A water-spray geoengineering system for haze control

Based on the optimization of collection efficiency for increasing precipitation scavenging coefficient.

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Abstract— **It is well known that Singapore is a country, which often encounters haze crises (as evidenced by the 2006 Southeast Asian haze crisis, the 2013 Southeast Asian haze crisis, and the subtly growing 2015 PSI levels[i]). There is a necessity to eliminate the haze's source as quickly as possible; curbing a haze crisis at its source itself is the best possible method for combating haze. This is not always possible; haze spreads around faster than one can imagine and it maybe too late, or the haze's source maybe too far away to be dealt with in a timely and effective manner. So, this paper focuses on the aspect of mitigation of haze in urban and residential areas, by suggesting a modern geoengineering system that focuses on increasing the precipitation scavenging coefficient, which is achieved by using nozzles optimized for release of water droplets with the optimum water intensity as well as with the optimum water droplet diameter (essentially, by optimizing the collection-efficiency). Care is taken to consider the aerosol particle size, as well as relative humidity of the location. An auxiliary haze-control system, utilizing plants, is also briefly alluded to. Certain necessary precautions, to ensure the smooth working of the haze control system, are also mentioned.**

Keywords: Haze, Geoengineering, Precipitation scavenging coefficient, Nozzle, Collection-efficiency optimisation, Auxiliary haze-control system, Precautions.

INTRODUCTION

Singapore suffers from air pollution periodically, albeit being one of the cleanest countries in the world. It is mainly affected by serious smoke haze as a result of forest fires in neighbouring countries. The reason for the aforementioned forest fires is most often the practice of open burning (a.k.a Slash-and-Burn agriculture) in the neighbouring countries of Singapore, which specifically include Malaysia and Indonesia.

Considering the 2006 haze crisis as a case study, it is noticeable, that the haze was not only the reason for an increase in the number of patients admitted (with respiratory diseases and asthma) to polyclinics, but also caused an economic loss to Singapore equivalent to 50 million USD. [1]

The infamous 2013 haze crisis was notable for causing record high levels of pollution in Singapore and several parts of Malaysia. The $PM_{2.5}$ concentration also reached 300 for the first time in the nation's history. The 3-hour Pollution Standards Index in Singapore reached a record high[ii] of 401 on 21 June 2013, surpassing the previous record of 226 set during the 1997 South East Asian Haze.

Measures taken, during both of these dire crises, included restricting outdoor activities, priority for treatment of haze-related illnesses, distribution of respirators to households, as well as adequate restocking of facemasks in drug stores.

The fact remains that not much could be done to stop the haze during these crises. Health Minister Khaw Boon Wan himself [2] said that there was "very little that (could) be done to stop the haze" during the 2006 crisis. 'Cloud seeding' was a suggestion to 'effectively' get rid of the haze (2013); unfortunately, the Singapore meteorological service found it to be not possible due to insufficient cloud cover.

The situation is worsened during dry seasons or when rainfall received is lower than usual, or even when the direction of wind unpredictably changes [3]. In fact, according to the ASEAN Specialized Meteorogical Centre, a few hotspots were observed in Peninsular Malaysia and Kalimantan as of 26th January 2015.

The above scenarios are enough evidence for the need of a haze control strategy, which works very well in the mitigation of haze in a short term, especially in urban and residential areas. Thus we seek to propose a modern geoengineering system utilizing a nozzle system optimized for the exploited propulsion of water drops (of optimum diameter) to increase the collection efficiency, and subsequently the precipitation scavenging coefficient (consequently reducing PSI levels).

MECHANISM OF THE HAZE CONTROL SYSTEM

The haze control system that we plan to use, will utilize a process, which goes by the name 'artificial below-cloud scavenging', - a wet deposition process (which is essentially a process of scavenging suspended aerosols).

Below cloud scavenging [4], happens when falling rain droplets or snow particles collide with aerosol particles through Brownian diffusion, interception, impaction and turbulent diffusion (the transport of mass, heat or momentum within a system due to random and chaotic time dependent motions).

Due to the fact that water droplets can simply collect pollutants [5] with them by interception, diffusion (Brownian) and impaction (inertial), this is one of the world's most efficient methods to remove aerosols from polluted air.

In order to understand how the system is actually responsible for the mitigation of haze, a few terms have to be introduced. The precipitation scavenging coefficient (represented as 'μ', and referred to as PSC), is a function of the location's characteristics, time, rain/water-droplet characteristics (includes rain intensity and size distribution) and even the aerosol characteristics (includes chemical composition and size distribution).

The PSC (μ) essentially has the unit of inverse time (t^{-1}). For the sake of simplicity (without gross oversimplification), consider the formula [6] to estimate the PSC for monodisperse (i.e., particles of approximately the same size) aerosols and raindrops:

$$\mu(d_{\mathrm{a}}) = \frac{3}{2}\frac{E(D_{\mathrm{r}}, d_{\mathrm{a}})P}{D_{\mathrm{r}}}$$

Where d_a is the aerosol particle diameter, D_{r} is the diameter of raindrop, $E\ (D_r,\ d_a)$ is the collection efficiency and P is the rainfall intensity (precipitation rate). Another term materializes here; the collection efficiency (CE). It refers to the level of efficiency of aerosol particles removed during the process of wet deposition. [7] (The precise mathematical expression for the collection efficiency (of water droplets), is overly complicated, and is beyond the scope of this paper.)

It is noticeable, that the PSC is directly proportional to the CE as well as the rain intensity. It is also observable that the PSC increases, when the water droplet's diameter decreases. So by exploiting these two facts, it is possible to design a nozzle system, which optimizes the CE by controlled decrease of the diameter of the propelled water droplets, and increasing the rain intensity by installation of numerous complimentary nozzles.

(Note: Velocity too can be increased to attain the same effect, but that would increase the number of collisions of water droplets, thereby making the water droplet's diameter bigger, ergo becoming less efficient in scavenging aerosol particles.)

It should be noted that while the collection efficiency due to diffusion increases when the water particle diameter decreases, the CE increases due to interception and impaction with increase in the water droplets' diameter. So it is necessary to take into account of all the three previously mentioned factors to decide upon an optimum diameter of the propelled water droplet.

Define a term 'critical particle diameter' as the diameter from which the impaction mechanism becomes important. The critical diameter is a particle diameter [8], at:

$$St - S^{*} = 0$$

$$\text{(where } \tau = \frac{\rho_d d_p^2}{18\mu}\ \ , St = \frac{2\tau U(D_d)}{D_d} = \frac{2\alpha\rho_d D_d^{\beta-1} d_p^2}{18\mu}$$
$$\text{and } S^{*} = \frac{1.2 + 1/12\ln(1+\mathrm{Re})}{1+\ln(1+\mathrm{Re})}\text{)}$$

Where Re the Reynolds number of a raindrop based on its radius, τ is the relaxation time, ρ_d is the density of the droplet of gm/cm^3, d_p is a particle with diameter d, D_d is the diameter of a collected raindrop (or water drop), $U(d_d)$ is the falling velocity of a raindrop with diameter D_d, μ is the viscosity of water and α and β are additional constants.

The critical diameter can be represented as [8]:

$$d_{crit} = d_{St=S*} = \sqrt{\frac{9\mu\left(1.2 + 1/12\ln\left(1+\mathrm{Re}\right)\right)}{\alpha\rho_d D_d^{\beta-1}\left(1+\ln\left(1+\mathrm{Re}\right)\right)}}$$

It has been shown ([9],[10]) that the critical diameter is more than several microns in diameter, which means the impaction mechanism does not influence the determination of the minimum collection efficiency diameter (MCED: The diameter at which least amount of aerosol particles are scavenged). This essentially means that it is enough if only the interception and diffusion factors be considered to obtain the MCED.

Relative Humidity (RH) is another factor that affects the collection efficiency [11]; they are inversely proportional. A very high level of RH in a region means that the CE would not be very high.

It is known ([6],[12],[13],[14]) that a change in the water droplet size (from bigger to smaller) can significantly increase the scavenging coefficient. Figure 1 and the paragraph following it, is an excerpt from Shaocai Yu's paper [6], highlighting the effectiveness of reduced water droplet size in aerosol scavenging:

(Note that the ~0.8μm aerosol particles are the least scavenged ones; fortunately, the haze caused due to forest fires (as opposed to anthropological fires) contains mostly fine particles.)

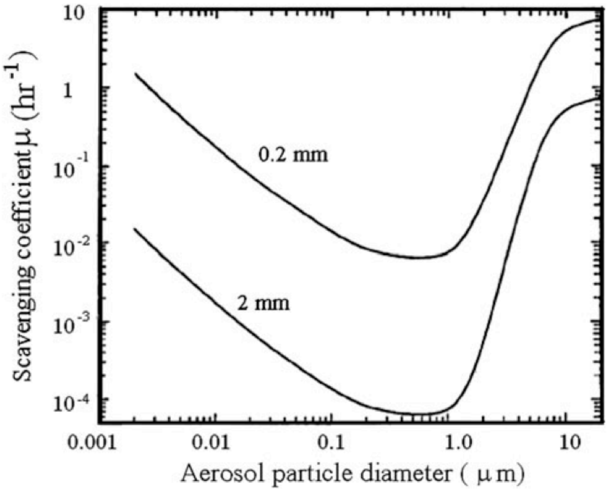

Figure 1 shows the scavenging coefficients (μ) as a function of aerosol particle diameters for two different raindrop diameters (0.2 and 2.0 mm) under the conditions of a simplified scenario: mono-disperse aerosols and raindrops, and precipitation rate of 1 mm hr^{-1} (created by modifying and redrawing figure 20.7 of Seinfeld and Pandis 2006 [4]). The precipitation scavenging coefficients for particle diameter of 1 μm can change by a factor of 100 from ~0.0001 to ~0.01h^{-1} when the raindrop diameter changes from 2 to 0.2 mm.

Droplet diameters' around 150 μm have a terminal velocity of around 0.51816 ms^{-1}, and are susceptible to early evaporation (around 16 seconds), making it counterproductive by unnecessarily increasing the RH. Theoretically, a water droplet diameter of ~189 μm would be an optimum diameter **[**this is because RH is relatively low (~60) during haze time in Singapore (since most of the haze is dry haze as opposed to mist haze, akin to that China faces); Singapore usually has an average RH[iii] of 78%**]**, but since 0.2mm (200 μm) is a tested value, we will be utilizing nozzles that will eject 200 μm water droplets.

Nozzles used will be attached to strategically selected buildings and skyscrapers, from the first floor to the seventh floor, and will be attached in a manner that the water ejected from each nozzle will not overlap, and will aim to cover as much expulsion area as possible, so as to drastically bring down PSI levels. Taking account of drift, the nozzles will be positioned at specific angles in response to measured haze levels and meteorological readings so as to maximize the collection efficiency of the water droplets (since this involves altering the falling velocity of propelled water to an optimum level). The source of water for the system in a building will be the tap water system in place for that particular building.

AUXILIARY SYSTEM FOR HAZE-CONTROL

No proposed method of haze control can be 100% efficient (at least in case of contemporary technology). It is always good to take measures, which ensure mitigation of haze at different levels.

Certain air-filtering plants, determined by the NASA Clean Air Study [15], have the capability to remove toxins from the air (some often found in haze) and make the air much cleaner than before. For this particular mitigation system, two specific plants, the Peace Lily (Spathiphyllum 'Mauna Loa') and the Red-Edged Dracaena (Dracaena Reflexa) have been chosen, based on a certain number of criteria:

1. Air-filtration capability for different chemicals.
2. Cost factor and Availability.
3. Maintenance.
4. Sunlight Requirement.
5. Water Requirement.

Although being quite affordable, quite easy to maintain, having good tolerance to insufficient sunlight[2] and being very good at tolerating infrequent watering, the main reasons as to why these two plants were chosen were due to the different chemicals they could filter out effectively. Both the plants are capable of filtering out Benzene, Formaldehyde, Toluene, Trichloroethylene and Xylene with the Peace Lily capable of removing even Ammonia.

Benzene is another common compound released by volcanic eruptions and forest fires, so introduction of these plants in households, and outdoor terraces/verandahs of skyscrapers (in various floors) can definitely help in further mitigation of haze.

PRECAUTIONS

In any mitigation system, there is a serious necessity to have precautions and/or guidelines which are to be strictly followed, so as to make sure that the system's efficiency is nigh optimum and that the system does not face any inadvertent collapse. Some of the precautions to be followed stringently, include:

1. Care must be taken to keep the water droplets free of dirt/particulate matter. Effective straining/filtering mechanism may be employed to ensure the same. Regular checks of nozzles and filters, in addition to maintenance of quality of

good pipes, which are adequately corrosion resistant, are deterrents to the mentioned problem.

2. The water used in the process is pumped at high velocities, and in huge volumes, hence the entire system is under a lot of pressure. Consequently, the equipment and piping must be robust and leak free. These must also be tested regularly to ensure they meet the desired quality specifications.
3. The nozzles used must be selected in accordance to the task they will perform. Different locations and types of water spraying systems might work under different magnitudes of pressure, hence requiring different types of nozzles. As a result, selecting the right type of nozzle is imperative.

4. The range of the nozzle sprays and the water used must be decided tactically, using statistical studies of the haze affects area and distribution of aerosol particles in the atmosphere. Keeping all three dimensions in mind, areas with maximum concentration of aerosol particles (or highest PSI rating) must be given priority to ensure maximum results in areas that need it most.

5. Appropriate manpower and resource planning is required to produce a timely and effective solution to the problem.

6. Most importantly, the project must be reported and reviewed throughout its implementation, so as to allow the system to grow and improve as its use continues.

CONCLUSION

The solution proposed in this paper is currently based on a theoretical mathematical and logical model of scavenging phenomena. The nozzle system coupled with the auxiliary system can help in short term mitigation of haze, and has the advantage of being an efficient, low risk pseudo-natural process. It can be developed further and taken up as a practical, experimental project with the availability of suitable funds, manpower and information.

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