Mitigating air problems and producing renewable energy with solar downdraft tower

Liu Yang, Zhou Li
Wuhan Business University, Wuhan, China

Abstract. Over the past three decades, China, especially in the megacity areas, has suffered from air pollution and heavy haze with its decades-long burst of economic growth and rapidly expanding clout as an industrial giant. The important two elements of air pollutant in China are the fine particles (PM 2.5-PM 10) and non-natural greenhouse gases. To overcome these problems, in this study, we propose a novel inversion solar chimney approach for mitigating the air pollution and haze problems in the megacities of China by using water to scavenge air pollution through spraying water into the atmosphere. For a water drop floating in air or falling through air, the sensible heat of air would transfer to the latent heat of droplets and will cause a decrease in drop size. In a quite short transient time, the droplet evaporates and cools down to air ‘wet-bulb’ temperature. The Direct air capture devices (DAC) are installed at the bottom of the solar downdraft tower to reduce the CO2 in the atmosphere.

1. Introduction
Over the past three decades, China, especially in the megacity areas, has suffered from air pollution and heavy haze with its decades-long burst of economic growth and rapidly expanding clout as an industrial giant. China, who are confronted simultaneously with the task to both urban and industrial development and air quality improvement. Air pollution has become a major issue in China and poses a threat to Chinese public health. In 2016, only 84 out of 338 prefecture-level or higher cities attained the national standard for air quality. [1]

The important two elements of air pollutant in China are the fine particles (PM 2.5-PM 10) and greenhouse gases. The most concentrated particulate matter pollution resulting from the burning of fossil fuels by transportation and industrial sources tends to be in densely populated metropolitan areas[2]. According to the U.S. Environmental Protection Agency, such fine particles can cause asthma, bronchitis, and acute and chronic respiratory symptoms such as shortness of breath and painful breathing, and may also lead to premature death. [3] The primary greenhouse gases in Earth's atmosphere which are carbon dioxide, methane, nitrous oxide, CFCs, HCFCs and HFCs would cause the greenhouse effect. Should greenhouse gas emissions continue at their rate in 2017, Earth's surface temperature could exceed historical values as early as 2047, with potentially harmful effects on ecosystems, biodiversity and human livelihoods [4].

A geoengineering approach by spraying water into the atmosphere at the top of high buildings (e.g., CCTV headquarters building), towers (e.g., Shanghai Oriental Pearl Tower), and flat areas (e.g., Tiananmen Square) was proposed to scavenge air pollution [5]. This approach seems impractical in
China because of its problems of possible flood, the humidification of the low atmosphere, slipping grounds in the cold seasons and the harmful impact on image of Chinese iconic scenes. A novel upside-down U-shaped tower was used to replace the traditional chimney to conduct the clean air back to ground level and improve the air quality in the spectrum of human activity [6]. A water spraying system on the top and a filtrating screen system installed on the bottom of the chimney were combined together to reduce PM 2.5 pollution. But the energy required to pump the water to the top of the tower, the running cost of the filtrating screen system and the construction cost of double high towers (the inverted U-type tower) were not considered in this paper.

A demonstration unit for the Solar-Assisted Large-Scale Cleaning System (SALSCS) was built in Xi’an, China, to study its effectiveness in terms of urban air pollution remediation [7]. In the SALSCS system, filter pressure drop should always be lower than the corresponding pressure difference generated by solar heating, otherwise a fan was needed to move the air in the tower. This will limit the use of high efficiency filter, which may result in the filter only mainly governing the air pollution PM10 but being inefficient in governing PM2.5, and the lifetime of the filter.

These solar-chimney-like approaches have two basic problems: first, the levelized electricity cost of such solar-chimney-like system increases rapidly over filter’s operating time, which becomes higher than on-grid price when the operating time of filter is longer than a certain day; second, it is very difficult for such solar-chimney-like system to be profitable from the point of sale of electricity when the such solar-chimney-like system has to undertake the task for governing air pollution[8].

A bold measure called solar updraft towers was mentioned to mitigate the dense haze in Chinese cities [9]. In this paper, solar updraft towers for power generation are proposed to drive the dense haze in cities due to buoyancy to ascend to a higher height and disperse the haze to farther distance. By means of solar updraft towers, the air pollution has not been removed yet but only dispersed and transported to high or to other areas through atmospheric motion. Moreover, the negative effect due to the transportation of pollutants can’t be predicted [8].

The majority of previous solar tower studies have either economic or engineering problems. To overcome these problems, in this study, we propose a novel inversion solar chimney approach for mitigating the air pollution and haze problems in the megacities of China by using water to scavenge air pollution through spraying water into the atmosphere. The differences between the traditional solar chimney and our proposal are: first, a downdraft solar tower is used to replace the traditional chimney; second, a water spraying system is installed at the top of the chimney, which will be used to produce the downdraft effect; third, the collection canopy of traditional solar chimney will not be necessary to construct, which will save the initial investment; fourth, the Direct air capture devices (DAC) are installed at the bottom of the solar downdraft tower to reduce the CO2 in the atmosphere.

The scientific rationale and mechanism for this solar downdraft tower with fine aerosol removal approach is described in section 2. The synergies of SDTs coupled with Direct air capture devices (DAC) which could capture CO2 in the atmosphere are discussed in section 3. The final module of SDTs combined the precipitation, air capture and photocatalytic effects is proposed in section 4 in which the future applications and limitations of SDTs are also discussed.

2. Cleaning aerosol in the solar downdraft tower

2.1 the mechanism of fine aerosol removal by water droplets

When a water droplet goes through the haze air, the particles and aerosol in the air collected by the water droplets fall down to the ground [10]. This process is also called precipitation below-cloud scavenging. The precipitation is highly efficient in the removal of aerosols from the atmosphere, which is described as the single most efficient way [5].

The precipitation process is influenced by water droplet size distribution, water intensity and collision efficiency between particles and rain droplets [11]. The precipitation scavenging efficiency is defined as the rate of loss of aerosol particles from the atmosphere by their incorporation into water drops.
2.2 Interest of solar downdraft tower

The solar downdraft tower was once called energy tower. Solar downdraft tower spray salt water on hot air at the top of the tower, making the cooled air in the tower with higher density than outside surrounding air fall through the tower and drive a turbine at the tower's bottom. The downdraft energy towers were initially designed for energy capture from the air temperature difference, which need to work best in hot dry climates to guarantee the system efficiency.

Omer and other researchers claimed that the solar downdraft tower can generate 68.8 million US dollar per year and with 15.1% internal rate of return for a 1280 m height and 400 m diameter tower in the Eilat area of Israel after optimal design[12].

The pressure difference between the cold air in the tower and the hot air outside is the integral of the product of the difference of the air densities by the gravity acceleration with respect to height:

\[ \Delta p = g \int_0^H (\rho_\infty(z) - \rho(z))dz \]

where \( H \) is the tower height, \( \rho_\infty(z) \) and \( \rho(z) \) are ambient air density and internal airflow density inside the chimney at any height \( z \), respectively.

The temperature \( \rho(z) \) in Earth's atmosphere decreases with an increase in altitude, or increases with the decrease in altitude [13]. This temperature change outside the tower is called dry adiabatic which is a process without exchanging heat. When the air contains little water, the change rate of temperature called lapse rate is known as the dry adiabatic lapse rate: the rate of temperature decrease is 9.8 °C/km (3.0 °C/1,000 ft)[14].

This specific potential energy due to cooling is transformed either to shaft power by turbines, frictional losses in the tower, and lost to the environment. The momentum conservation equation for the flow in the direction of chimney axis is given by Kashiwa and Kashiwa[15]

\[ \Delta p (1 - n) = \left[ \varepsilon + \frac{\varepsilon}{d} \right] \frac{1}{2} \rho_0 \rho_0 V_0^2 \]

where \( n \) is factor of pressure drop at the turbine (when not considering the power output, the factor can be set equal to 0; \( V_0 \) is the flow velocity in the chimney axial direction at the inlet of the chimney. Coefficients in the brackets represent the exit loss (with unit coefficient), other point losses, and wall friction. The factor \( \varepsilon \) accounts for the following energy losses: (1) the energy losses in the turbine; (2) energy losses at the location where the flow area changes; (3) the turbulent flow losses; (4) the vapor condensation at any location of the chimney. The wall is not too rough, so \( d = 0.01 \) for high Reynolds number flow in a pipe is adopted in the calculation.

2.3 Synergies of SDTs coupled with precipitation

Below-cloud scavenging process (rain droplets fall through the atmosphere) can result in scavenging air pollution quickly. Technological feasibility for this spraying water system approach is that all technologies and material required are: high towers, water, automatic sprinkler head to spray water, etc. all of the facilities were already constructed by SDTs.

Epidemiological studies have shown that premature mortality and respiratory hospital admissions risks have linear positive correlations with PM10 concentration. Tuberculosis, pneumonia and bronchopneumonia are seen as the representative diseases of the respiratory illness. It can be calculated from the 2013 China Health Statistical Yearbook that the average direct expense of hospital admission on the three respiratory illnesses per day was 3035.43 RMB yuan and the duration of hospital stays was 8.33 days in the metropolitan regions in 2012. If the air pollution problems were settled by the water spraying systems, the international images of our nation would also be improved, which would also boost the travel economy.
3. Removal CO2 before the air move out from the solar downdraft tower

3.1 Direct air capture (DAC) or dilute carbon dioxide capture from the atmosphere

The main principal of capture CO2 is using an alkali component to react with weak acidic CO2 in order to separate it from neutral gases.

The alkali component can be a solution of sodium hydroxide. When the air passes through the sodium hydroxide, the sodium carbonate is formed, which will cross-react with calcium hydroxide to form calcium carbonate as a precipitate. The solid calcium carbonate is then submitted to thermal decomposition with capture of the CO2 released.

An “artificial or synthetic tree” to emulate the action of natural trees by absorbing CO2 directly from the atmosphere with solid alkaline absorbents proposed by Lackner[16], which need to be constructed high enough to guarantee the sufficient wind travel through the tree. The high “tree trunk” in the “artificial tree” can take more than 25% of the initial investment cost. To remedy this defect, a DAC device coupled with SDTs is proposed to make enough air pass through the alkali resin polymers with no high “tree trunk” needed.

3.2 Synergies of SDTs coupled with DAC

According to [17], the SDT with 10,000 m2 opening constructed in a desert climate would cause a downdraft flow in excess of 15 m/s which is nearly 15 km3 of air per day (9,500 tons of CO2) through the tower. The air leaving at the bottom could drive wind turbines or flow over CO2 absorbers. The CO2 flowed through the tower equals a 360 MW power plant emission.

The DAC device not only can capture CO2 passed through the SDT, but also can play the role of control mechanism to regulate turbine output. During base load, at times when less power is required or the air pollution value is in the acceptable level, less water would be sprayed on the top resulting in less air flow rate, some sections of DAC at the bottom can be closed to narrow down the air flow channel in order to keep the flow velocity in the turbine working range. At the same time, the alkali resin would be regenerated in the device. If more power is required, more water would be sprayed on the top, more sections at the bottom will be opened in a controlled manner. So, the investment costs for the CO2 capture infrastructure which can act in synergy with the power generation part of SDTs is worth.

4. Discussion

With the continuous growth of Chinese economy, people paid more attention on the environmental problems. In order to control the air pollution, it is a good choice to introduce the SDTs with DAC and Photocatalysis function which could handle with most of the pollutions in the atmosphere.

When considering the aerosol removal function of SDTs, precipitation plays an important role through the below-cloud scavenging process, by which the falling water droplets sprayed on the top of the SDT deposits aerosol particles on the ground surface. The water droplets can work efficiently to remove the particles in the atmosphere at different diameter, particularly in the range of PM 2.5-PM10 which is the main component of the haze weather in China big cities.

When considering the CO2 removal function of SDTs, DAC installed at the bottom provides a route to manage CO2 from atmosphere and allows industrial economies of scale to deal with global carbon emissions source. SDT combined direct air capture devices result in a fuller utilization of transmission capacity, allowing better matching of power generation with utility loading and peak loading.

The SDTs is feasible in Chinese big cities. Even ignoring the energy produced by the turbines, the SDTs system can be much profitable constructions comparing with the transportation and big factories regulation losses.

For a lack of accurate model to evaluate the reduction of air pollution concentration in a certain space, the health and economic benefits should be accurately estimated in a large area and in a long period. Quantitative analysis of the benefits calls for further research. More detailed analysis needs to be investigated.
5. Conclusion
In this paper, a giant solar downdraft tower combined with photocatalytic reactor and direct air capture (DAC) was proposed, which is able to produce renewable electricity and at the same time remove or capture aerosols and CO2. The working principal of the solar downdraft tower were discussed. The methods of tackling the pollutions in the air by precipitation and direct air capture devices were proved to be practical and can be very efficient with proper arrangements.

Acknowledgments
This work was financially supported by the Science and Technology Research Grant of the Wuhan Business University (Project No.:2019KY021).

References
[1] 84 cities met the national standard of air quality in 2016, 11 more compared to last year. China News. 2017.
[2] contributors W. Wikipedia, The Free Encyclopedia.; 2018 [Available from: https://en.wikipedia.org/w/index.php?title=Particulates&oldid=869977496.
[3] Agency USEP. PM 2.5 2013 [Available from: https://www.epa.gov/pm-pollution.
[4] Mora C, Frazier AG, Longman RJ, Dacks RS, Walton MM, Tong EJ, et al. The projected timing of climate departure from recent variability. Nature. 2013;502:183.
[5] Yu S. Water spray geoengineering to clean air pollution for mitigating haze in China’s cities. Environmental Chemistry Letters. 2014;12(1):109-16.
[6] Gong T, Ming T, Huang X, Renaudde Richter. Numerical analysis on a solar chimney with an inverted U-type cooling tower to mitigate urban air pollution. Solar Energy. 2017;147:68-82.
[7] Cao Q, Kuehn TH, Shen L, Chen S-C, Zhang N, Huang Y, et al. Urban-scale SALSCS, Part I-Experimental Evaluation and Numerical Modeling of a Demonstration Unit. Aerosol and Air Quality Research. 2018;18:2865-78.
[8] Tan D, Zhou X, Xu Y, Wu C, Li Y. Environmental, health and economic benefits of using urban updraft tower to govern urban air pollution. Renewable and Sustainable Energy Reviews. 2017;77:1300-8.
[9] Zhou X, Xu Y, Yuan S, Wu C, Zhang H. Performance and potential of solar updraft tower used as an effective measure to alleviate Chinese urban haze problem. Renewable and Sustainable Energy Reviews. 2015;51:1499-508.
[10] Cherrier G, Belot E, Gerardin F, Tamière A, Rimbert N. Aerosol particles scavenging by a droplet: Microphysical modeling in the Greenfield gap. Atmospheric Environment. 2017;166:519-30.
[11] Andronache C, Grönholm T, Laakso L, Phillips V, Ven’al’aïnen A. Scavenging of ultrafine particles by rainfall at a boreal site- observations and model estimations. Atmospheric Chemistry and Physics. 2006;6:4739-54.
[12] Omer E, Guetta R, Ioslovich I, Gutman PO, Borschchevsky M. Optimal Design of an “Energy Tower” Power Plant. IEEE Transactions on Energy Conversion. 2008;23(1):215-25.
[13] Jacobson, Zachary M. Fundamentals of Atmospheric Modeling. Second ed: Cambridge University Press; 2005.
[14] Kittel, Kroemer. Thermal Physics: W. H. Freeman; 1980.
[15] Kashiwa BA, Kashiwa CB. The solar cyclone: A solar chimney for harvesting atmospheric water. Energy. 2008;33(2):331-9.
[16] Lackner KS. Capture of carbon dioxide from ambient air. The European Physical Journal Special Topics. 2009;176(1):93-106.
[17] Lackner KS, Grimes P. Capturing Carbon Dioxide From Air. 2010:505-667.