

## Are sprays an answer to global warming?

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### Abstract

Global climate change is a serious problem for which there may be dire consequences, and to prepare for the worst case scenarios, some are calling for the development of geo-engineering schemes. For example, Salter *et al.* [1] proposed a scheme to inject a fine mist of seawater into stratocumulus clouds. This is intended to increase cloud reflectivity and thereby reduce the solar radiation that reaches the earth's surface. In this article we address the feasibility of the ultrasonic atomizer proposed to create the fine mist. It is shown that the energy required by such a device greatly exceeds the amount available, and many years of research and development are needed before a practical device can be constructed. The article concludes with a brief discussion of effervescent atomization which may be a viable alternative for the near-term construction of a proof of concept.

### Introduction

Improved atomization and spray devices are critical to combating global climate change. For example, enhancing the efficiency of hydrocarbon combustion requires greater control of the fuel distribution via advanced injection. However, despite significant progress in this and other technologies, many climate change experts are concerned that the reduction in greenhouse gas emissions has not advanced fast enough. This has led some to propose environmental engineering (geo-engineering) schemes which could be used if the worst predictions of global climate change become a reality [2]. Here too sprays and atomization play a crucial role.

Salter *et al.* [1] outline a novel scheme to increase the reflectivity of stratocumulus clouds over the oceans. Seawater drops are to be injected into the turbulent boundary layer, after which natural circulation will transport them to the cloud layer. At that point evaporation will have reduced the drops to salt crystals. These crystals will serve as initiation sites which redistribute the moisture already contained in the cloud, thereby reducing the mean particle size and increasing drop concentration. Twomey [3] has shown that increasing drop concentration leads to dramatically increased cloud reflectivity. As a consequence the device proposed by Salter *et al.* [1] could reduce the solar radiation reaching the earth's surface thereby lowering the mean global temperature.

Of course geo-engineering proposals of this nature are controversial and have led to a number of unanswered scientific, ethical, and logistical questions [2]. This article does not attempt to address all of these issues. Rather, only the feasibility of the proposed spray device and issues arising therein are considered.

The current design (Figure 1) proposes a fleet of approximately 1000 ocean vessels to create the spray plume. These vessels are to be autonomous and completely powered by the wind. Consequently, the power available for spray formation is exceedingly limited. Furthermore, the requirements of small drop sizes and high flow rate present exceptional challenges.

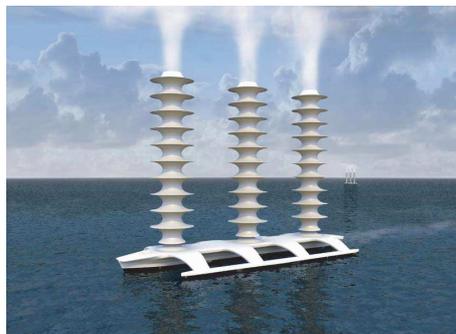


Figure 1. Artist rendition of a geo-engineering spray vessel [1]

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Based on the calculations of Salter *et al.* [1] a global spray rate of between 30 to 70 m<sup>3</sup>/s of 0.8 μm drops would be sufficient to offset the global warming effect of doubling pre-industrial CO<sub>2</sub> levels. Assuming a fleet of 1000 spray vessels and the properties of seawater shown in Table 1 the minimum spray rate per vessel is somewhere around 30 kg/s [1].

**Table 1.** Physical properties of sea water, 3.5% salinity,  $T_0 = 25$  °C [4]

density, $\rho$	1025	kg/m <sup>3</sup>
dynamic viscosity, $\mu$	$9.6 \times 10^{-4}$	Pa·s
surface tension, $\sigma$	0.0728	kg/s <sup>2</sup>

However, the most important parameter determining the success of the proposed device is the increase in drop concentration rather than volume. Therefore, the rate of drop production is most critical. In the original calculations of Salter *et al.* [1] a monodisperse spray was assumed with 0.8 μm diameter drops. At 30 kg/s this results in  $1.1 \times 10^{17}$  drops/s. As shown in Figure 1 each vessel is to contain three spray devices resulting in  $3.6 \times 10^{16}$  drops/s per sprayer.

Practical spray devices produce a range of drop sizes which are most often well above 0.8 μm. Therefore, an estimate is needed on the upper limit of drops sizes which will produce the desired effect. Based on concern for the formation of drizzle, Dr. Salter estimates that drop sizes should be less than 2.5 μm (personal communication).

Finally, as previously mentioned, the power available to produce the desired spray is extremely limited. Currently, only 100 kW (30 kW/nozzle) are reserved for the entire seawater intake, processing, and spraying system [1].

Table 2 summarizes the requirements on the spray device. In addition, the device should be low cost, technically feasible, and provide many months of continuous, maintenance free operation.

**Table 2.** Requirements of spray system

spray rate, $n$	$3.6 \times 10^{16}$	drops/s
drop diameter, $D$	$\leq 2.5$	μm
power consumption, $W_{tot}$	$\leq 30$	kW

Any atomizer that can meet all of these requirements would be a great leap forward in spray technology and would have numerous applications beyond the one considered here. From our initial design work it is clear that meeting the energy requirement will be exceptionally challenging, and the remainder of this presentation focuses on this issue.

### Evaluating energy efficiency

Evaluation of proposed atomizer designs requires consistent analysis techniques. In this section, we discuss the techniques most appropriate for the current problem.

Practical atomizers produce drops whose sizes can be described by a number probability density function,  $f_0(D)$ . Here we are most interested in the total number of drops which fall within the acceptable diameter range given in Table 2. This can be written as:

$$n/Q_l = \int_{D_{\min}}^{D_{\max}} f_0(D) dD \bigg/ \int_{D_{\max}}^{D_{\min}} \frac{\pi}{6} D^3 f_0(D) dD, \quad (1)$$

where  $n$  is the number of drops per unit time,  $Q_l$  is the volumetric flow rate,  $D_{\max}$  is the maximum acceptable drop size, and  $D_{\min}$  is the minimum acceptable drop size.

If all drops fall within the acceptable size range then Eq. (1) becomes:

$$n/Q_l = 6/\pi D_{30}^3 \quad (2)$$

where  $D_{30}$  is the diameter whose volume multiplied by the total number of drops in the spray volume [5].

In [6] Walzel presents a spray energy analysis. There, an efficiency ratio,  $e$ , is defined as the fraction of the total input energy transformed into drop surface energy [6]. This can be written as:

$$e = 6Q_l \sigma / D_{32} W_{tot} \quad (3)$$

In [7] Zimmels considers reversible processes and concludes that a thermodynamic upper limit exists at  $e = 0.6$ .

Here we are interested in minimizing the total energy required to achieve the desired spray rate. This is equivalent to maximizing the total number of drops produced per unit energy,  $n/W_{tot}$ . Combining Eqs. (2) and (3) results in:

$$n/W_{tot} = e/\pi\sigma D_{20}^2, \quad (4)$$

Based on the requirements listed in Table 2 a spray device is sought for which  $n/W_{tot} \geq 1.2 \times 10^{12}$  drops/J. Accomplishing this at the ideal thermodynamic limit ( $e = 0.6$ ) requires  $D_{20} \leq 1.5 \mu\text{m}$ . In reality, practical devices have  $e \ll 0.6$  [6]. Consequently, to satisfy the energy requirement outlined in Table 2, a realistic device must produce drops in the sub-micron range.

Unfortunately, the energy efficiency,  $e$ , is not often reported in the literature. Therefore, an alternative method to estimate  $n/W_{tot}$  is required. Most spray techniques rely on pressurization of a liquid or gas to supply the energy necessary to cause atomization. Here we will assume that this pressurization is done reversibly. For an incompressible liquid, isentropic, reversible pump work is given by:

$$W_l = Q_l \cdot \Delta p_l. \quad (5)$$

Here  $\Delta p_l = p_l - p_0$  where  $p_l$  is the liquid injection pressure and  $p_0$  is the initial pressure, assumed to be atmospheric. Likewise the minimum work needed to pressurize an ideal gas is that given by isothermal compression:

$$W_g = m_g RT_0 \ln(p_g/p_0), \quad (6)$$

where  $m_g$  is the mass flow rate,  $R$  is the gas constant,  $T_0$  is temperature, and  $p_g$  is gas injection pressure. Combining Eqs. (2), (5), and (6) results in:

$$\frac{n}{W_{tot}} = \frac{6}{\pi D_{30}^3} \left[ \frac{1}{\Delta p_l + ALR \cdot \rho_l RT_0 \ln(p_g/p_0)} \right], \quad (7)$$

where  $ALR$  is the air to liquid mass flow ratio.

Of course, it should be noted that spray drop sizes are typically a strong function of operating conditions. Therefore, a condition of maximum efficiency must be found and will depend on the relation between  $D_{30}$  and  $\Delta p_l$ ,  $ALR$ , and  $p_g$ .

### Ultrasonic atomizer proposed by Salter *et al.* [1]

In [6] Walzel calculated the energy efficiency for a number of different atomizers and showed that disintegration of a jet via the capillary instability is the most efficient. For this reason, Salter *et al.* [1] call for the development of a high-flow rate, capillary atomizer consisting of  $6 \times 10^9$  micro-drilled orifices. This is to include ultrasonic excitation at the optimum frequency to achieve a nearly uniform drop size distribution and would be similar to the device discussed in [8] but on a much larger scale.

Here it is assumed that the micro-orifices are sized to achieve a mean final drop size of  $D = 0.8 \mu\text{m}$ . According to Rayleigh's theory the required orifice diameter,  $d$ , can be estimated from  $D = 1.89d$ , giving  $d = 0.4 \mu\text{m}$ . Furthermore, assuming  $D_{30} = 0.8 \mu\text{m}$ , Eq. (2) gives a total required flow rate of  $Q_l = 0.01 \text{ m}^3/\text{s}$  to achieve  $3.6 \times 10^{16}$  drops/s. This results in a mean velocity at the exit of the orifices of  $\bar{u}_l = 13 \text{ m/s}$ .

In [9] Weber uses observations from multiple investigations to create a morphology for the fragmentation of a round liquid jet, and Rayleigh type breakup is shown to occur within a range characterized by the Reynolds number,  $Re$ , and Ohnesorge number,  $Oh$ . For the proposed device  $Re = 5.5$  and  $Oh = 0.18$ , which lies well within the range for Rayleigh breakup [9]. This confirms that the device as proposed by Sauter *et al.* [1] could work as intended. However, a number of concerns must be addressed, the most important of which is the power consumption.

Salter *et al.* [1] plan to etch the  $d = 0.4 \mu\text{m}$  micro-orifices into a  $8 \mu\text{m}$  thick layer of silicon resulting in a nozzle length to diameter ratio of 20. For this ratio and the given  $Re$ , the discharge coefficient can be estimated to be  $C_D \approx 0.1$  where  $m_l = C_D \pi d^2 (2\rho_l \Delta p_l)^{0.5}/4$  and  $m_l$  is the mass flow rate per orifice [10]. Using this, a pressure loss of  $\Delta p_l \approx 9.0 \text{ MPa}$  is expected across the nozzle. This pressure loss may be slightly reduced through shaping of the nozzle passage or reducing the thickness of the silicone layer. However, design freedom is likely to be limited due to issues arising from manufacturability and mechanical strength.

Because of the very small nozzle orifices, special precautions must be taken to avoid clogging. Plastics, which make up 60 to 80% of ocean contaminants, include both large scale matter, which is easily removed by low pressure loss screens, as well as material that is invisible to the naked eye. The latter necessitates filtering to a level significantly smaller than the atomizer orifice diameter. A sample PMC polypropylene filter capable of

removing 98% of particles with sizes under about 0.3  $\mu\text{m}$  requires about 1 bar of pressure drop for 1 kg/s of liquid pumped and assuming a filter that is 1 m long. This is small compared to the orifice pressure drop.

Here it will be assumed that the pump work required to achieve  $\Delta p_l$  dominates over other sources of energy requirements including the ultrasonic excitation and control electronics. With this, Eq. (7) results in  $n/W_{tot} \leq 4.1 \times 10^{11}$  drops/J.

Despite having ignored many sources of energy consumption, the estimated power required is already three times greater than the design goal given in Table 2. It is interesting to note from Eq. (4),  $e \approx 0.06$  which is much less than the ideal energy efficiency of  $e = 0.6$ . This is mostly due to the high viscous losses which occur when the liquid flows through the very fine nozzles.

In addition to the concerns arising from the energy analysis, the proposed design presents a number of other significant challenges. For example, the ultrasonic device would be designed to operate near the optimum frequency for Rayleigh breakup. This is given by  $f = \bar{u}_l / \lambda$  where  $\lambda$  is the most unstable wavelength for capillary breakup given by  $\lambda = 4.5d$  [11]. Therefore, the design proposed by Slater *et al.* [1] requires an ultrasonic device operating at  $f = 7.2$  MHz. However, most current ultrasonic atomizers operate in the kHz range. It is unknown if an industrial scale device could be produced which excites the nozzle mass at frequencies in the MHz range.

Furthermore, assuming the device operates as intended, a linear chain of  $D = 0.8 \mu\text{m}$  droplets would issue into an atmospheric environment at a speed of 13 m/s. Using Stokes drag law and ignoring the effects of entrainment, these droplets would decelerate to 1% of their original velocity in less than 10  $\mu\text{s}$  (and a distance of 26  $\mu\text{m}$ ). Therefore, drop coalescence is a major concern. Avoiding this would require very precise control of the updraft air. Alternatively, each drop could be slightly charged using electrostatic inductance, and repulsion between like charged drops would help to avoid droplet collisions. However, this option would also increase power requirements.

As outlined here, a number of significant challenges exist before the current proposal can be converted into a working design. Whether these challenges can be overcome remains a question for open debate. However, what is certain is that significant research and development are required.

In the mean time, many other questions exist regarding the feasibility of the proposed climate control scheme. To answer these questions in the short term, an alternative spray design is needed.

### Effervescent atomizer

Compared to ultrasonic atomization, effervescent atomization has already been successfully applied to much higher flow rates. Furthermore, the design is simple and rugged.

Figure 2 illustrates the basic operation of an effervescent atomizer [12]. Liquid (seawater) and gas (air) mix inside the atomizer forming a two phase flow. Upon exiting the atomizer the rapidly expanding gas penetrates the liquid ligaments causing breakup into a multitude of fine drops.

In this method of atomization, drop sizes are much smaller than the orifice diameter. Furthermore, according to Savani *et al.* [12] changes in exit orifice diameter have little effect on the final drop sizes. Consequently, a large exit orifice can be used, and nozzle clogging is of significantly less concern. Therefore, the required amount of filtration is greatly reduced.

Sovani *et al.* [12] summarize the extensive research conducted on this topic. A review of that article reveals that the lowest drop sizes produced using the effervescent method were achieved by Satapathy [13] for an application to diesel injection. Figure 4.2 of his thesis shows  $D_{32} = 2.5 \mu\text{m}$  at  $\Delta p_l = 25.4$  MPa and  $ALR = 2\%$ . A non-combustible liquid was used with properties similar to diesel.

Here it is assumed that the atomizer of Satapathy [13] can be scaled to the desired flow rate at the same operating pressure and  $ALR$ . For this approximation, differences in performance due to the different physical properties of seawater and diesel fuel have been ignored. (Due to its higher surface tension actual drop sizes are expected to be slightly higher for water compared to diesel fuel.)

Approximating the drop size distribution as monodisperse ( $D_{30} = 2.5 \mu\text{m}$ ), Eq. (7) predicts a drop production efficiency of  $n/W_{tot} = 3.5 \times 10^{12}$  drops/kJ. This is over 110 times less than the efficiency of the proposed ultrasonic atomizer. Furthermore, assuming  $D_{20} = 2.5 \mu\text{m}$  and using Eq. (4) results in an estimated  $e = 0.005$ .

Clearly the proposed ultrasonic atomizer is advantageous from an energy standpoint. However, as mentioned above, from the standpoint of technology readiness the effervescent atomizer has a distinct advantage. For this reason the effervescent device is currently being studied at Purdue with the goal of creating a prototype atomizer for proof of concept testing. Initial results are reported in a companion article [14].

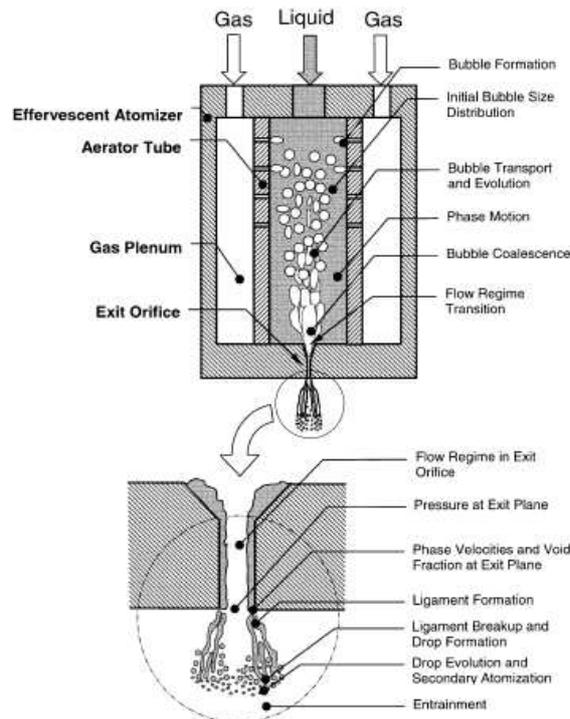


Figure 2. Effervescent atomizer [12]

### Conclusions

Based on the analysis presented here it seems unlikely that any spray device can be created which meets all of the requirements given in Table 2. Certainly the amount of power devoted to the spraying system must be increased before any of the designs presented here are feasible.

If the available power were increased to somewhere between 100 and 200 kW per sprayer, then the ultrasonic method may prove viable. However, the challenges would still be significant.

The large power consumption of the effervescent atomizer makes it poorly suited to the current application when compared to ultrasonic atomization. However, as already mentioned, the design and fabrication of high flow effervescent atomizers is fairly well understood and filtering is not required. Therefore, effervescent atomization could be used for initial testing to determine if the climate control scheme proposed by Salter *et al.* [1] will work as envisioned. At the same time, design and development of ultrasonic atomizers should continue as the best option to create ultrafine atomization with low power consumption.

### Nomenclature

- $ALR$  air to liquid mass flow ratio,  $m_g/m_l$
- $C_D$  nozzle discharge coefficient,  $4m_l/\pi d^2(2\rho_l\Delta p_l)^{1/2}$
- $d$  nozzle diameter [m]
- $D$  drop diameter [m]
- $D_{xy}$  characteristic mean diameter,  $D_{xy} = (\int D^x f_0 dD / \int D^y f_0 dD)^{1/(x-y)}$  [m]
- $e$  efficiency coefficient
- $f$  frequency [Hz]
- $f_0(D)$  drop size probability density function [1/m]
- $m$  mass flow rate [kg/s]
- $n$  drop production rate [drops/s]
- Oh jet Ohnesorge number,  $\mu_l/(\rho_l \sigma d_l)^{1/2}$
- $p$  pressure [Pa]
- $Q$  volumetric flow rate [m<sup>3</sup>/s]
- $R$  gas constant [J/kg·K]
- $Re$  jet Reynolds number,  $\rho_l \bar{u} d / \mu_l$
- $T$  temperature [K]
- $\bar{u}$  mean velocity [m/s]
- $W$  power [kW]

$\Delta p$	pressure drop, $p-p_0$ [Pa]
$\lambda$	wavelength [m]
$\mu$	dynamic viscosity [Pa·s]
$\rho$	density [ $\text{kg/m}^3$ ]
$\sigma$	surface tension [ $\text{kg/s}^2$ ]

## Subscripts

0	atmospheric
g	gas
l	liquid
tot	total

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