wall friction and point losses. Taking these factors into consideration, the momentum conservation equation of the airflow along the chimney axis can be simplified as [48].

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

where n is the factor of pressure drop at the turbine, V_0 is the flow velocity at the inlet of the chimney, and C is the averaged atmospheric scale height. The three coefficients at the right end of the equation represent the entrance and exit losses, other point losses, and wall friction loss, respectively. In this paper, the wall roughness is assumed to be normal, so $f = 0.01$ is selected for the study.

The flow rate going through the chimney consists of two parts, including the dry airflow and the water vapor.

$$\dot{m}_{total} = \rho_0 V_0 A = \rho_H V_H A + \dot{m}_{total} \cdot d_s \tag{15}$$

where ρ_0, A, and $\dot{m}_{total}$ are the air density, cross-sectional area of the chimney, and total mass flow rate, respectively.

The mathematical model is solved by an iteration method presented in Fig. 5.

The model built in this paper is validated by comparing the modeling result with the experimental data documented for the SCPP prototype operated at Manzanares in Spain [80,81]. When $\Delta t = 10\,^{\circ}C$, with the turbine load factor set as 0.67, the updraft velocity predicted by the model was 6.84 m/s. In the literature [80,81], the average flow velocity was 6.5 m/s. The difference between the modeling result and the experimental result is less than 5.0%.

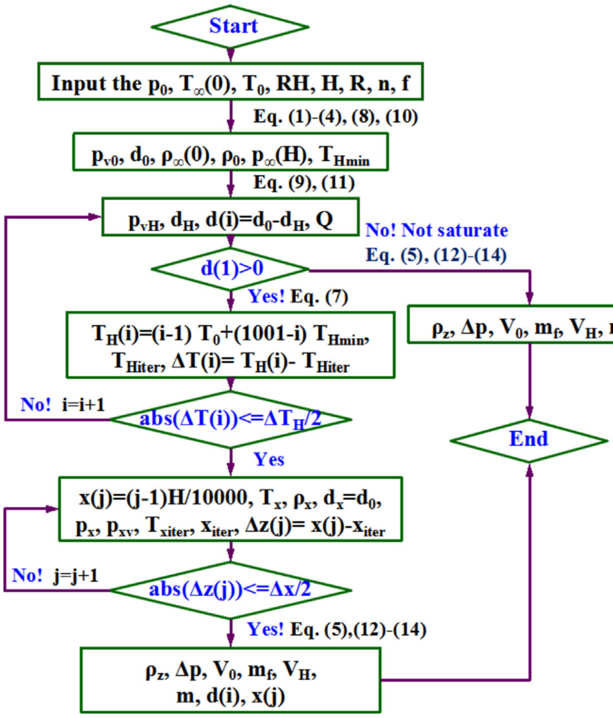

Fig. 5. The iteration algorithm to solve the mathematical model.

The *AeAc* advanced by Starr and Anati [3] is located near the seashore. And Bonnelle's devices are proposed to float over the ocean [15,68]. All of them are fed with air at ambient temperature and natural relative humidity. In this paper, the chimney building is located at the seaside on land. And the device configuration is similar to that shown in Fig. 3, where the air is heated to a temperature higher than ambient. To increase the relative humidity up to 95%, the sea water passes a black tube to warm it and then showers the air entering under the small GH and the chimney. The chimney is used to condense water 365 × 24 h continuously. The diameter of the chimney is 100 m (the same than Starr and Anati [3]). The model chimney height varies from 500 m till 3000 m.

3. Results and comparisons

The annual sea surface temperature (SST) in the coastal region of the Red Sea is about 30 °C in average, and an air relative humidity average of 75% with an average air temperature of 35 °C at sea level. The proposed AeAc system uses the black tube to pump the seawater to the showers at the entrance of the chimney. In this model, it is assumed that the pipe is sufficiently long to warm the water to a temperature significantly higher than ambient temperature. The pipes help to increase the average air temperature to 40, 45, and 50 °C, and a RH of with 95%. The water condensation rates for different inlet conditions and chimney height are summarized in Table 1.

For the first case, though the temperature difference is small ($\Delta T = 5$ K), the AcAe can still generate considerable freshwater from the air. This happens because the air temperature can sustain a temperature higher than the ambient air due to the water vapor condensation where the released latent heat prevents temperature from decreasing along with the chimney. Condensation in altitude inside the chimney helps to increase the driving force of the chimney. In the region of the Red Sea, the SST is above 25 °C all year-round. Obtaining an air temperature difference of more than 5 °C between the inner air and outside the chimney can be easily achieved. Thus, the given predicted annual water production is conservative. The system gains additional importance as the Red Sea region suffers from severe water shortage and hyperthermia all

Table 1
Water condensation rate for different inlet conditions in the Red Sea region.

Air temperature at chimney entrance at 95% RH (°C)	Water content at 95% RH (water content when saturated or 100% RH) in g/m^3	Dew point (°C)	Amount of drinkable water that can be collected when chimney height is 1 km (kg/s)	Amount of drinkable water that can be collected when chimney height is 1.5 km (kg/s)
35	37.7 (39.9)	34.1	96.44	193.25
40	48.5 (51)	39.0	133.31	260.59
45	61.4 (64.6)	43.9	160.44	314.70
50	76.6 (80.7)	48.9	182.05	359.02

year-round. With an additional electricity generation, floating SCPPs or plants built on artificial seawater reservoirs can be of economic competitiveness. For the other cases with the air temperature at chimney entrance being 40, 45, and 50 °C, the buoyancy force is even larger to generate a strong flow in the chimney. As shown in Table 1, the dew points are only slightly lower than the heated air temperature at the entrance. Condensation will occur quickly as the air ascends in the chimney.

The interactions of the chimney inlet velocity, the rate of water condensation, the height at which vapor condensation starts, the chimney inlet air temperature, and the *RH* are examined to gain more insight into the influence of vapor condensation on the performance of *AeAc*. In the following section, a typical operation environment is assumed as $T_\infty(0) = 20°\mathrm{C}, R = 50\ \mathrm{m}, f = 0.01, \varepsilon = 0.1$, and $n = 0$ for a normal sea area.

According to Fig. 6, when the heated air temperature is 25 °C, slightly larger than the environmental temperature, the flow velocity at the entrance increases with *RH* as the latent heat released by the vapor condensation strengthens the buoyancy effect inside the chimney. For a specific chimney height, V_0 is almost constant at small *RH*, because the airflow temperature in the chimney does not drop to the dew point. When other conditions being the same, the higher the chimney is, the larger is the chimney inlet velocity.

Considering a chimney with a height of 1000 m and *RH* = 0.95, the water condensation rate is predicted to be 340.7 kg/s even if the heated air temperature is only 5 K higher than the ambient environmental temperature. The typical urban water usage per capita is about 100 *l*/day in China and about 300 *l*/day in the U.S. It can be expected that the daily water production of a single chimney can reach 2.944×10^7 kg, which can meet the demand for more than 294,000 residents in China and 98,121 residents in the U.S., respectively.

As illustrated in Fig. 7, the chimney height and *RH* of the heated air at the entrance are very important factors for water condensation. For *RH* = 0.95 and a heated air temperature of 25 °C at the entrance, the water condensation rate is 108.3 kg/s for a chimney height of *H* = 500 m and 627.9 kg/s for *H* = 1500 m. The latter value is nearly six times the former. For a chimney height of 1500 m, the water condensation rate is 137.5 kg/s for *RH* = 0.60 and 703.5 kg/s for *RH* = 1.00. The latter value is more than five times the former. As expected, increasing the chimney height and RH will substantially increase water production in the chimney.

The height at which the vapor condensation starts is of great importance for the designer. If the ambient environmental temperature and *RH* are preset, a minimum chimney height should be guaranteed to take advantage of the latent heat from the vapor condensation. For *RH* = 1.00 at the entrance, the vapor condensation starts as soon as the air flow enters the chimney. As may be inferred from Fig. 8, the lower the *RH* is, the higher is the altitude at which the water condensation starts. For a chimney operating in the same ambient environment, the higher the heated air temperature at the inlet is, the higher is the altitude at which the vapor condensation starts although the differences are small.

As shown explicitly in Fig. 9, the flow velocity at the chimney entrance increases with RH. It is obvious that the latent heat can also enhance the power generation capacity of the plant. At a inlet temperature of 25 °*C*, the flow velocity increases from 14.9 m/s at RH = 0.60–20.0 m/s at RH = 1.0, representing a increase of 34.2%. The higher inlet velocity generate larger volume flow rate, which can significantly increase the water generation and power generation capacity of the AeAc. It is also observed that the flow speed increase dramaticly with the inlet temperature. When RH = 1.0, with the inlet temperature increasing from 25 °*C* to 45 °*C*, the flow velocity increases from 20.0 m/s to 41.8 m/s. Enhancing the temperature difference and RH can significant increase the power-

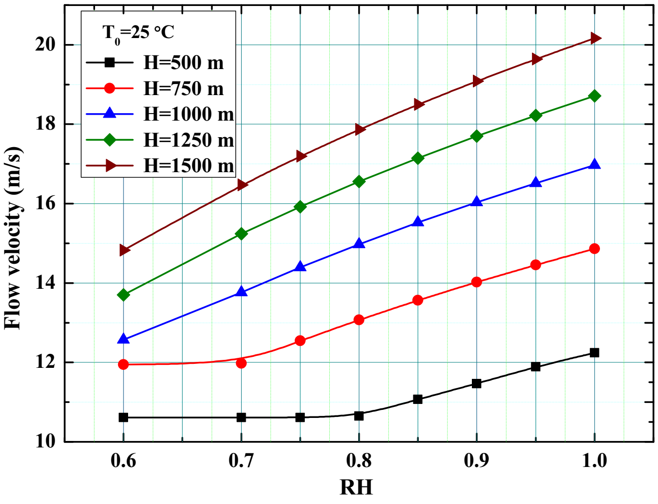

Fig. 6. Flow velocity at the entrance versus *RH*. The temperature at the air inlet T_0 is 25 °*C*, and the ambient temperature at sea level is 20 °*C*.

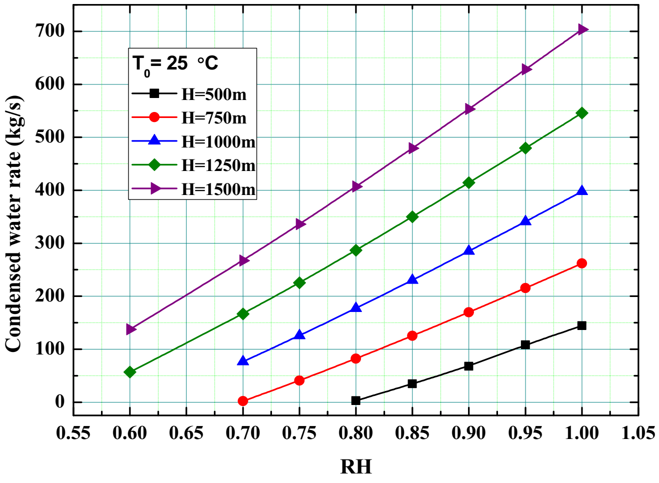

Fig. 7. Condensed water rate versus *RH*. The temperature at the air inlet T_0 is 25 °*C*, and the ambient temperature at sea level is 20 °*C*.

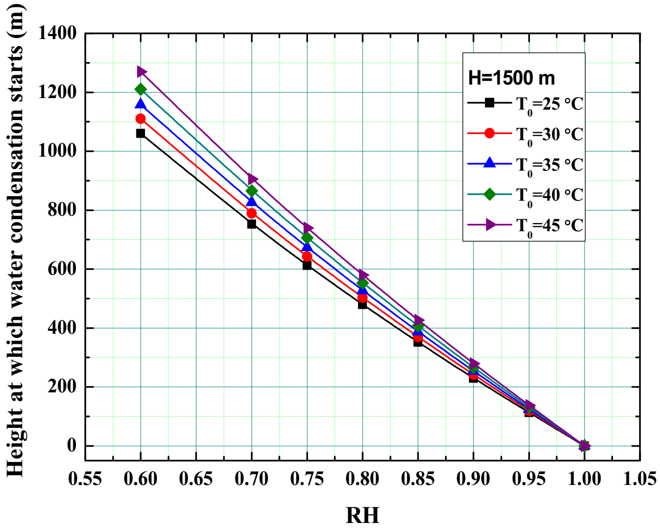

Fig. 8. Vapor condensation height versus RH with a chimney height of 1500 m.

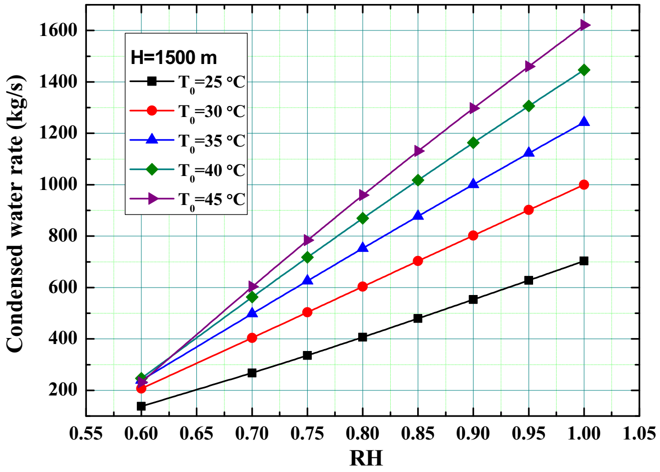

Fig. 10. Condensed water rate versus *RH* with a chimney height of 1500 m.

generation capacity of the AeAc system.

A nearly linear relationship between the water generation rate and the RH is shown in Fig. 10. The water generation rate increases with the temperature and the RH of the heated air at the entrance. With RH ranging from 0.60 to 1.0, the water generation rate increases from 225 kg/s at to 1625 kg/s. When RH = 1.0, the water generation rate increases from 715 kg/s at $T_0 = 25\ ^{\circ}C$ to 1625 kg/s at $T_0 = 45\ ^{\circ}C$. Enhancing the temperature difference and RH are critical to increase the water-generation capacity of the AeAc system.

The flow velocity and the rate of water condensation at the inlet increases with the chimney height, as illustrated in Figs. 11 and 12. For the case with RH = 0.90 and $T_0 = 45\ ^{\circ}C$, the flow velocity increases from 26.0 m/s with a chimney height of 500 m–45.6 m/s with a chimney height of 2000 m, representing an increase of 75.4%. For the case with $RH = 0.9$ and $T_0 = 45\ ^{\circ}C$, the rate of water condensation is 152.8 kg/s for a chimney height of 500 m and 2013.7 kg/s for a chimney height of 2000 m. The latter value is more than 13 times the former. Enhancing the height of the chimney is an efficient way to increase the water generation capacity of the plants, especially for the system with a relatively high inlet air temperature.

The chimney is a specific thermal engine. The efficiency of the system can be described by $\eta = \eta_{Carnot} \cdot \eta_{Reduced} = (T_0 - T_H)/T_0 \cdot \eta_{Reduced}$. The chimney height enlarges the temperature drop, making full use of the internal energy of the humid air. Another important concern for the system is the height where vapor condensation starts. As shown in Fig. 13, for the same *RH*, the height at which the dew point occurs increases with the inlet air temperature. This happens because the moisture content increments per kelvin (K) increases with temperature. For the cases with high air temperature, to reach the dew point, the temperature drop should be larger, which is reflected by a higher condensation position in the chimney. It is also observed that, for the same RH,

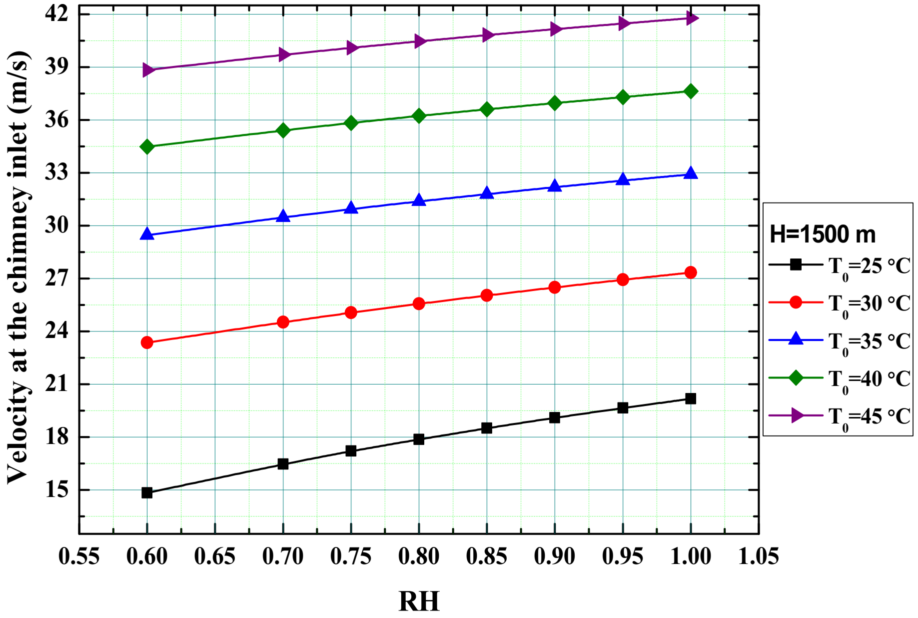

Fig. 9. Flow velocity at the entrance versus *RH* with a chimney height of 1500 m.

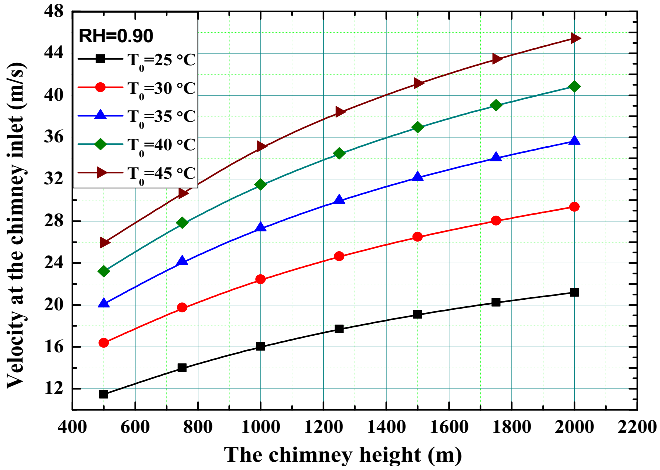

Fig. 11. Flow velocity at the chimney inlet versus chimney height with $RH = 0.90$.

the height at which the dew points occurs do not change noticeably with the chimney height. In the chimney, the thermal energy of the air was converted into the potential energy and kinetic energy. In this paper, the air density in the chimney is assumed to linearly correlated with the height. To achieve the same temperature drop in the chimney, the condensation height do not show significant variation with the chimney height for the same RH.

In arid regions apart from the ocean, as in a desert, for example, the air's *RH* is much lower. Here, vapor condensation starts at much larger height, which is a great challenge for the SCPP construction. The average *RHs* for the main cities in China are listed in Fig. 14. In certain seasons the *RHs* are higher than 0.70 for most of the cities, even at cities located in arid regions, such as Hohhot, Sining, and Urumchi. The economic development in Northeast China is significantly affected by the shortage of water and energy. It is possible here to improve the development conditions through the generation of freshwater and of electricity by building *AeAcs* not higher than 1500 m.

4. Conclusions

Taking advantage of the buoyancy effect and energy conversion process in the chimney, the modified SCPP system proposed in this article can generate renewable electricity and water at the same time. The electricity generation capacity of the system is largely determined by the heated air temperature at the entrance, and the system size, especially it's chimney height. The water generation capacity of the system, besides affected by the factors mentioned above, is greatly influenced by the *RH* at the chimney entrance.

Although the device proposed is for the moment more on the conceptual side than on the practical side, *AeAcs* brings at least three effects to the local environment. Firstly, the system captures more solar energy by taking profit of latent heat of condensation. Secondly, the chimney transports more energy into a higher altitude and enhances the Earth outgoing thermal radiation rate. Besides, some of the formed clouds reflect some part of the solar radiation to space. Thirdly, the larger vapor supply into the atmosphere may help to increase the precipitation in local regions. The irrigation helps to enhance the water content in the air as an additional effect. The mega-drought risk for the American Southwest under different levels of warming has been studied by Ault et al. [82], whose maps suggest that the risk can be reduced by 50% with 5–10% increase in precipitation to compensate for that warming. In effect, a favorable freshwater circle may be established in the local region and effects on larger areas, and global effects are possible, but are out of the scope of this article and will be taken in serious consideration if further work. It is generally believed that a warmer ocean can lead to more powerful typhoons and hurricanes as it was observed in the past decades. An additional benefit of the *AeAcs* might be to help weaken such hazards.

Realizing that ocean water is available and practically unlimited, the proposed *AeAcs* may bring a long-term solution for a sustainable supply of water and green energy for many regions.

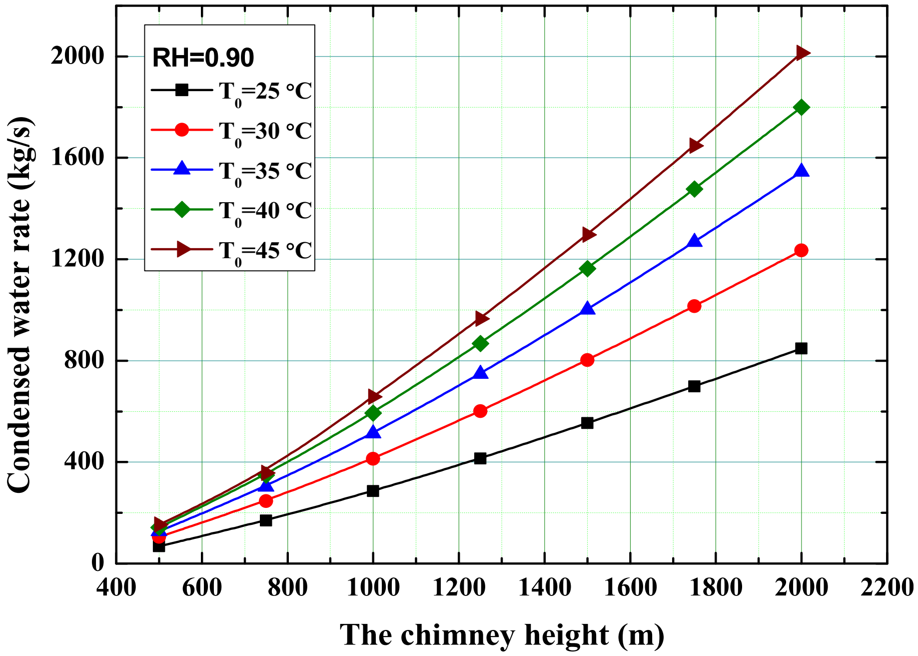

Fig. 12. Condensed water rate versus chimney height with $RH = 0.90$.

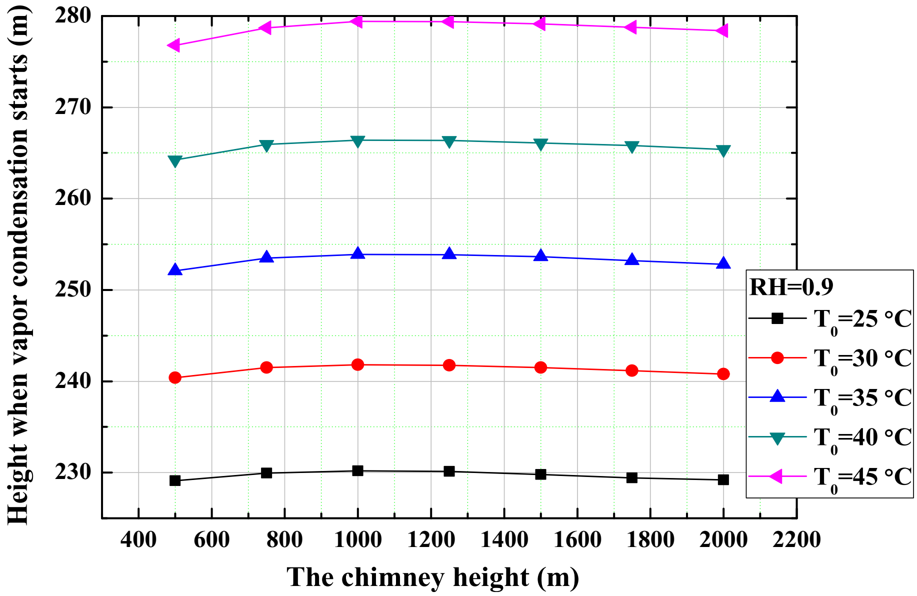

Fig. 13. Vapor condensation height versus chimney height with $RH = 0.90$.

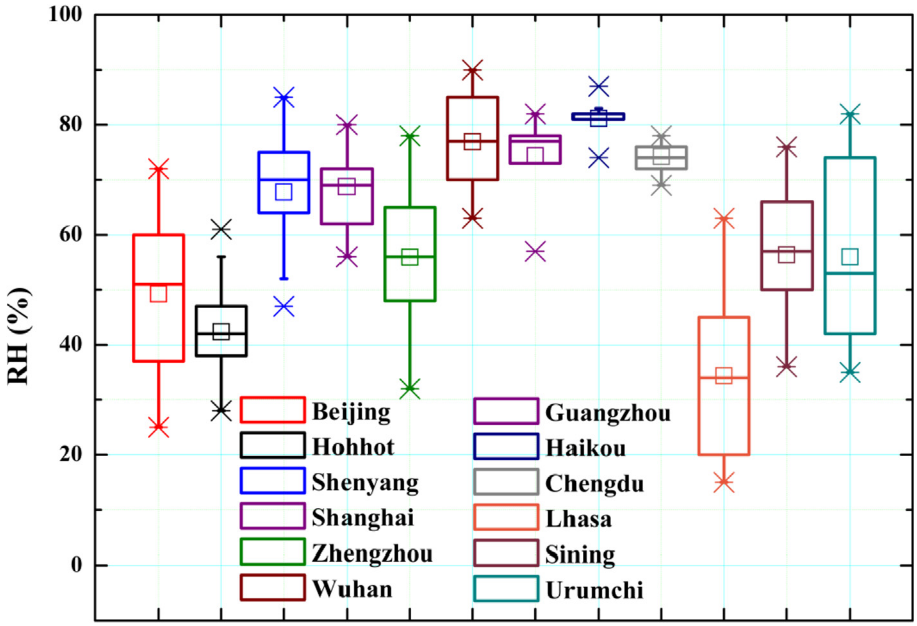

Fig. 14. Average *RHs* for the main cities in China (Box range: Perc (25,75); Symbol '—': Max/Min value; Symbol '×': Perc 99/1; Symbol '□': Average value).

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Symbols

A	chimney cross-section area (m^2)
C_p	specific heat capacity (J/(K•kg))
d	chimney diameter (m)
d_v	moisture content per kilogram dry air (kg/kg (dry air))
f	friction factor
g	gravitational acceleration, 9.8 (m/s^2)
H	chimney height (m)
L	latent heat (J/kg)
$\dot{m}$	condensed water per kilogram moist air (kg/kg)
$\dot{m}_{total}$	total mass flow rate of the moist air (kg/s)
M_v	molar mass of water vapor (kg/kmol)
M_a	molar of air (kg/kmol)
n_v	mole number of water vapor
n_a	mole number of air
p	Pressure of the moist air (Pa)
p_v	water vapor partial pressure (Pa)
p_s	saturated water vapor partial pressure (Pa)
p_z	pressure at some height (Pa)

s	moisture content per kilogram moist air (kg/kg (moist air))
t	Celsius temperature (°C)
T_0	heated air temperature at the chimney entrance (K)
T_z	temperature at some height (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)

Greek symbols

Δ	difference
κ	specific heat ratio
ρ	density (kg/m^3)
ρ_H	Air density at the exit of the chimney (kg/m^3)
ε	the entrance and exit losses factor

Subscripts

0	chimney inlet
H	chimney outlet
l	water liquid
s	saturated state
v	water vapor
z	at any given height z
∞	ambiance far away from the chimney inlet

Abbreviations

AeAc	aerological accelerator
GH	greenhouse
GW	global warming
RH	relative humidity
SCPP	solar chimney power plant
SST	sea surface temperature
CFD	computational fluid dynamics

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