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Mitigating air pollution strategies based on solar chimneys

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Abstract

During their rapid economic development and industrialization, megacities in the developing nations with high populations (especially in the east and south Asia) are plagued by severe air pollution problems (e.g., heavy haze), which impose a threat not only to public health but also to the sustainable development of society and the economy. To relieve the burden of air pollution for the general public, this article reviewed several geoengineering measures based on solar chimneys, which have the large-scale elimination ability on pollutants in the air, particularly for particulate matter. These geoengineering measures include driving the polluted air penetrate the planetary boundary layer into the troposphere to avoid the dramatic growth of concentrations of particulate matter, spraying water on the top of the solar chimney into the air to scavenge pollution, and intercepting fine particles in the air driven by the solar energy with large filters. Compared with traditional methods (e.g., giant spray trucks), those solar chimney geoengineering measures have the following advantages: 1) they can be operated 24 hours a day, thus keeping the pollution removal function stable and continuous; 2) they are environment-friendly and can generate clean electricity to compensate for energy consumption; 3) they are also robust and operational with very low maintenance for a long period. Given the advantages of the solar chimney geoengineering measures and the economic and human health losses caused by air pollution, those geoengineering approaches deserve to be studied further and implemented in those countries that are suffering from heavy air pollution problems.

Keywords: solar chimney; air pollution; haze; mitigation strategy

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List of abbreviations:
PBL, planetary boundary layer; PM, particulate matter.

Main finding:
Several geoengineering measures based on solar chimneys reviewed in this paper can eliminate air pollution on a large scale and generate clean electricity simultaneously.

1. Introduction

Air pollution problems caused by atmospheric aerosol are growing in megacities of many developing nations, especially for the rapidly expanding and industrializing countries with high populations (e.g., China and India). Atmospheric aerosol comprises solid or liquid particles (Hu, 2012), which can be divided by aerodynamic diameter into fine particulates (PM2.5), respirable particulates (PM10) and total suspended particulates (Hu, 2012; Liang, 2013; Pöschl, 2005), mainly from industry and transport activities, and a series of photochemical reactions (Liu et al., 2013). A high concentration of fine particles is the principal contributor to haze because the incident of sunlight is scattered and absorbed (EPA, 2020a). This is a weather phenomenon feature in reduced visibility (Wu et al., 2007), which has been observed in many countries in recent years (Gao and Ji, 2018; Jose et al., 2015; Lin et al., 2018; Sulong et al., 2017).

The aerosols particles in the air could alter the weather pattern. Since cloud droplets condense on tiny particles, more anthropogenic aerosols in the cloud could lead to smaller cloud droplets, more water will be retained for a longer time. As a result, precipitation would be suppressed and more solar radiation would be reflected back to space (Rosenfeld et al., 2019). The dramatic increases of aerosols in China are also believed to be the main cause of the recent southward migration of the summer monsoon rain belt resulting in the weather pattern of “South Flood-North Drought” in the summer (Li et al., 2018; Yu et al., 2016).

The particulate matter (PM) not only affects the environment but also imposes a threat to public health and sustainable development. Fine particles in the air can cause asthma, respiratory diseases, and even lead to death (EPA, 2020b). The adverse health effects as a result of short-term or long-term exposure to particulate matter in the air are high in many cities throughout the world (Burnett et al., 2014; Lu et al., 2016; Song et al., 2017). A special report by the Health Effects Institute showed that more than half of the global public health burden affected by the polluted air was from China and India (Institute, 2018). It was estimated that 4.2 million deaths were caused by exposure to PM2.5 in 2015, with 59% of them contributed from east and south Asia (Cohen et al., 2017). Exposure to ambient fine particles was ranked as the eighth leading risk for deaths globally (Kumar, 2018).

A comprehensive control strategy for air pollutants is urgently needed in densely populated cities in those developing countries, which face the difficult challenge of balancing economic growth and environmental protection. To restrict air pollutant emissions, intensive remedial measures have been made by the government, including the temporary shutdown or curtail operations at industrial plants emitting large quantities of air pollutants or the traffic restrictions imposed in major metropolitan areas in China (Li et al., 2017). Although annual average concentrations of PM2.5 in Chinese 74 key cities decreased by 33.3%, and PM10 by 27.8% between 2013 and 2017, both of the two indexes were still higher than the National Standard (35 $\mu g/m^3$, GB 3059-2012) (Huang et al., 2018a). It was also found that the concentration of PM reduced rapidly at first, but the reduction rate slowed down gradually, which meant that long-term air quality improvement methods were needed to tackle this issue (Greenbaum, 2018).

At the emission sources, traditional emission control devices for particles including cyclones, the electrostatic precipitators (ESP), the bag filters, and the wet scrubbers are designed for and used in specific systems in industry (e.g., coal-fired system). However, they may be effective against large particles but with unsatisfying performance against fine particles (Y.H.Pui et al., 2014). More importantly, they do not apply to the open atmosphere in public places of megacities. In China, specially designed trucks with a giant water sprayer (water cannon) are dispatched to public areas, patrolling and spraying water to the air surrounding the streets and buildings to relieve the adverse effects of PM, but which has the ability for improving air quality in a limited area.

To tackle the haze problems and improve urban environmental air quality, some ambitious and promising geoengineering measures have been proposed and some prototypes have been built in recent years. These measures include driving the polluted air penetrate the planetary boundary layer into the troposphere to avoid the dramatic growth of concentrations of particulate matter, spraying water on the top of the solar chimney (tower) into the air to scavenge air pollutants and intercepting fine particles in the air driven by the solar chimney with large filters (Tan et al., 2017; Yu, 2014; Zhou et al., 2015). Those geoengineering approaches newly proposed or constructed to treat aerosol were summarized in Table 1. Their scientific rationale, environmental impacts, and feasibility with some novel modifications based on the solar chimney were analyzed and compared in the following sections.

Table 1
Overview of Principal Air Pollution Removal Measures

Measures	Mechanism(s) proposed

High solar chimney	Utilizing the heat island effect to drive the polluted air up to the free troposphere (Zhou et al., 2015).
Spraying water on the top of high chimneys to wash out pollutants	Pumping water to the top of high chimneys, then spraying droplets into the atmosphere to wash out air pollutants (Lodhi, 1999; Yu, 2014; Yu, 2019).
	Scavenging the air pollutants in the spray scrubber (Cui et al., 2017).
Spraying condensed water vapor from the air to wash out pollutants	Driving the humidified air up into a high chimney to be saturated and condensed naturally (VanReken and Nenes, 2009) or with the help of a condenser (Ming et al., 2017) to create precipitation in the chimney.
	Utilizing the condensation latent heat to form self-sustained updraft air-cleaning chimneys (Bonnelle, 2004).
Air filter measures	Driving the air through a filter by the heat gained from the solar canopy (Cao et al., 2018a; Cao et al., 2018b; Cao et al., 2015; Cao et al., 2018c).
	Using an inverted U-type system to channel the filter-cleaned air back to ground level (Gong et al., 2017).

2. The potential use of solar chimneys to alleviate haze

2.1 The solar chimney power plants

The solar chimney power plant concept was initially proposed by Schlaich, and a 200 m high solar chimney power plant prototype was constructed and tested in Manzanares, Spain (Schlaich et al., 2005). The prototype is shown in Fig. 1. It is composed of a chimney mounted on a low circular transparent or translucent canopy open at the periphery. As the hot air under the canopy heated by solar radiation has a lower density than the air outside, it ascends in the chimney and generates a strong airflow to propel the turbines installed under the chimney and produce carbon-free renewable electricity.

Although the solar chimney was designed for power generation for the original plan, many variants for other purposes based on the solar chimney have been proposed in recent years. Using modified solar chimneys to generate freshwater from the humid air was proposed by Wu et al. (2020). Ming et al. (2016a) suggested several measures utilizing the solar chimney to enhance the atmospheric convection and thus to fight global warming. Maia et al. (2019) reviewed the major studies on using the solar chimney for desalination. Here, for the first time, the geoengineering measures for large-scale air pollution mitigation based on the solar chimney will be reviewed in this paper.

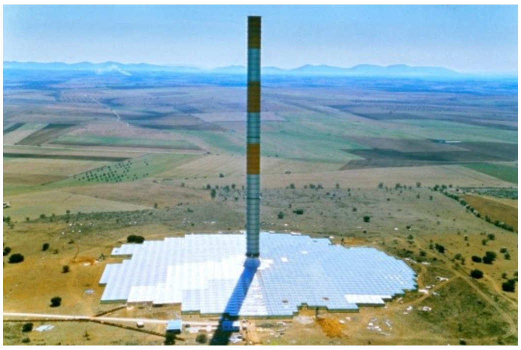


Fig. 1. Solar chimney prototype in Manzanares, Spain (Schlaich et al., 2005).

2.2 Proposal for the use of solar chimneys to alleviate haze

A solar chimney has been proposed to mitigate the dense haze by transferring the polluted air through the planetary boundary layer (PBL) into the high troposphere in Chinese megacities (Zhou et al., 2015). Since the PBL acts as a natural barrier to the vertical dispersion of pollutants, if the pollutants are lower than the upper edge of PBL, they spread by advection inside the PBL. While, when the pollutants travel through the boundary layer, they would extend to long distances over the troposphere (Đorđević and Šolević, 2008).

The proposed tall solar chimneys can use the urban heat island effect (the difference in air density of the warmer air in cities compared to surrounding areas) to drive air upward and transport the polluted air into the free troposphere. The urban heat island effect can be significant; the annual mean temperature difference in Beijing can be 7.78℃ (Zhou et al., 2015). Those solar chimneys are able to not only break through the PBL barrier (which was shown as stable stratification in Fig. 2) but also provide a large domain for haze mixture. The PM2.5 pollutants would ultimately be diluted and rendered harmless for human beings. The mechanism of this measure is illustrated in Fig. 2.

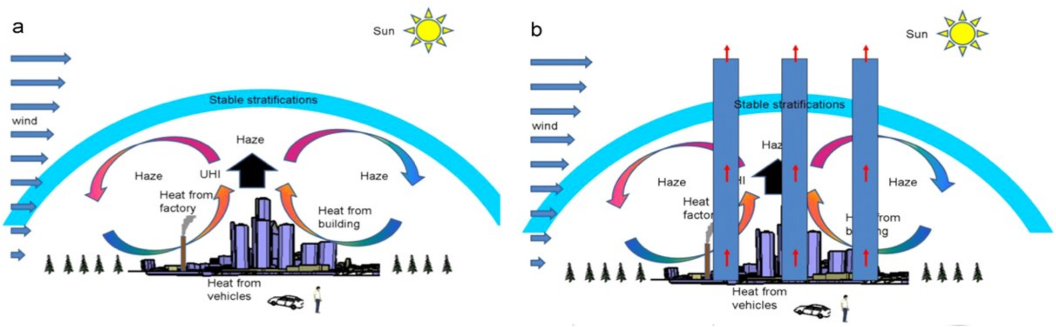


Fig. 2. (a) Haze recirculated under the PBL and (b) haze transported above the PBL by solar chimneys (Zhou et al., 2015).

Solar chimneys have several potential advantages and disadvantages. They have the potential advantage of not only removing the haze from urban residents' surroundings but also generating green energy using turbines mounted under the chimneys. Preliminary estimates also indicated that just nine solar chimneys would be enough to transfer the atmospheric air below 1 km over Beijing to a higher altitude in three months of operation (Zhou et al., 2015). Disadvantages include that air pollution is not removed but transported and dispersed into higher or other areas through atmospheric motion (Huang et al., 2020b), and the following potential negative effects are difficult to predict (Tan et al., 2017). To study the rationale of this large-scale and high-efficient air pollutant removal proposal, a comprehensive analysis is made in the following part.

2.3 Rationale for the use of solar chimneys to alleviate haze

Since the relationships among the solar chimneys, the haze and the PBL link directly to the mitigation effects of PM in the air, this part would discuss the relationships between the PBL and the PM first, and then give the rationale for the use of solar chimneys to alleviate haze.

2.3.1 The planetary boundary layer

The PBL is the lowest layer of the atmosphere, extending from the surface of the Earth to approximately 1000 m. The exchange rate of particulate matter (PM) between the air below and the free troposphere above the boundary layer is affected by the turbulent airflow in this layer (Brancher et al., 2017).

The internal structure of PBL varies significantly with the time of day. When the sun rises, a relatively higher convective mixed layer is generated due to the heat gain from the sun radiation, where the air pollutants spread and mix within it by turbulent airflow. When the sun falls, a relatively lower stable boundary layer is formed because of the decayed turbulent airflow, with the residual layer left in the upper part (Hu, 2015). See Fig. 3.

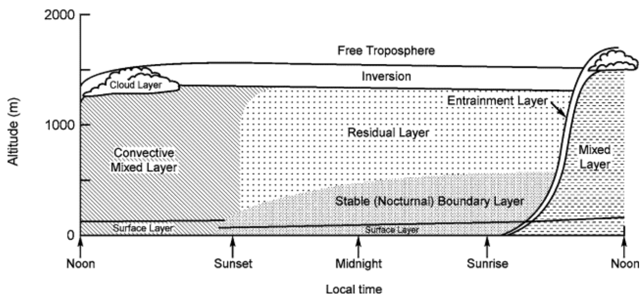


Fig. 3. Schematic of the daily mix process within PBL (Finlayson-Pitts and Pitts, 2000).

2.3.2 Relationship between the PBL and the haze

The relationship between the haze and the PBL is reciprocal, as heavy aerosols pollution could affect the height and structure of PBL (Liu et al., 2019; Miao et al., 2018; Quan et al., 2013; Zhong et al., 2019b). When haze occurs, the radiation is absorbed by aerosols or scattered away, which reduces incoming solar radiation on the Earth’s surface, leading to smaller surface heat gain and weaker turbulence (Li et al., 2020). In a case study, the radiative cooling effects of aerosols would cause a reduction of 89% surface direct radiation exposure accumulated in one day during a haze event (Zhong et al., 2018). This cooling effect would result in a contraction of PBL due to the weaker turbulence. On another side, the solar energy absorbed by the aerosols would heat the upper PBL, making a temperature inversion within the PBL (Ding et al., 2016;

Huang et al., 2018b; Zhong et al., 2018). This inversion would be adverse for the transportation of pollution from the lower surface layer (which is colder) to the higher atmosphere (which is warmer).

The lowered PBL caused by the aerosol radiation cooling effects compresses the aerosol and leads to an increase in aerosol concentration, making the haze more serious. This positive feedback loop can lead to a continuous increase in aerosol concentration (Quan et al., 2013). The way in which accumulated aerosol pollution would alter the height and structure of PBL due to the radiative cooling and this contracted and stable PBL would further promote aerosol accumulation was called "two-way feedback mechanism" (Liu et al., 2019; Zhong et al., 2019b).

It was also found this positive feedback would trigger the dramatic growth of fine particulate matter (a tenfold or more increase from tens $\mu g/m^3$ in 2-3h), leading to a persistent haze event. The dramatic growth of fine particulate matter was regarded as the first and most important stage in the four evolution stages of the severe haze episode (Sun et al., 2016a). The lower and stable planetary boundary layer was attributed to being the prime reason (approximately 84% of the contributory causes) for the dramatic growth of PM2.5 in the initial cumulative phase of a persistent haze event (Zhong et al., 2017). The threshold value for the dramatic growth of PM2.5 was proved and suggested as 100 $\mu g/m^3$, under which the dramatic growth of PM2.5 and the occurrence of a persistent haze event would be avoided (Zhong et al., 2019a). A similar PM threshold for a non-linearly quick improvement of air quality from the haze event (the contrary process to the haze formation) was also suggested (Ding et al., 2016).

The two-way feedback mechanism shows that the concentration of accumulated particle pollutants should be restricted within a certain level (threshold) by any methods (e.g., the solar chimney measure). When the concentration reaches the specific level (threshold), the height and structure of the boundary layer would be changed due to the radiative cooling, which would significantly worsen the pollution diffusion condition or even close the way for it (Zhong et al., 2019b), leading to the dramatic growth of particulate matter.

2.3.3 Natural chimney effects on pollution dispersion

The measure of solar chimneys to disperse air pollution takes advantage of the chimney effect that is also found in cities located near high mountains. This effect similarly does a certain amount of pollution dispersal naturally which is called the “mountain chimney effect” (Rong and Turco, 1996). The vertical transportation of ozone over the Los Angeles Basin was simulated and shown in Fig. 4a. Ozone measured above this Basin in 2009 (Fig. 4b) also showed ozone was transferred from the surface of the Earth to the troposphere due to the lift force of the San Gabriel Mountains (Langford et al., 2010).

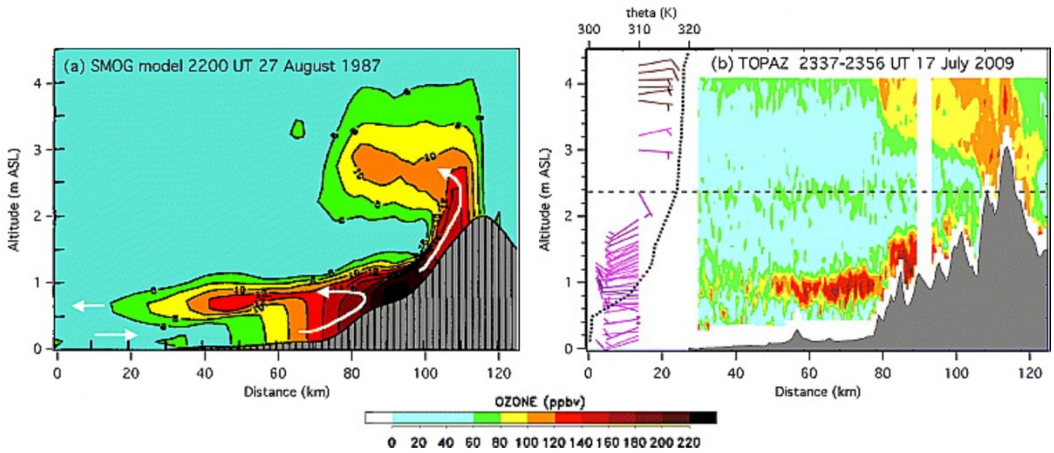


Fig. 4. Cross-section of ozone concentration (parts-per-billion-by-volume, ppbv) over the LA Basin, (a) in 1987, and (b) in 2009 (Langford et al., 2010).

The mountain chimney effect (also called the mountain-valley breeze) was observed using aircraft measurements (Chen et al., 2009). The authors observed a distinct two-pollution-layer structure in the region of Beijing, one near the ground within the PBL and another elevated layer above the free troposphere at an altitude of 2500 to 3500 m with identical in composition and similar concentrations. This mountain chimney effect could lead to a reduction of PM2.5 by 70-80 $\mu g/m^3$ and the achievement of "APEC Blue" (blue sky days during APEC summit in Beijing) (Sun et al., 2016b). It was also observed that the concentrations of PM started to build up immediately when the mountain chimney effect disappeared.

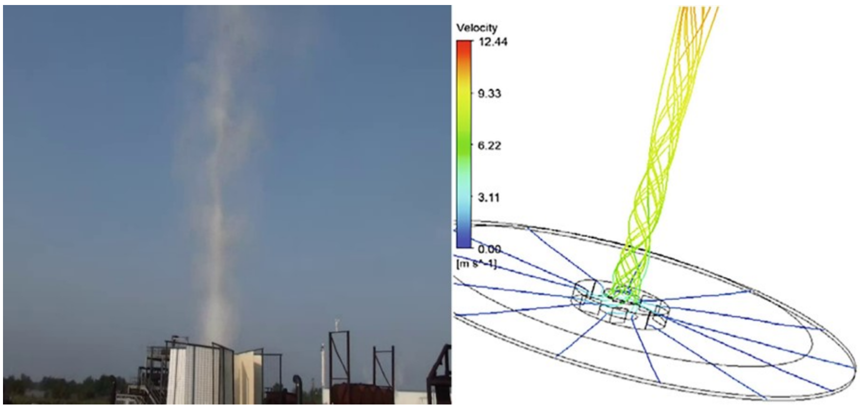
The evidence discussed above shows that the solar chimneys can be a feasible way to drive pollutants across the PBL and vertically transport them to the troposphere by taking advantage of the chimney effect in those megacities plagued by the haze events. Although the solar chimneys cannot physically eliminate pollution and can only transport air pollutants in the PBL into the free troposphere, it provides an opportunity to keep the concentration of pollutants within a controllable level, otherwise, the air quality would deteriorate because of the "two-way feedback mechanism". In particular, the solar chimneys can keep fine particles under the specific concentration threshold to avoid the dramatic growth of fine particulate matter that could facilitate the initiation of persistent haze events.

2.4 Evaluation of the high solar chimney measure

First, a high chimney is needed in this measure. The variations of height of the PBL above Wuhan were studied, which showed that the height of the PBL displayed clear seasonal variations (Zhu et al., 2018). In the daytime, the year-mean height of PBL varied around 1100 m (higher in summer and lower in winter), and the mean height during winter varied from 903 m to 1044m. In the nighttime, the year-mean height of PBL was never higher than 659 m. As the haze happened more frequently in the winter than summer (Zheng et al., 2019) and the airflow still had upward vertical velocity at the outlet of the chimney, a solar chimney of 1000 m would be sufficient in this location.

Second, the high cost of the chimney must be considered in this measure. Floating solar chimneys, which utilized the buoyancy forces of the balloon attached to the chimney to sustain the weight of the structure, have been proposed and studied to solve the problems of high-cost solar chimney structures (Papageorgiou, 2007; Papageorgiou, 2008). A floating solar chimney that is stiffened by attachment to a mountainside has also been proposed, able to extend several thousand meters up a high mountain (Zhou and Yang, 2009). Floating chimneys are less expensive than those made of reinforced concrete with a similar dimension compared using the full life-cycle cash flows analysis (Zhou et al., 2009b).

Third, the construction of the high chimney may be an engineering problem even though the floating chimneys are used. A concept of atmospheric vortex engine was proposed to generate a cyclone column by Louis Michaud to replace high chimney with the cyclone (http://vortexengine.ca, accessed on 12 October 2020). The air heated by the canopy (or other waste heat) travels through the swirl vanes set at the center of the canopy. The hot air rises from the canopy with rotation; thus, a cyclone is formed. The cyclone could suck the out air into the device due to the negative pressure produced by the centrifugal force and the density (temperature) difference. Because of the high tangential velocity of the cyclone, the heat exchange between the cyclone and the cold ambient air was isolated. The cyclone will continuously rise until the vortex is weak and the airflow temperature reaches the same as the surrounding air. A prototype was built by Michaud's team (see Fig. 5a) and simulated by Zuo et al. (2020) (see Fig. 5b). In this simulation, with 8 m high swirl vanes and a 112 m-radius collector, the cyclone can rise more than 200 m. This technology may meet the engineering challenge of the construction of a high chimney in the future.



(a) (b)

Fig. 5. The atmospheric vortex engine, (a) The prototype (http://vortexengine.ca), and (b) its simulation result (Zuo et al., 2020).

Fourth, when the urban heat island is formed, the air temperature in the urban area is larger than in the rural area. The temperature difference is compared between two places with a long distance between them. A chimney just erected in the downtown of the city will not induce the natural flow inside due to the small temperature difference between inside and outside. A high chimney with a canopy to gather heat energy from the sun is needed in this measure.

Fifth, to ultimately settle the problem of PM, a similar 1 km filter-contained solar chimney has been proposed to filter the air pollution driven by the urban heat island effect and to compensate for the replacement expense of filters by the generated electricity from the turbines (Tan et al., 2017). It was claimed that the achievable health benefits (lower premature mortality and reductions in hospital admissions for respiratory issues) gave this filter-contained solar chimney a positive return on investment.

Lastly, one may concern that a high wind speed under the canopy will influence the daily life of citizens nearby. The velocity of air in the solar chimney was illustrated by Fig. 6 in a case study under the weather conditions in Orkney, Scotland (Jafarifar et al., 2019). The total height of this system is 202 m, the canopy radius is 120 m, the canopy inlet height is 2 m, and the radius of the chimney is 5m. It was shown that the velocity of the air under the canopy is much lower than in the chimney because the radius of the canopy is several times larger than the radius of the chimney.

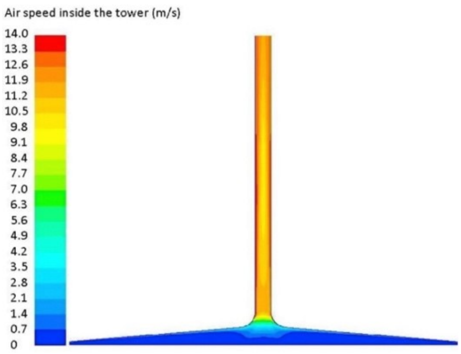


Fig. 6. The velocity of air inside the solar chimney (Jafarifar et al., 2019).

3. Elimination of air pollution by spraying water droplets in solar chimney

A solar chimney can transport air pollutants into the free troposphere and provide an opportunity to keep the concentration of pollutants within a controllable level, but it cannot physically eliminate the pollution.

Many researchers have studied the effect of eliminating pollutions by water droplets passing through the air. The geoengineering approach by the means of spraying water droplets on high chimneys to eliminate air pollution, which mimics the rain process, is reviewed in this section.

3.1 The mechanism of fine aerosol removal by water spraying

When a water droplet passes through the haze, the aerosol in the air would be scavenged by the droplet and gathered, thus cleansing the air. The scavenging mechanisms at work are direct inertial impaction, Brownian diffusion, diffusiophoresis (vapor concentration gradient), thermophoresis (temperature gradient), and deposition because of various electrical interactions (Cherrier et al., 2017; Wang et al., 2010).

Brownian diffusion and electrical interactions dominate the ultrafine aerosols scavenging process (radius r < 0.01 μm), while coarse-mode or larger aerosols with radius r > 1 μm are collected as a result of inertial impaction and interception (Chate et al., 2011; Seinfeld et al., 2006).

Fredericks and Saylor (2016) gave a refined model to predict the droplets scavenging via inertial impaction for a relatively large particle. The diffusional collection efficiency of submicron particles by a raindrop (Kang et al., 2015). For particles around the Greenfield gap (Greenfield, 1956), microphysical modeling was proposed to estimate the scavenging efficiency, where particles are significantly sensitive to inertia and Brownian motion (Cherrier et al., 2017). Wang et al. (2010) gave the contour lines of the total droplet-particle scavenging efficiency as a function of both droplet diameter and particle diameter. Based on this relationship, a two-stage spray system was devised to promote scavenging efficiency. An air-atomized nozzle was placed at the first stage for the sub-micron particle collection through diffusion by the generated droplets around 1 μm. Then, a full cone nozzle would jet water droplets around 20 μm to collect those droplets at the first stage by the interception and inertial impaction effect (Koo et al., 2010).

The aerosol scavenging effects of the rain droplets were also observed by many researchers (Lu et al., 2019; Roy et al., 2019; Yoo et al., 2014) when the rain droplets pass through the polluted air. It was claimed the rain can clean up 40% of the PM2.5 in the study area due to the scavenging effect (Lu et al., 2019). It was observed that the fine particles with a diameter between 0.2 and 0.4 μm were mainly scavenged by rain droplets with a diameter ranging from 0.3 to 1 mm, while the coarse particles (>1 μm) could be efficiently collected by all drop sizes, mostly from raindrops larger than 1.5 mm (Blanco-Alegre et al., 2018). A geoengineering approach by the means of spraying water into the polluted air on the top of high buildings on the scale of a whole city, which aimed to mimic the rainfall, was proposed to scavenge the aerosols in the air (Yu, 2014). It was also claimed that the enhanced ambient moisture through spraying would moderate ozone pollution at ground level by the prevention of ozone formation and the destruction of the ozone photochemical reaction chain (Yu, 2019).

3.2 Synergies of solar chimneys coupled with water spraying

The geoengineering approach by spraying water into the polluted air on the top of high buildings is creative and it can keep the air around the buildings with special duties (e.g., the hospitals) clean. But to remove the air pollutants on the city scale, a more efficient method should be proposed, since the polluted air needs to be drawn to the area that is spraying. This creative geoengineering approach could be improved by spraying water droplets within a solar chimney.

Spraying water on the top of the solar chimney to suppress air pollution in big cities was proposed and gave the advantages compared with the rain scavenging process (Lodhi, 1999). Those advantages include: 1) the spray nozzle could be selected for the particulate matter with specific diameters; 2) a continuous spraying system that can work for 24 hours a day; 3) a controllable rate of airflow driven by the air pressure difference.

Spraying water into the solar chimney involves not only the aerosol scavenging process but also heat and mass exchanges between the droplets and air during direct contact. If the sprayed water droplets are hotter than the air (e.g., in the cold winter), the heat is transferred from water to air. Cold air enters from the bottom of the solar chimney and becomes saturated and warmer as a result of the sensible and latent heat transferred from water. Both the temperature and humidity increase reduce the air density and produce the updraft airflow in the chimney (Akbarzadeh et al., 2009; He et al., 2016). If the sprayed water droplets are colder than the air (e.g., in summer), heat is transferred from the air to water droplets, which results in a decline in the air temperature. The decreased air temperature increases the air density and induces the natural downdraft flow in the chimney.

The concept of spraying hot brine in the solar chimney (see Fig. 7) was proposed by Akbarzadeh et al. (2009). The brine in a solar pond (60,000 m^2) heated by the solar radiation was sprayed in the chimney to warm the air and form the natural updraft flow in the chimney. Air velocity could reach 17.1m/s (which means $4.83\times 10^6 m^3/h$ air will be purified) in a 200m high chimney with a diameter of 10 m when the air was heated from 20℃ and 50% relative humidity to 60℃ and 100% relative humidity. During this process, the water loss due to evaporation was about 165.8 kg/s. For comparison, 441kg/s water will be lost in a typical cooling tower to reject condenser heat from a 500 MW power plant (Leffler et al., 2012).

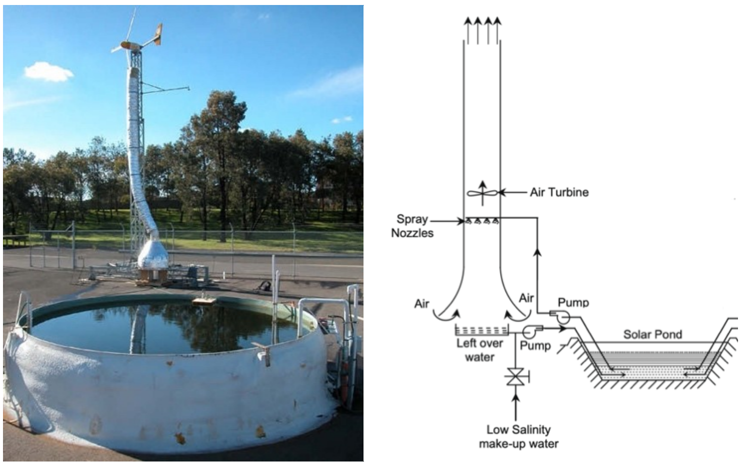


Fig. 7. The picture of a solar chimney combined with a solar pond and its schematic design (Akbarzadeh et al., 2009).

Spraying cooler water in the solar chimney to generate downdraft flow was called Energy Tower (Altmann et al., 2005). By cooling hot and dry air through the evaporation of water spray, the air velocity at the bottom of the 1200 m high tower with a diameter of 400 m could reach 17.8 m/s, while the sprayed water discharge was 14.2 m^3/s. For the purpose of treatment of air, such a high tower is not needed and the high speed of airflow may disturb the residents near around. Variations of the main parameters of air (density ρ, relative humidity ϕ, air velocity u, and the temperature of air T) in this 1200 m high tower against the distance from the top (x, m) are presented in Fig. 8 (Bauer and Gasser, 2012). From this figure, both the temperature and the relative humidity of the air will get the final value after it travels 400 m down from the top. So, the need for such a high tower should be discussed when it is converted to treat pollution in the air. When the relative humidity of ambient air ϕ is 50%, the final velocity of air is about 7 m/s. The final velocity is about 32 m/s when ϕ is 30%.

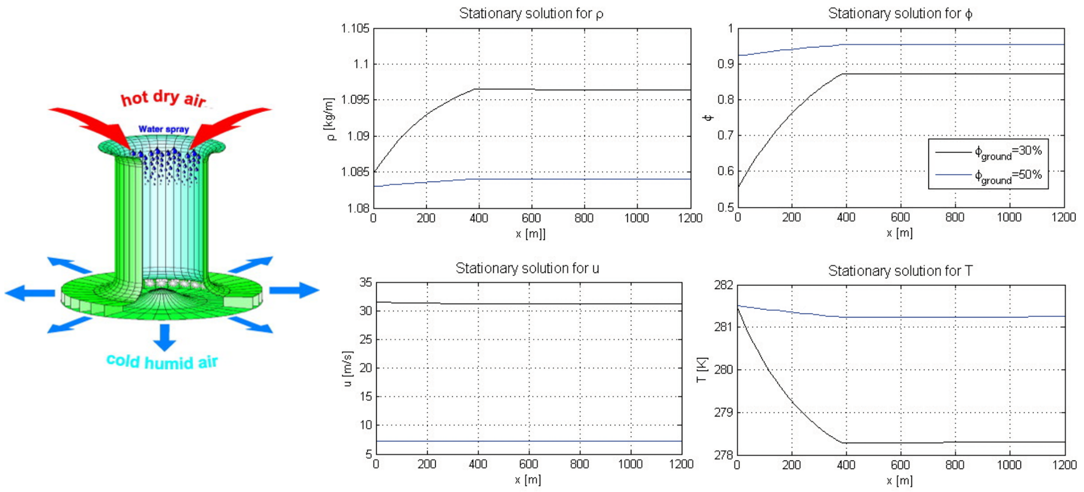
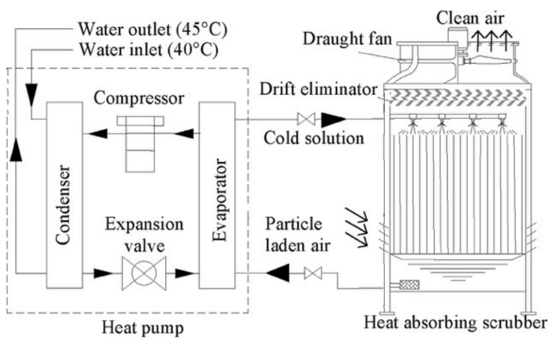
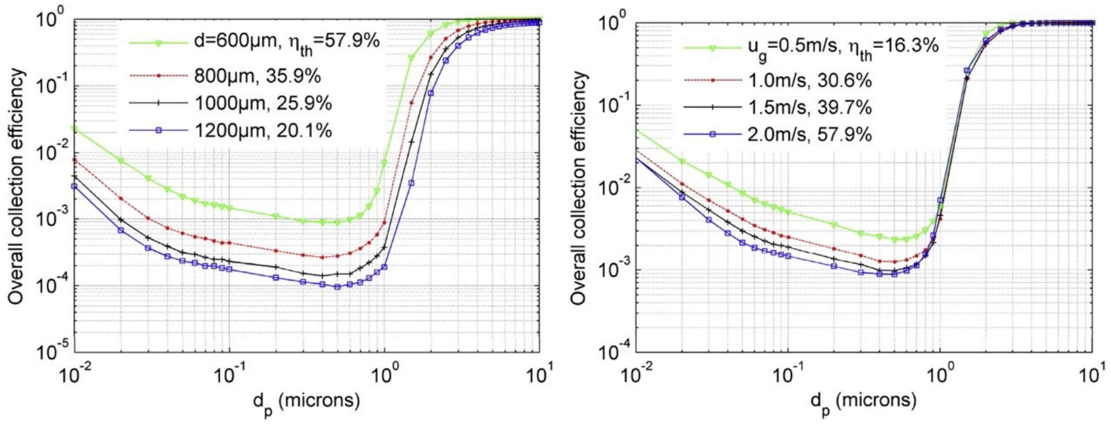


Fig. 8. Variations of the parameters of air in the tower against the distance from the top (x, m), the blue line is ϕ=50%, the black line is ϕ=30% (Bauer and Gasser, 2012)

A heat-absorbing scrubber was proposed to mitigate haze pollution and absorb heat from the air (Cui et al., 2017). The cold water from the evaporator is sprayed on top of the scrubber, absorbing heat from the warm air, then transfers the heat to the heat pump system to supply warm water in a building. During the direct contact between the water droplets and the air, the pollutants in the air are scavenged by the water droplets. The scavenging efficiency (which is defined as the ratio of the particle concentration reduced to the inlet particle concentration) depends on the diameter of the particle (d_p, microns), the diameter of water droplets (d, μm) and the relative velocity (u_g, m/s). See Fig. 9b and Fig. 9c. The η_{th} is heat transfer efficiency. Smaller water droplets and a lower relative velocity between droplets and air are preferred for the scavenge of particles, but a higher relative velocity will transfer the heat faster and suck in more air.



(a)



(b) (c)

Fig. 9. The heat-absorbing scrubber, (a) schematic diagram, (b) collection efficiency varies with droplets diameter, and (c) collection efficiency varies with air velocity (Cui et al., 2017).

The devices involving aerosol scavenging process or simultaneous water-air heat and mass transfer process are summarized and reviewed in Table 2. Although those devices do not have the large-scale scavenging ability as the solar chimney geoengineering approach, they provide the basic principles for the study on this method.

Table 2

Comparison between Some Similar Devices with the Solar Chimney Measure

Devices	Initial design objectives	Differences
Heat absorbing scrubber	To acquire heat from the air and scrub the air by water spray (Cui et al., 2017).	1. Limited distance for droplets and air direct contact due to the tower height. 2. Air is driven into the tower by the fan, not by the air pressure difference. 3. No power generation to offset the pump and fan consumption.
Natural draft wet cooling tower	To cool the cycling water of steam turbines in the power plant (Wei et al., 2020).	1. The scavenging effect of sprayed water was not considered. 2. Limited rain zone height for droplets-air contact to save pump energy (Zhao et al., 2016). 3. No power generation to offset pump consumption.
Spray passive downdraft evaporative cooling system	To clean and cool the captured air using water evaporation for space cooling in the building (Kang and Strand, 2018).	1. Limited distance for droplets and air direct contact due to the tower height. 2. No power generation to offset pump consumption. 3. The air volume is determined by both the air pressure difference and the wind catcher.
Energy tower	To produce energy by spraying salt water in the hot and dry climate (Omer et al., 2008b).	1. The scavenging effect of sprayed water was not considered. 2. Complete evaporation of the falling water droplets to maximize the energy generation from the tower (Omer et al., 2008a), while the complete evaporation must be avoided in a solar chimney as droplets are needed to carry the particles down to the ground.

To summarize, it is demonstrated that the water spray system can scavenge the pollution in the air, although the scavenging efficiency depends on the spray nozzle type, spray pattern, water mass flow rate, spray angle, and droplet size (Sun et al., 2017). One may concern that the pollution in the air will be transferred to the water and contaminate the water. However, this water collected after the spraying process is quite different from the industrial wastewater, which has the same property as the natural rainwater (the air pollution will also be gathered by the rainfall). The water collected after spraying can be treated as rainwater at a small cost (compared with industrial wastewater or domestic sewage).

4. Elimination of air pollution by condensed water within a solar chimney

Since the pollutants in the air were eliminated by spraying water in the chimney at the expense of water loss, this section introduces one variation of solar chimney sourcing the water to be sprayed from the air itself. Water droplets can be formed under certain conditions from vapor in the air and can be used to scavenge air pollutants.

4.1 The mechanism of fine aerosol removal by condensed water

As the air temperature declines with the increase in altitude, if the air ascends in the chimney and reaches its saturation point due to the temperature drop, water vapor begins to condense into cloud droplets, coalesce, grow, and become precipitation. This precipitation would have the scavenging function as the natural rain to eliminate pollution in the air. It was found that if the air humidity at the entrance of the chimney was maintained at 80%, the saturation point could be reached within the chimney of 500 m and 700 m, and the droplets from vapor were formed. At the top of the chimney (1000 m), some droplets had grown to 15 μm in diameter (D_p in Fig. 10, μm) (VanReken and Nenes, 2009). But if a higher chimney was provided, the diameter of the droplets would be increased to the 25-30 μm diameter threshold, beyond which a large scale of coalescence occurs, leading to the drizzle rapid formation process (light rainfall) (Sauvageot, 1995).

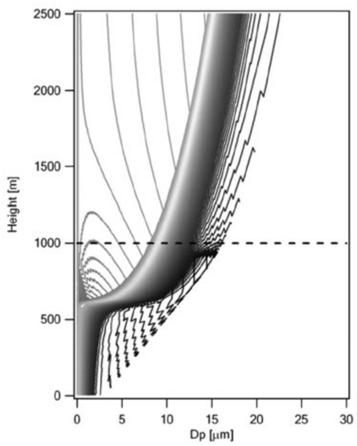
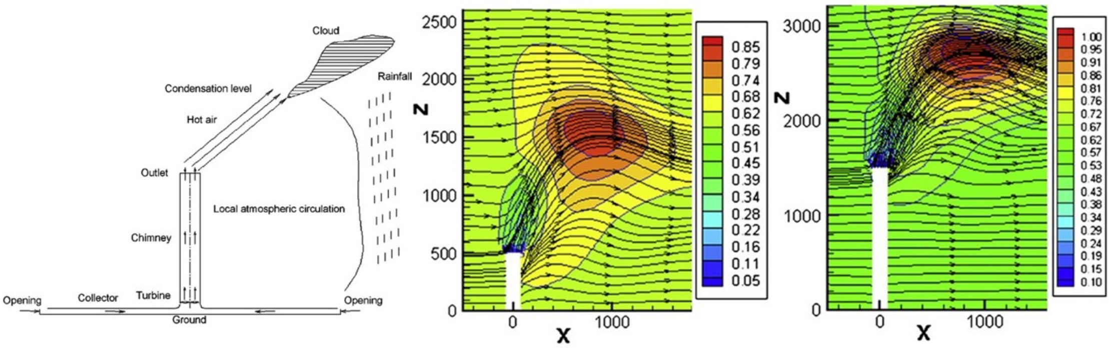


Fig. 10. Cloud droplet evolution in a chimney (cloud formation from ~600 m above and the top of the chimney is shown by a dashed line) (VanReken and Nenes, 2009).

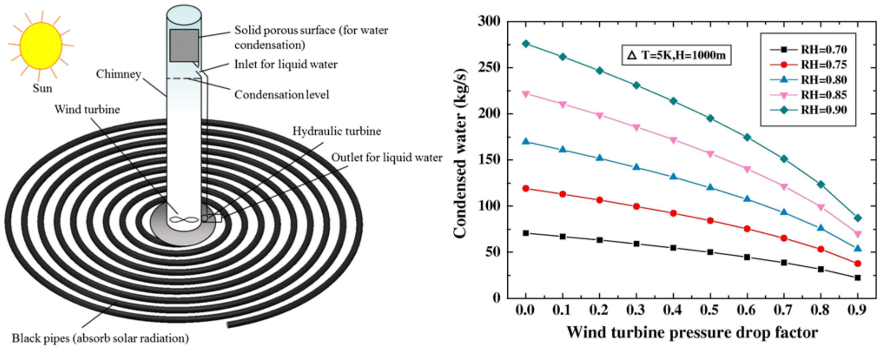
This theory of artificial rain was also analyzed by Zhou et al. (2008). Since the air at the outlet of the chimney is still warmer and lighter than the ambient air, this air will rise above the chimney until the temperature difference between the airflow and the surrounding air (or the relative velocity) becomes zero. During the rise, the temperature of airflow drops due to the adiabatic cooling, and its relative humidity increases, then rainfall may be formed after the 100% relative humidity is reached (see Fig. 11a). A numerical simulation of this artificial rainfall theory was made to validate this concept (see Fig. 11b) (Zhou et al., 2009a). The horizontal and vertical axis in this figure shows the horizontal distance from the chimney (m) and the altitude (m), respectively. The white column is the chimney and the color vertical bar on the right side indicates the variation of relative humidity. It was shown that a higher chimney had a larger chance to make the plume reach the saturation point. It was also claimed that this artificial climate can support agriculture in the arid region (e.g. the large parts of North and West China) and may rehabilitate the desert lands (Zhou et al., 2010). This rainfall will also support the purpose of air pollution elimination.



(a) (b)

Fig. 11. Artificial rainfall formed by the solar chimney, (a) schematic illustration (Zhou et al., 2008), and (b) the simulation results (Zhou et al., 2009a).

To collect the condensed water vapor at a lower height and more efficiently, a solid porous surface condenser mounted on the top of a chimney (above the saturation point level) was proposed (Ming et al., 2017) and shown in Fig. 12. The vapor in the air will condense and adhere to these solid porous surfaces and be collected underneath the solid porous surface by gravity. More than 100 kg/s condensed water could be collected in a 1000 m high chimney with 100 m in diameter when the relative humidity of ambient air is 0.70. At the same time, the mass flow rate of air driven into the chimney is 14 m/s. More water will be generated from the air with higher relative humidity, see Fig. 12b. This water collected by the condenser will not go to the hydraulic turbines and the wind turbine will not work when it is used for air treatment. The black pipes are for the storage of solar energy during the daytime.



(a) (b)

Fig. 12. A chimney with a condensation device, (a) schematic design, (b) the production rate of condensed water (Ming et al., 2017).

The seasonal and diurnal variation in vapor condensation performance were studied and analyzed under Wuhan's moist climate conditions in a 1500 m chimney (Xu et al., 2015). Fig. 13 shows the condensation height (saturation point level) and daily condensed water mass flow rate varied in this chimney over 24 h in Wuhan on a typical summer day (July 21). The condensation level in the chimney varied with the ambient air humidity, with condensation occurring from about 6:50 pm to 7:50 am and no condensation at other times due to the relatively low humidity. The lowest condensation height was about 644.07 m, while the maximum condensation water mass low rate could reach to 450 kg/s, which is comparable with the water loss of a cooling tower for the 500 MW power plant and much larger than the water needs for spray in the solar chimney proposed by Akbarzadeh (see section 3).

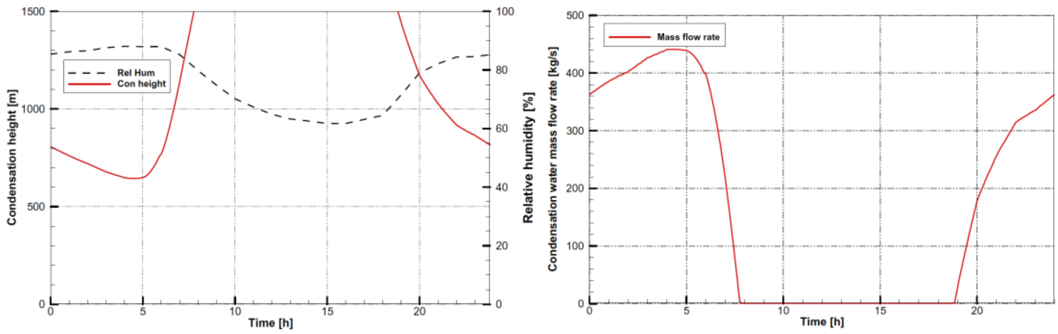
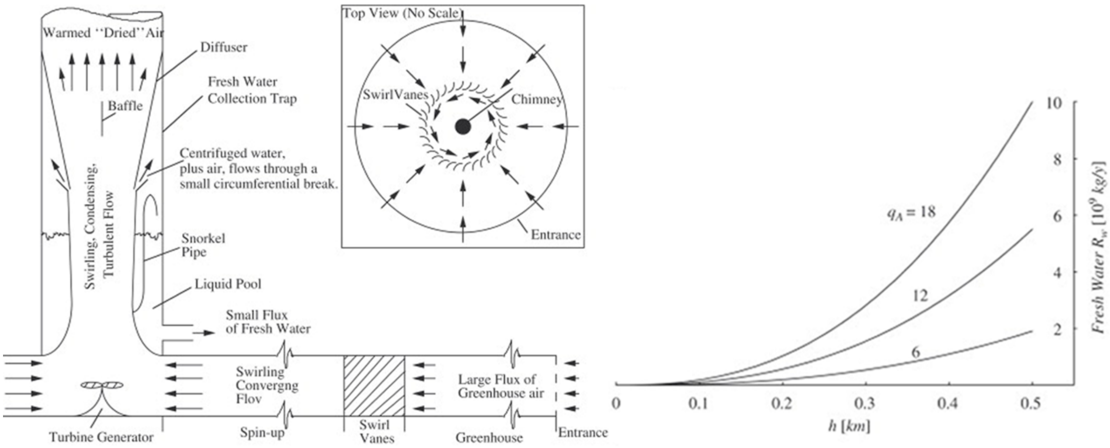


Fig. 13. (a) Daily variation of the condensation height, and (b) Daily condensation water mass flow rate (Xu et al., 2015).

A solar cyclone (a variation of the solar chimney, see Fig. 14) was introduced to harvest water from the atmosphere (Kashiwa and Kashiwa, 2008). The swirl vanes that were set in the path of the air moving towards the chimney induced the radial flow of air (from the periphery to the center) to spin. Both the radial and swirl part of velocity rise when the airflow path contracts from the canopy to the chimney. The temperature of the air will drop with the velocity increase due to conservation. The air temperature reaches the lowest point (lower than the dew point of air) when the velocity gets its maximum at the turning point from horizontal to vertical and causes the condensation to happen. A separator was set at the bottom of the chimney to separate the condensed water with air. For a 500m tall solar cyclone, 6×10^{9} kg/year (190 kg/s) water can be generated from the air with 12.00 g/kg humidity ratio. It was also indicated in this paper that the 12.00 g/kg humidity ratio is a typical value in many areas of populated Asia where the serious haze may happen. That means the water generated by the solar cyclone could cover the water loss caused by the spray system in the solar chimney. Water production will increase with the rise of chimney height and the growth of humidity ratio of the ambient air, see Fig. 14b.



(a) (b)

Fig. 14. The solar cyclone, (a) the vapor condensation process, (b) water production rate varied with the chimney height (h, km) and the humidity ratio (q_A, g/kg) (Kashiwa and Kashiwa, 2008).

4.2 Evaluation of the condensed water measure

To promote the economic feasibility of this geoengineering measure, many innovations were proposed to reduce the construction and operational cost of the huge chimney system. Due to the large proportion of initial investment of the canopy (Ming et al., 2016b), Bonnelle (2004) proposed a solar chimney with no canopy, using the condensation latent heat of the vapor in the updraft airflow as the driving force (see Fig. 15). When the updraft airflow reaches the saturation point level in the chimney, the vapor condensation would happen in the air which could emit the latent heat and heat the air. This heat from the air itself was used to substitute for the heat gained from the canopy. This procedure can be self-sustained and with no additional energy needed, similar to natural convective processes (Wu et al., 2020). As stated by Kashiwa and Kashiwa (2008), the temperature rise generated by vapor condensation in the arid region would reach 10 K. While the temperature rises from a canopy with 244m in diameter at Manzanares, Spain is only 15 K.

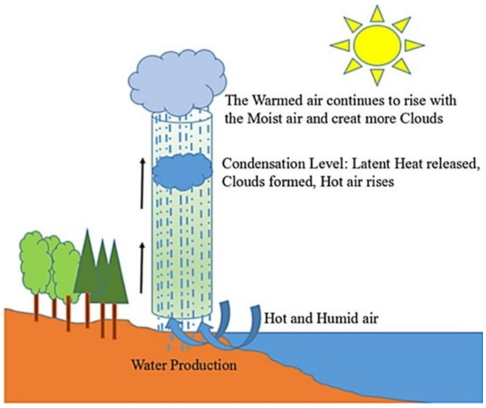


Fig. 15. The process of water vapor condensation in a chimney without canopy (Ming et al., 2016b)

The ideas of using heat discharged by power plants or from natural geothermal energy as the driving force in the solar chimney instead of the canopy have also been proposed and studied by several research teams (Cao et al., 2014; Chen et al., 2014; Fathi et al., 2018; Hu and Leung, 2017). By using this essentially free energy, these solar chimneys have almost no operational costs with condensation in the chimney occurring.

Some of the chimneys proposed in this study are quite high, but several articles from NASA (U.S.) describe the feasibility of chimneys several kilometers tall, and patents on this high conduit for aerosol spraying have been approved in many countries (Ming et al., 2014). Bolonkin (2011) even proposed a 3 km high chimney made from inexpensive inflatable tubes to harvest fresh water from the atmosphere. It was claimed that the water production could be $7.86\times 10^{7}\ \mathrm{m^3/year}$ at the initial construction cost of 20 million dollars and 4 km^2 land.

To summarize, it is demonstrated that the water needed in the spray system to scavenge the air pollution can be harvested from the air itself at a high place in the chimney (except the solar cyclone). More water will be generated in the humid region. Although the initial investments of a tall chimney are large, it is pointed out that the solar chimney method is the only method that can produce water and induce air simultaneously on a large scale compared with sorption methods, condensation method using vapor compression cycle, the desiccant wheel method, and membrane assisted methods (Tu and Hwang, 2020).

5. Elimination of air pollution by a filter within a solar chimney

A significant amount of water is needed in the water spraying approach. For the megacities that are plagued by water scarcity and haze events simultaneously, another alternative measure to eliminate aerosols in the air by a filter in a solar chimney is proposed and discussed in this section.

5.1 The mechanism of filter measure

Utilizing the chimney effect to suck the polluted air and channel the air through filters is proposed (http://www.except.nl/en/, accessed on 12 October 2020), which is similar to the giant vacuum cleaners. A concept of a solar-assisted large-scale cleaning system (SALSCS), which was a variation of the solar chimney, was proposed to filter the polluted air (Cao et al., 2015). This SALSCS for air pollution abatement included a 500 m chimney with filter banks mounted under the solar radiation canopy. Its air processing capability was claimed up to be 2.64×10^5 m^3/s.

To investigate the real air pollutant removal ability and the efficiency of the SALSCS, a prototype (see Fig. 16) is built in the downtown of Xi'an, China. It has a 43×60 m^2 solar radiation canopy and a 60 m high chimney (Cao et al., 2018b). The initial cost of this prototype was US$2 million (Cyranoski, 2018). The filtration efficiency for PM2.5 obtained reached 73.5% on average, with the rate of airflow reaching 35 m^3/s. According to released experiment data, PM2.5 concentration in the air within the 10 km^2 surrounding area would be reduced by 15%, which means it would benefit about 300 thousand nearby people (https://www.sohu.com/picture/277749907, accessed on 12 October 2020).

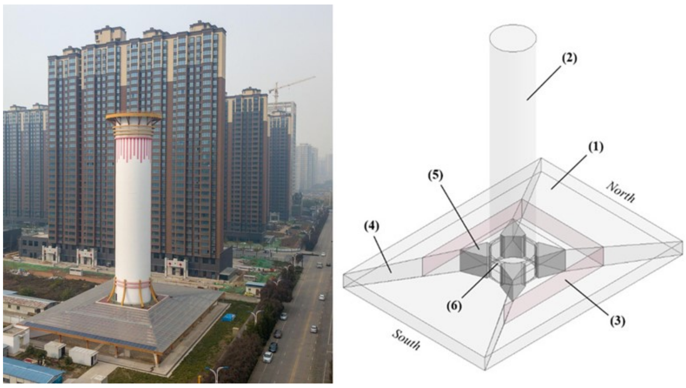


Fig. 16. The picture of SALSCS and its schematic design with (1) solar collector, (2) tower, (3) filters, (4) partition walls, (5) storage room, and (6) rolling doors (Cao et al., 2018b).

The performance of this air filter system is affected by the weather condition. As displayed in Fig. 17, a higher solar radiation flux will induce more air into the system. However, the temperature of the surrounding air has little influence on the airflow rate of the system.

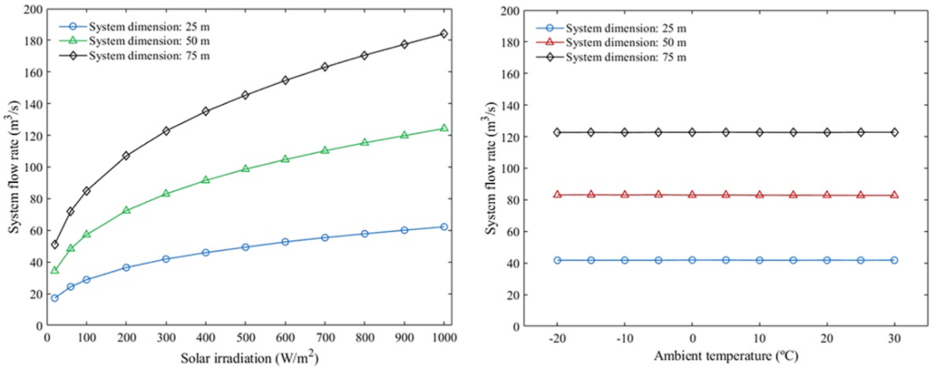


Fig. 17. Performance of SALSCS affected by the weather condition, (a) solar irradiation, (b) ambient temperature (Cao et al., 2018a)

The performance of this air filter system is also affected by the configurations. From Fig. 17, a higher chimney will suck more air into the chimney (system dimension indicates the height of the chimney). A larger collector and a wider chimney will be beneficial for the performance, see Fig. 18.

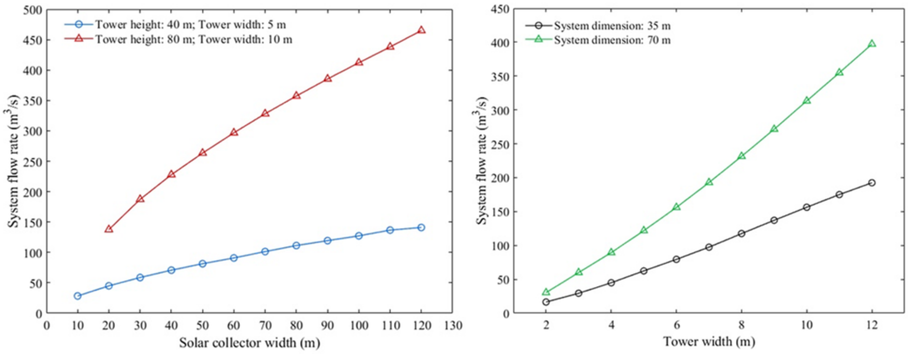


Fig. 18. Performance of SALSCS affected by the configurations, (a) solar collector width, (b) tower width (Cao et al., 2018a)

5.2 Evaluation of this filter measure

5.2.1 Discussion of the solar chimney used in the filter measure

One problem with those filter systems based on solar chimney is its low efficiency. The kinetic energy of the air current in the chimney is converted from the heat gains obtained from the solar radiation. The energy conversion efficiency that defined as the ratio of the kinetic energy to the solar radiation is expressed as (Zhou and Xu, 2016):

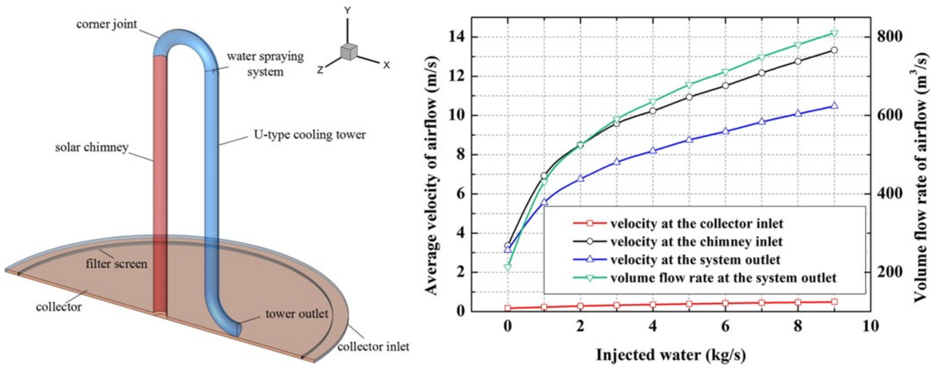
$$\eta = \eta_{ch} \cdot \eta_{coll} = \frac{gH_{ch}}{c_p T_{in}} \cdot \frac{c_p m (T_{out} - T_{in})}{A_{coll} S_g} \tag{1}$$

where the η_{ch} is the chimney efficiency (the ratio of the kinetic energy of the air to the heat gains), η_{coll} is the solar collector efficiency (the ratio of heat gains of the air to the solar radiation), H_{ch} is the height of the chimney (m), c_p is the constant-pressure specific heat of air (J/kg · K), A_{coll} is the area of the collector (m^2), S_g is the global solar radiation (W/m^2), T_{in} and T_{out} is the air temperature at the inlet and outlet of the collector (K), and m is the mass flow rate of air (kg/s). The η_{coll} is approximately 32% for the Spanish porotype (Guo et al., 2019). One can easily calculate the η_{ch} and conclude that this efficiency is lower than 5% for a 1000m chimney.

To increase the efficiency of the solar chimney and induce more air into the system at fixed solar radiation, Huang et al. (2020a) proposed a system based on the SALSCS, but the glass canopy under the chimney was replaced by photovoltaic panels. The photovoltaic panels were used to generate power to drive suction fans and propel the air into the chimney. A 194.6 m high chimney with 113 m glass canopy in diameter could induce 975.93 m^3/s air into the chimney. While, when the entire top surface of the canopy was replaced by photovoltaic panels, the total air flow rate would increase to 2.21 times. The mass rate of airflow is lower due to the shade effects of the photovoltaic panels but increased by the electricity generated by those panels. This output was achieved by the combined efforts of the chimney and photovoltaic panels. Without the cooling effects of the airflow in a chimney, the efficiency of photovoltaic panels will deteriorate due to their temperature rise (Jamali et al., 2019).

Another problem with the filter system is that the clean air driven out of the chimney ascended into the upper level of the atmosphere and not to the level where human activity takes place. The average mass mixing ratio of filtered air with the atmosphere below 50 m (from the surface of the Earth) reached only 5.22×10^{-3} (kg/kg dry-air) (Cao et al., 2018c). A higher chimney could drive more polluted air in but may result in even less filtered air reaching the breath area due to the longer mix distance and a higher outlet air velocity.

To address this problem, a novel 200 m solar chimney cooling tower combined system was proposed by Gong et al. (2017) and shown in Fig. 19. The hot air heated by the solar collector travels through the filter screen and rises in the solar chimney due to buoyancy. When it moves through the corner joint, the air will be cooled by the water spraying system. This cooled air will become denser and heavier than the air in the chimney and drag the air from the chimney to the cooling tower. Fig. 19b presents that the volume rate of air sucked into the system is more than the volume rate without a spraying system. When more water is injected by the spraying system, the air becomes further cooled and heavier. This gives a larger air pressure difference between the pressure in the chimney and the tower, which will drive more polluted air into the system to be purified.

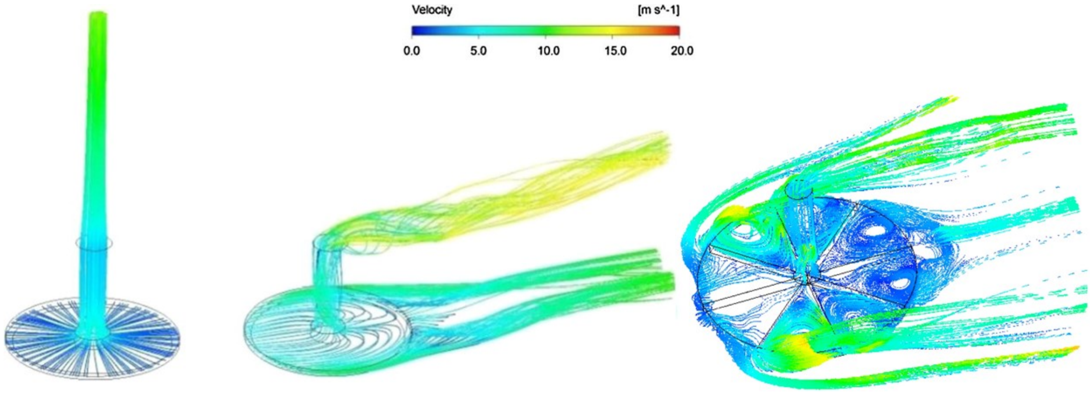


(a) (b)

Fig. 19. The solar chimney cooling tower combined system, (a) 3-D model, (b) the variation of volume flow rate and the velocity of airflow (Gong et al., 2017).

The airflow in the solar chimney is also affected by the crosswind, which is shown in Fig. 20. The simulation concluded that the crosswind near the outlet of the chimney would compel the flow to incline and hinder the updraft to flow out. While, the crosswind near the inlet of the canopy would blow the hot air heated by the canopy out of the canopy and hamper its converge at the bottom of the chimney (Zou et al., 2017). See Fig. 20a and Fig. 20b. The state of the flow pattern would be improved in the same chimney but with union-jack-shaped windbreak walls under the canopy because parts of the wind were blocked by walls and forced to enter into the chimney, see Fig. 20c.

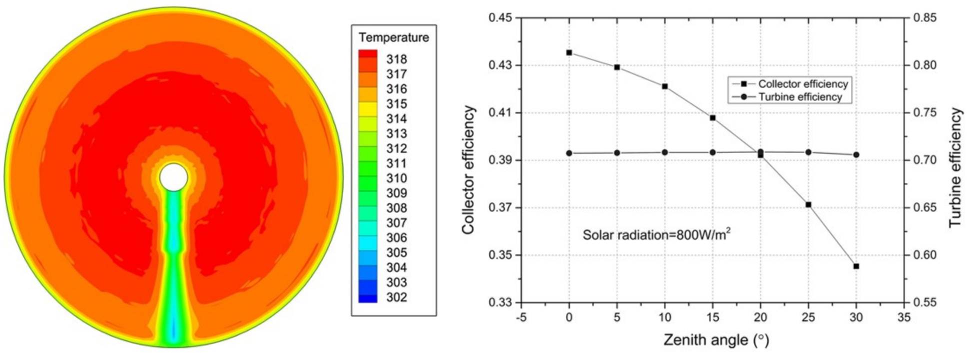
It was claimed that this system would filter the particles out from the air driven into the chimney at the rate of 3.5 kg/h when the concertation of particles was 500 $\mu g/m^3$ and the filter efficiency was 0.8 (Zhu et al., 2019).



(a) (b) (c)

Fig. 20. Airflow pattern of a solar chimney affected by the crosswind, (a) no wind, (b) crosswind velocity is 10 m/s (Zou et al., 2017), and (c) crosswind velocity is 10 m/s with windbreak walls (Zhu et al., 2019).

Since the driving force of the airflow is the heat gained from the canopy, the canopy (collector) efficiency (which is defined as the ratio of the solar energy gained by the air to the solar radiation flux) affected by the solar zenith angle will have an impact on the performance of the solar chimney (Guo et al., 2015). If the solar radiation flux is fixed, the collector efficiency will decrease with the solar zenith angle increase because of the shade effects of the tall-and-opaque chimney on the collector (the angle is 0° when the radiation is aligned with the chimney). From Fig. 21a, the temperature of the collector roof shaded by the chimney was much lower than other parts of the collector roof when the solar zenith angle was set to be 30°. The variation of collector efficiency with the solar zenith angle was depicted in Fig. 21b. With the zenith angle increasing, the collector efficiency will decrease, thus the rate of airflow driven into the chimney will reduce.



(a) (b)

Fig. 21. The shade effect of the chimney on the collector, (a) temperature variation on a collector roof, and (b) efficiency variation with the solar zenith angle (Guo et al., 2015).

5.2.2 Discussion of the filter technology

The filter technologies described here require some advances to be commercially viable. First, a filter's efficiency and holding capacity (the maximum dust that can be gathered during the service life of a filter) can vary against different particle size distributions (Chang et al., 2019). The holding capacity of the filters treating fine particles was lower compared with the coarse particle filter process (Tang et al., 2018). Since the chemical and physical components of air pollution will be distinct in different places and different seasons (Jiang et al., 2018), custom filters need to be developed for specific systems to maintain efficiency at a reasonable level.

Second, traditional commercial air filters could not filter out the precursors to particulate matter (e.g., sulfur dioxide gas and nitrogen oxides), which resulted in visually clear air but poor air quality. To remedy this issue, a metal-organic air filter modified by carbon nanotube was produced for ultrafine particle filtration and SO_2 absorption (Feng et al., 2018). A kind of air filter made by biodegradable cellulose was developed, which has fine filtration efficiency and antibacterial capability (Ma et al., 2019).

Lastly, most of the commercial air filters are fabricated from petroleum-based materials with low degradability, which may also become solid pollutants after usage (Ma et al., 2019). A kind of environment-friendly and high-efficient material needs to be developed for the solar chimney. Though a new porous material made from calcium iodate, sodium alginate, and silica fume was proposed for air particle collection (Zanoletti et al., 2018), which can be regenerated by rainfall. It still needs to be tested in a large-scale application in further research.

6. Overview of the air pollution removal techniques proposed

To put those air pollution removal techniques based on the solar chimney in practice, the economic aspects need to be considered. The investment always contains the chimney cost, the canopy cost, and the land cost. Though the measure of pollution scavenged by the sprayed water droplet may not need the canopy, it needs a reservoir to store the water. The cost of a solar chimney was reviewed by Zhou and Xu (2016). The chimney cost varied from 175.4 to 419 €/m^2, which was calculated by dividing the chimney cost by the superficial area of the chimney assumed in a cylindrical shape. The canopy cost varied from 7.27 to 34.22 €/m^2, which was calculated by dividing the collector cost by the collector area. The cost depends on the construction time, construction site, and physical size of the solar chimney. Most of those solar chimneys for power generation were proposed to be built in the desert or mountainous regions, the land cost was always neglected. However, those measures aimed at air pollution removal should be built in the city in which the land cost will be higher. For reference, the price of Class III land (the land is divided by five classes, Class I is near the downtown) for the industry is about 1,000 RMB/m^2 ($\approx$143 \$/m^2) in Wuhan, the largest city in Central China (http://www.whtdsc.com/jzdj/10391.jhtml, accessed on 12 October 2020). For the spray measures without a canopy, the price of a water supply and spray system including a 1,000,000 m^3 reservoir is about 59.8 million dollars (Altmann et al., 2005). Since the water collected after the air pollution scavenging process by spraying has a similar property as the rainwater, a natural reservoir (pond, lake, or river) may be used to save cost. Although a huge initial investment is needed for the construction of an air-purification system based on the solar chimney, the achievable health benefits (lower premature mortality and reductions in hospital admissions for respiratory issues) cannot be weighted by monetary terms.

Table 3 shows the key innovation and strengths of those four geoengineering measures based on the solar chimney reviewed in this paper. Those measures not only can handle pollutions in the air at low operational expense without large-scale negative impacts on the environment but also can be controlled by human beings without waiting for a special weather condition. Though none of those geoengineering measures is perfect for managing air pollution at this stage, they do provide health benefits for the public and they also propose a starting point and a platform to develop a more economic, more efficient and smaller environmental impact measure in the future.

Table 3
Comparison of Air Pollution Removal Measures

Measures	Technological novelty	Strengths and weaknesses	Environmental impacts	Requirements and costs
High solar chimney	Utilizing the heat island effect or solar energy to avoid the dramatic growth of PM2.5 and haze formation (Zhong et al., 2019a).	It opens the meteorological channels for pollution dispersion, preventing the "two-way feedback mechanism" (Miao et al., 2018; Zhong et al., 2019b), but cannot eliminate pollution physically.	The uplifted air pollution may be transported to a long distant location (Langford et al., 2010; Minoura et al., 2016).	A chimney must be higher than PBL (Zhou et al., 2015); a floating chimney could be feasible and more economical (Papageorgiou, 2007; Zhou and Yang, 2009; Zhou et al., 2009b).
Solar chimney with water spraying	Combining the large-scale scavenging effect of spraying and the ability to generate power.	It can remove particles in the air (Cui et al., 2017; Wang et al., 2010; Yu, 2014) at a relatively low water loss (Akbarzadeh et al., 2009).	Water loss; The water collected after scavenge could be treated as natural rainwater.	A high chimney, pumps, spray system and sufficient water resources are needed (Akbarzadeh et al., 2009).
Solar chimney with condensed water from vapor in the air	The water for scavenging particles can be harvested from the air itself.	The water harvested from the air itself can satisfy the need in the spraying system to scavenge the air pollution (Kashiwa and Kashiwa, 2008; Ming et al., 2017).	Improve the climate near the chimney (Zhou et al., 2010). The water collected after scavenge could be treated as natural rainwater.	A high chimney is needed (Ming et al., 2017; Xu et al., 2015).

Table 3 (continued)
Comparison of Air Pollution Removal Measures

Measures	Technological novelty	Strengths and weaknesses	Environmental impacts	Requirements and costs
Solar chimney with air filter	Using solar energy to drive the polluted air through air filters.	Not only filter aerosol(Cao et al., 2015; Cao et al., 2018c) but also eliminate acid gas pollutants (Feng et al., 2018); Some filters can be regenerated by rain (Zanoletti et al., 2018).	Filters may need to be replaced regularly; those petroleum-based filters are not degradable (Ma et al., 2019).	A chimney; Tailored filters for specific air pollutants (Jiang et al., 2018).

7. Discussion and conclusion

With the continuous economic growth and rapid industrialization of many developing countries with high populations (e.g., China and India), governments and the general public encounter the growing air pollution problems (particularly the serious PM problem) and determine to address these issues. The haze caused mainly by particles, which has negative impacts on human health and leads to unsustainable regulation of transportation and high-polluting industries, must be overcome in the coming years.

The fundamental solution to the PM problem is to replace fossil fuels with clean and renewable energy. However, we cannot wait for the day when fossil fuels are completely phased out and do nothing at present time. To relieve the harmful effects of PM on the health of the general public in the near term, several geoengineering measures based on solar chimneys were reviewed in this article. They have the large-scale elimination ability on pollutants in the air, particularly for particulate matter. The measures include driving the polluted air penetrate the planetary boundary layer into the troposphere to avoid the dramatic growth of concentrations of particulate matter, spraying water on the top of the chimney into the air to scavenge pollution, and intercepting fine particles in the air driven by the chimney with large filters.

Compared with traditional methods (e.g., emission control at sources, giant spray trucks), those solar chimney geoengineering measures have the following advantages: 1) They can be operated 24 hours a day and thus keep the pollution removal function stable and continuous. 2) They are environment-friendly measures, which can generate clean electricity by turbines from the airflow to compensate for the consumption of energy that is most likely from fossil fuels in the developing countries and thus reduce emissions. 3) They are also robust, need very low maintenance and can work for a long time. After reimbursement of the initial investment, those geoengineering measures could generate power at low operational costs.

Given the advantages of the solar chimney geoengineering measures and the economic and human health losses caused by air pollution, those geoengineering approaches deserve to be studied further and implemented in those countries that are suffering from the heavy air pollution issue.

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