High flow-rate ultrasonic seeder for continuous operation

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Abstract

Application of optical techniques to gaseous flows usually requires the previous seeding of the fluid with tracers sufficiently small to follow the flow as accurately as possible, added in suitable concentrations. This work describes the design and manufacture of a seeder based on ultrasonic atomization capable of operating in a continuous way with high atomization rates. It includes a dozen piezoceramic disks that oscillate at 1.65 MHz, generating droplets with SMD in the range of 4-5 μm with rates over 0.6 g/s when operating with water. To test its performance, the device has been used to seed a simple free air jet issuing from a 3.5 cm diameter nozzle with exit velocities of 2.9 m/s, 5.8 m/s and 8.7 m/s. Initially the seeding density is very satisfactory, but if only water is nebulized the droplets evaporate in a short time and the concentration becomes too low when moving downstream. The situation can be greatly improved if a small percentage of glycerol is mixed with the water (here 5% vol has been tested), although the atomization rate strongly decreases when increasing the viscosity.

Introduction

Application of optical techniques to gaseous flows usually requires the previous seeding of the fluid with adequate tracers. To obtain satisfactory results, the tracers have to follow the flow as accurately as possible. Rapid response to fluctuations can be characterized by the Stokes number, St, and is strongly dependent on the marker diameter. Hence, small tracers are desirable, especially for highly varying flows. As compared to solid particles, small droplets are sometimes preferred because they can be generated *in-situ*, avoiding storage and agglomeration problems.

Popular devices for seeding purposes are fog generators, in which small droplets are produced by evaporation and re-condensation of specific fluids, usually glycerol, silicone oil or other mineral oils diluted in water. Liquid absorbed from a deposit is evaporated in a heat exchanger and expands in a nozzle, usually impelled by the pressure built up during vaporization. If an auxiliary propellant gas is not used, this operation principle prevents the device from operating in a continuous manner, because it requires a certain time to evaporate the liquid and allow its pressurization.

Here, an alternative is proposed in which droplets are generated by ultrasonic atomization. Ultrasonic atomization is common in household humidifiers, but the low flow rates of most commercial devices do not satisfy the needs imposed by many gaseous flows. The details of an ultrasonic seeder specifically designed to provide a high flow rate are presented in this work.

Theoretical background

The possibility to generate a cloud of droplets by means of ultrasonic waves was first reported by Wood and Loomis in 1927 [1]. Two different mechanisms have since been invoked to explain the ultrasonic atomization, capillary waves, and cavitation. Scientific publications on the subject can be divided into two groups, with different approaches depending on which one of these mechanisms is considered to be responsible for the spray formation. However, the interaction between them and the limits in which one could predominate over the other depending on the different atomizing situations are still not clear. They appear to depend both on the ultrasonic frequency and on the energy delivered to the fluid, but in most cases, the characteristics of the resulting spray respond to a common pattern.

A standard way to implement ultrasonic atomization consists in depositing the fluid over an ultrasonic transducer that is driven by a periodic signal of a resonant frequency. This process generates a fine mist of droplets that are ejected from the transducer with very low velocity. After many years of ultrasonic atomization experimental studies, it is generally accepted that the spray mean droplet diameter is essentially determined by the oscillation frequency. The oscillation amplitude, dependent on the driving signal voltage, controls the spray

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flow rate, although does not have a major influence on drop diameter. When trying to quantify these phenomena most papers resort to the well known Lang's equation [2] as the only tool to describe the spray characteristics. This formula is expressed as

$$D_{n0.5} = k\left(\frac{8\pi\sigma}{\rho F^2}\right)^{1/3} \tag{1}$$

where $D_{n0.5}$ is the number median particle diameter, σ is the surface tension coefficient, ρ is the liquid density, F is the forcing frequency and k is an empirically determined constant whose value, according to Lang, was reported to be 0.34. In essence, Lang´s contribution was relating droplet diameter with the wavelength of the capillary waves originated by acoustic forcing on a free surface obtained from an instability analysis by Kelvin in 1871 [3] and Rayleigh in 1883 [4]. Evidently, this expression completely ignores any possible contribution of cavitation to the atomization process.

The influence of fluid physical properties has been analyzed in a relative low number of papers, almost always based on experimental considerations [5,6]. The study of possible industrial applications is presented in Topp and Eisenklam [7]. A more complete historical review of the study of ultrasonic atomization can be found in Barreras et al. [8].

Description of the Experiment

In the present experiments atomization has been performed using commercially available ultrasonic transducers as the one shown in Fig. 1. They consist of PZT-4 piezoceramic disks with a diameter of 20 mm, a thickness of 1.3 mm and a resonance frequency measured to be 1.65 MHz. The disks have been excited with a sinusoidal wave coincident with the resonance frequency and variable amplitude. It has to be noted that this type of disks only oscillate with a significant amplitude when the excitation wave coincides with the main resonance peak which is quite narrow and depends on the ceramic type and the disk geometry, and this is the only frequency for which atomization occurs. It is very important to be sure that the disks are operated submerged into the fluid volume, because in this way, the liquid also acts as a cooling medium preventing the disk from overheating. Otherwise, the Curie temperature, defined as the point where the material undergoes a transition from ferromagnetic to paramagnetic, might be reached. In this case, the magnetic moments would become randomly oriented, and the ceramic element would depolarize losing its electrostrictive properties. As the disk heating increases with the applied voltage, the maximum delivered value has been limited to 65 V to avoid damaging the ceramic. Values over 100 V would also risk the integrity of the power transistor in the electronic oscillator circuit. For voltages below 20 V no atomization has been observed. The voltage values describing the operating conditions are specific for disks used in this work. A more generic option would be to give the disk oscillation amplitude, but unfortunately, the displacement could not be measured during real operation. Without water, and applying time-averaged interferometry, the surface vibration amplitude was estimated to be of 0.2 μm for a driving voltage of 20 V and 0.5 μm for a driving voltage of 30 V.

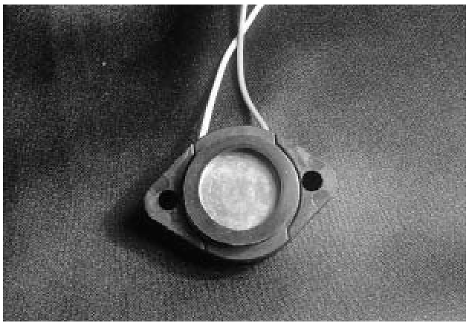

Fig. 1 Image of one of the piezoceramic disks used in the present experiments

Ultrasonic atomization occurs according to the following scheme. The piezoceramic disk submerged 3 or 4 cm below the fluid surface starts vibrating when excited with a 1.65 MHz sinusoidal wave. For voltages below 15 V the only noticeable effect is the appearance of some waves on the liquid surface over the disk. As the voltage is increased, this part of the surface assumes a conical shape, irrespective of the waves, which will be probably due to an acoustic streaming phenomenon [9]. This shape would be indicative of a fundamental vibration mode of the ultrasonic transducer. Occasionally, the tip of the cone detaches, and falls on the liquid pool forming big droplets due to splashing, with diameters around 500 μm, that quickly fall under the action of gravity. At a determinate voltage (slightly over 20 V in the present experiments when operating with pure water), superimposed both to the whole mass displacement that produces the conical shape and the interfacial waves, a fine mist of small droplets is generated particularly in the cone region close to the tip. This process is what can be properly denoted as ultrasonic atomization.

All the steps described above are illustrated in the series of images in Fig. 7, taken from Lozano et al. [10], where water has been used as the atomized fluid. The field of view of each image is 31 mm x 40 mm, with a resolution of 30.3 μm/pixel. Voltages are 20 V, 20.5 V, 23 V, 25 V, 35 V and 40 V. Right over 20 V, detachment of the cone tip and incipient atomization can already be observed. A dense cloud of small droplets is clearly visible for higher voltages. It is interesting to note how the cone elongation increases with voltage. From tests with different water-glycerin mixtures, it has been observed that the minimum voltage required to initiate the atomization increases with viscosity.

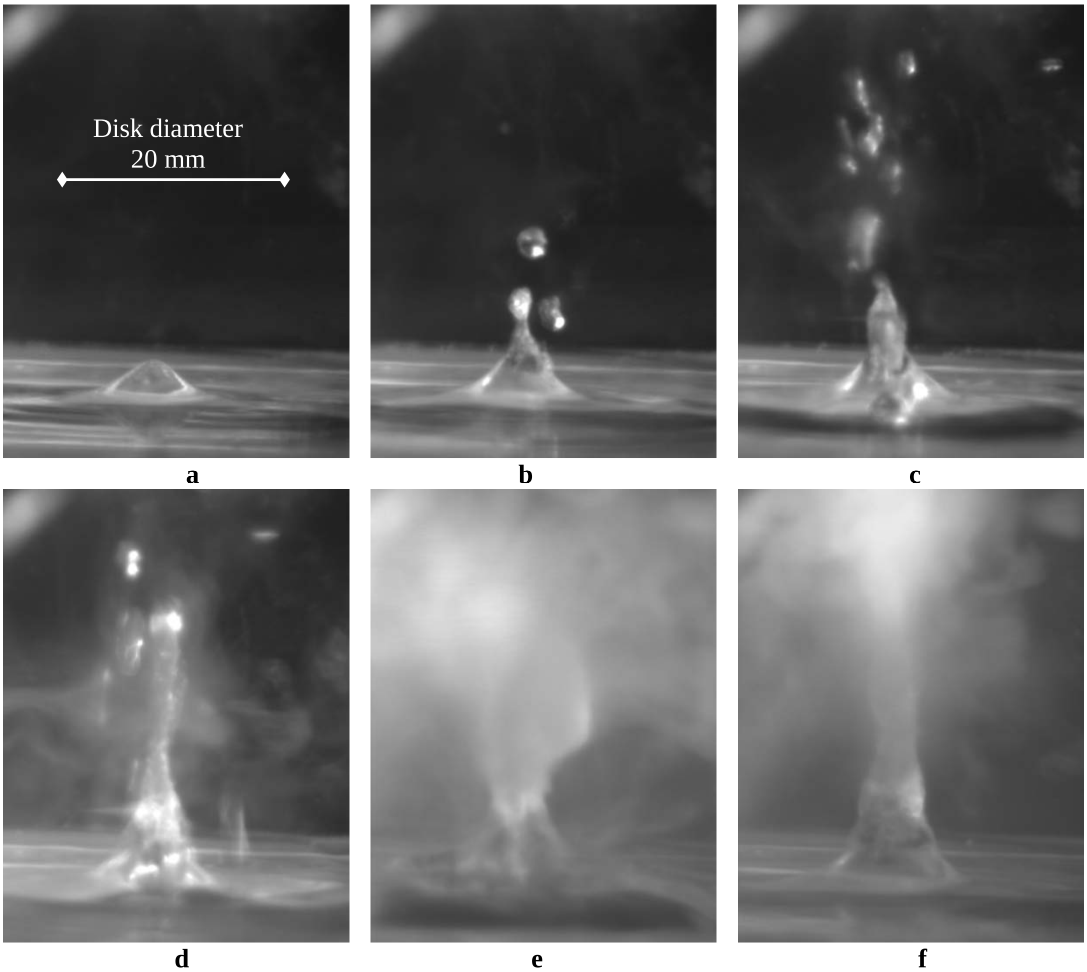

Fig. 2 Evolution of the ultrasonic atomization process for increasing voltages: a) 20 V; b) 20.5 V; c) 23 V; d) 25 V; e) 35 V; f) 40 V. Atomized liquid is water [10].

In general, atomization rate increases as voltage is increased, as measured in previous water experiments [8]. It has also been observed that, apart from a moderate increase in the fraction of big droplets generated by splashing, droplet size distribution remains nearly constant when voltage is raised, corroborating the relative independence between size and forcing amplitude. The plot in Fig. 3 clearly demonstrates that the droplet size distribution is nearly independent of voltage. In all cases there are two peaks at 3.9 μm and 5.3 μm. Visually it can be noticed that for very high voltages, the atomization is more violent, and the formation of big droplets due to splashing of the cone tip on the pool surface increases. The distributions in Fig. 3 can be used to obtain mean diameter values. For example, for a forcing voltage of 50 V, an SMD of 4.6 µm is calculated, while a mean median diameter of 2.8 µm is obtained, in a remarkably good agreement with the prediction of Lang's formula (2.97 µm for 25ºC). To examine the response of these particles to flow fluctuations, a Stokes Drag Coefficient C_D will be assumed

$$C_D = \frac{24\mu}{\rho_f D_p (U_p - U_f)} \tag{2}$$

where D is diameter, U velocity , the subscript p stands for particle and f for flow, respectively. With C_D so defined, the droplets will follow the flow up to frequencies defined by

$$f = \frac{18}{D_p^2} \frac{\nu}{\rho_p / \rho_f} \tag{3}$$

which for water droplets in air at 25ºC yields a value of 16 kHz. Smaller droplets can only be obtained using disks with higher oscillation frequencies

If such small droplets are going to be used for seeding purposes, evaporation becomes an important issue, especially if they are introduced in a fast gaseous flow. To increase the residence time of the droplets, it is convenient to use different atomization liquids instead of water. Adding a certain amount of glycerol to the water can help solving this limitation, but the change in viscosity modifies the atomization conditions. It has been measured [10] that droplet size distribution is relatively independent of viscosity. However, the atomization rate rapidly decreases if viscosity is increased. This dependence is shown in Fig. 4, for experiments atomizing mixtures of glycerol and water with a single piezoceramic disk [10].

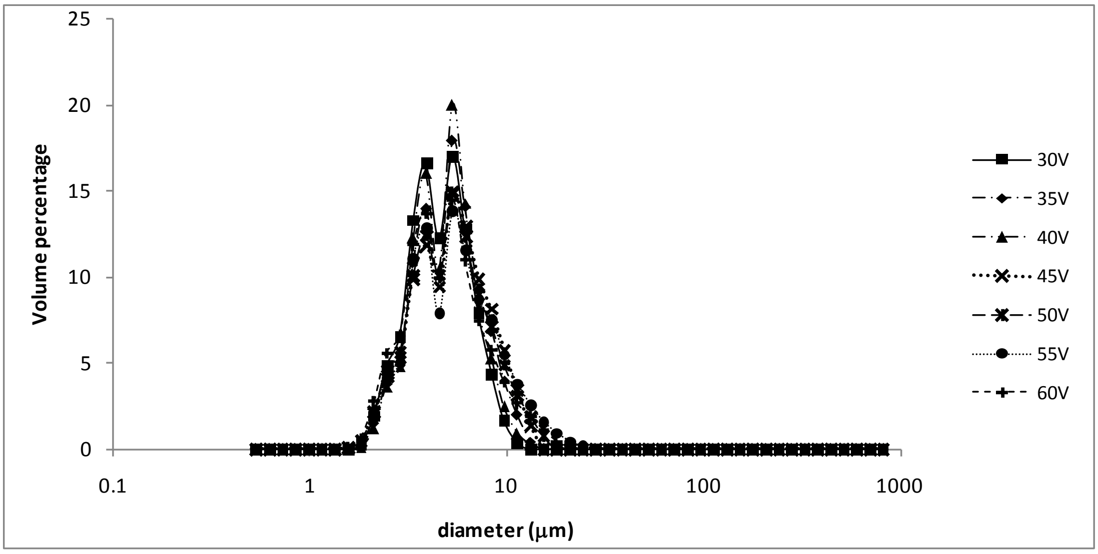

Fig. 3 Variation of the droplet size distribution with voltage for water atomization [10]

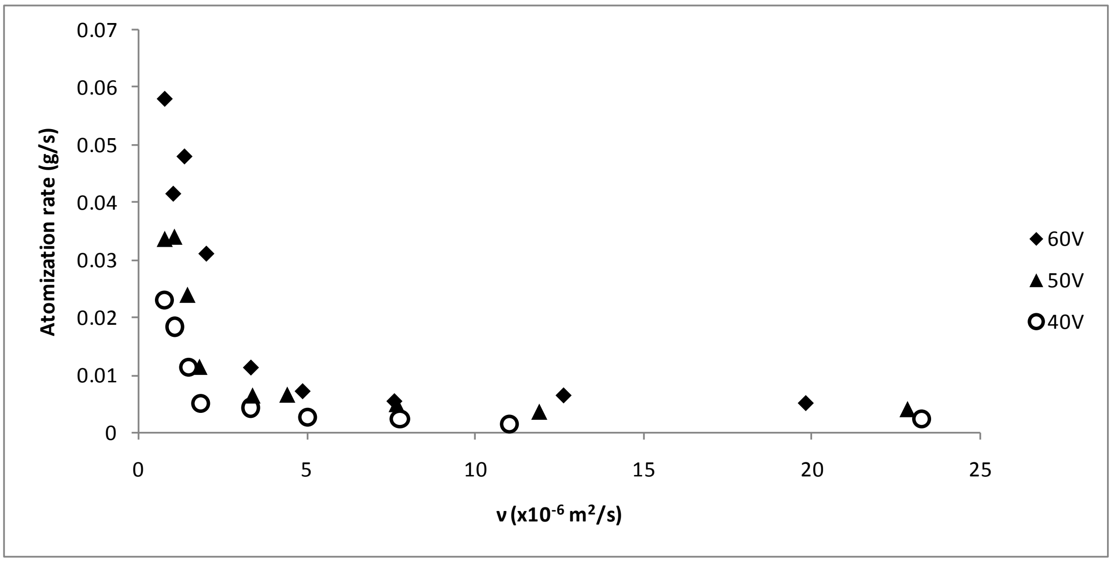

Fig. 4 Atomization rate as a function of kinematic viscosity, ν for a single disk [10]

For pure water atomization, the flow rate obtained for a forcing voltage of 50 V was 0.034 g/s. These values are excessively low when seeding in high flow rate experiments. To circumvent this limitation, an ultrasonic seeder has been designed and manufactured capable of generating a higher droplet flow rate.

The basic idea consists in incorporating to the device a number of piezoceramic disks and a large reservoir to enable continuous operation for a long time. The present prototype includes 12 disks and a 10 l container. The twelve resonators are excited by individual oscillators connected to a common power supply that can give a maximum of 80 V. The system has a float switch that disconnects the power if the fluid level decreases below a determined minimum so that the disks never operate without being immersed in liquid. Without this cooling effect they could get damaged instantly. Finally, the system has been designed to maintain a fixed liquid level over the disk surfaces, in a similar way as a bird drinking fountain. The liquid is stored in a tank with an airtight cover, which connects in its lower part with the container where the disks are placed. A tube comes out of the cover, and its end is submerged in the liquid film over the disks. The distance between this end and the disks surface determines the height of the fluid over them. A sketch of the device and an image of the complete prototype, including the power control unit, are presented in Fig. 5. The two valves on the seeder cover are to refill the tank while venting the air in it. A thermocouple has been included to monitor the liquid temperature. The two bigger holes on the top and side are to continuously circulate gas to drag the droplets out of the device, as they are generated with a very low velocity (typically below 10 cm/s). The dragging gas flow has to be regulated to efficiently extract the droplets without perturbing the flow that is to be seeded.

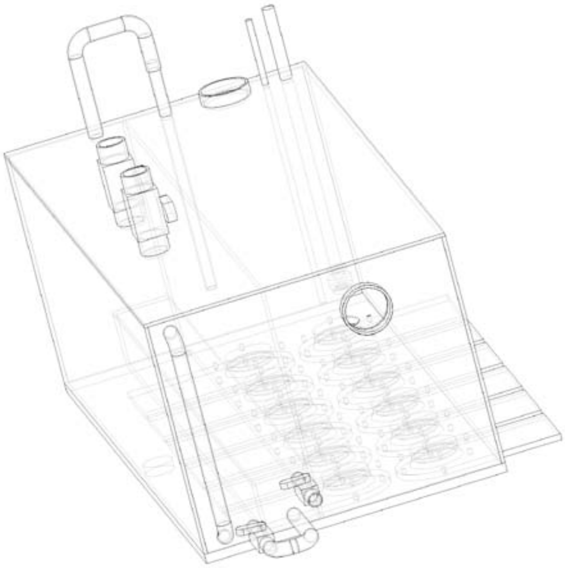

Fig. 5 Sketch of the seeder and image of the complete device including the power control unit.

Results and Discussion

Once completed the operative prototype, several tests have been performed. First, the droplet flow rate for water atomization has been measured as a function of the voltage applied to the disks. In order to extract the droplets, a 30 m^3/h air flow was circulated through the seeder. The measured atomization rates are shown in Fig. 6. The results are in good agreement with the measurements obtained for a single disk. It can be observed that atomization rates over 0.6 g/s can be achieved, and it is expected that higher values could be obtained increasing the number of disks.

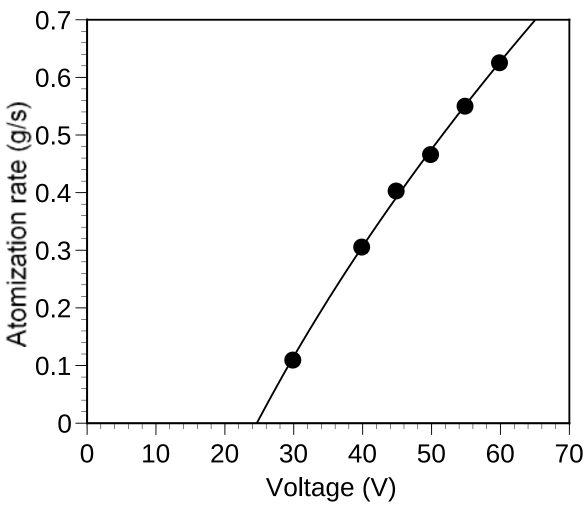

Fig. 6 Water atomization rate of the 12 disk device as a function of voltage.

Another issue that has been analyzed relates to the height of the liquid level over the piezoceramic disks to obtain the maximum atomization rates. According to some reports [11] there is an optimum depth to maximize the atomization efficiency that for the type of disks in the present experiments is indicated to be 40 mm. Trying to validate this assessment, measurements have been obtained for different water depths, at an excitation voltage of 40 V. Unfortunately, the results, that are presented in Fig. 7, are not conclusive. It seems that going over 30 mm worsens the efficiency but it is not clear if there is a maximum. Values below 20 mm were not attainable, because the float switch was disconnecting the power supply below this minimum level. In any case, it has to be considered that the liquid depth was measured from the nebulizer floor were the disks were attached, but they were receded 5 mm from the mount, and the floor width is 8 mm, so the measured maximum atomization rate might actually be obtained for a total liquid depth of ~40 mm.

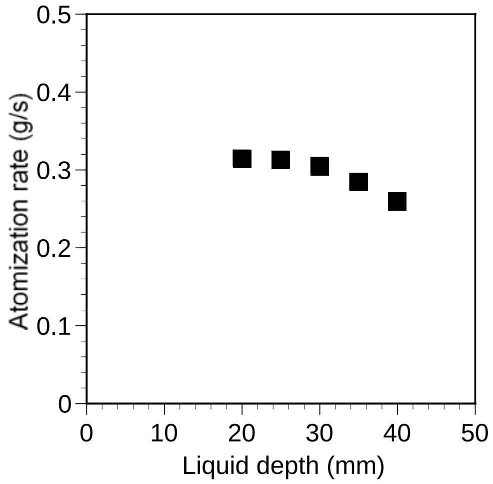

Fig. 8 Atomization rate as a function of the liquid depth over the disks

As a test, the droplets generated by the ultrasonic seeder have been introduced in a simple free air jet. The disks have been operated with voltages ranging from 30 V to 55 V. The jet was issuing from a 35 mm diameter tube with exit velocities of 2.9 m/s, 5.8 m/s and 8.7 m/s, corresponding to Re numbers of 6322, 12622 and 18944 respectively. It has been attempted to mix with the air the total amount of droplets produced by the seeder, and thus, the droplet density is higher for the slower flows.

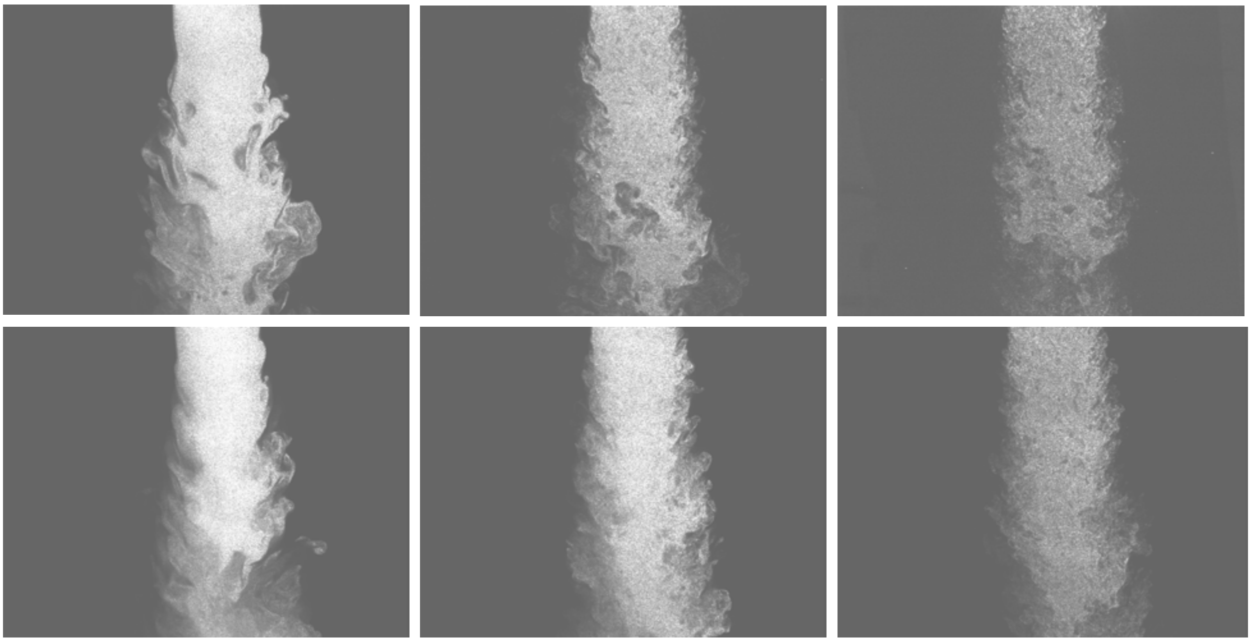

Fig. 8 Images of the air jet seeded with droplets. Upper row for an excitation voltage of 30 V, and lower for 55 V. From left to right, air velocities of 2.8 m/s, 5.8 m/s and 8.7 m/s. Image intensities have been rescaled as explained in the text.

Images have been obtained illuminating the flow with a 532 nm, 120 mJ laser sheet along a diametrical plane, and recording the scattered light with a 1344 x 1024 pixel CCD camera with a magnification of 130 μm/pixel. Figure 8 shows some of the images. The ones in the upper row correspond to a voltage of 30 V and, from left to right, increasing air velocities. The forcing voltage for the ones in the lower row was 55 V. All the images are represented with the same linear grey scale, but in order to see them more clearly, the images corresponding to the 30 V voltage have been multiplied by a 4.5 factor with respect to their 55 V counterparts, and the images corresponding to air speeds of 5.8 m/s and 8.7 m/s have been multiplied by 2 and 4 respectively compared to those obtained for 2.8 m/s.

At distances close to the jet exit, droplet evaporation is not a serious problem. However, the situation changes when images are taken farther downstream. To illustrate this point, images have also been acquired at 20 cm from the nozzle. At this position the concentration of water droplets is quite low, especially far from the jet axis. However, adding a small amount of glycerol (5% volume) the persistence of the droplets is notoriously increased. Figure 9 shows the difference. The image on the left corresponds to water atomization with a voltage of 30 V and an air velocity of 8.7 m/s. The image on the right is for the water-glycerol mixture for the same operating conditions. To fill the printer dynamic range, the image on the left has been multiplied by a factor of 2. The same idea can be reflected from average images. The line profile of the average of 200 instant shots at a distance of 20 cm from the nozzle when atomizing only water and the 5% vol glycerol-water mixture is represented in Fig. 10. The difference is evident. Increasing the percentage of glycerol, the evaporation rate decreases, but so does the atomization rate (see Fig. 4), hence a balance has to be found to obtain the best results.

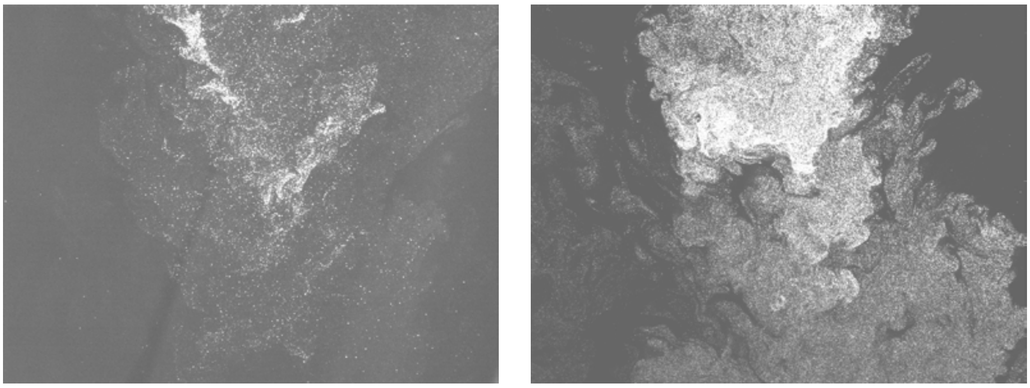

Fig. 9 Images of the air jet at 20 cm from the nozzle seeded with water droplets (left) and a 5% vol glycerol-water mixture. Left image has been multipled by a factor of 2.

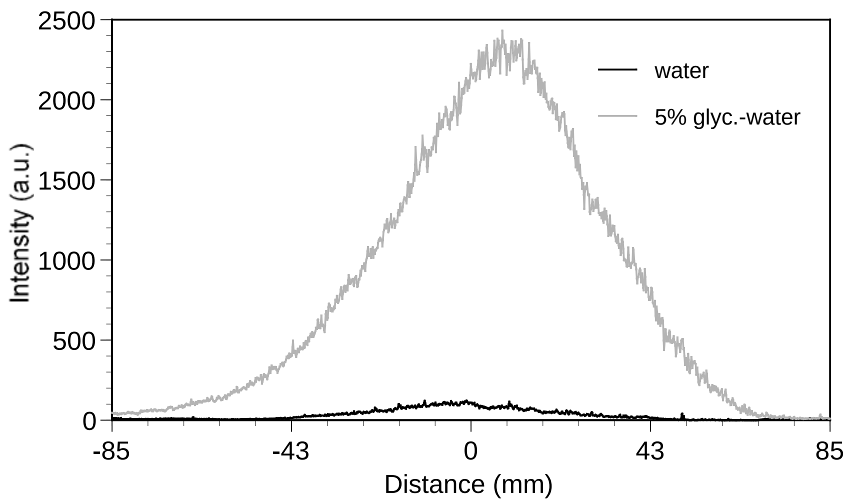

Fig. 10 Line profile of the average of 200 instant shots at a distance of 20 cm from the nozzle when atomizing water and a 5% vol glycerol-water mixture.

Summary and Conclusions

The design and manufacture of a seeder based on ultrasonic atomization capable of delivering a high rate of droplets has been described. The device integrates a dozen piezoceramic disks that oscillate at 1.65 MHz, with excitation voltages up o 60 V. These ultrasonic transducers generate droplets in the range of 4-5 μm SMD, adequate to be used as tracers in gaseous flows with fluctuation frequencies below 16 kHz. As expected, the atomization rate increases with increasing voltage, but a maximum value should not be exceeded to avoid damaging the disks or the power transistor in the oscillator circuits.

The rapid evaporation of water droplets of these small diameters can be a problem especially if they are added to a fast moving flow. Addition of a small percentage of other liquids, for example glycerol can notoriously alleviate the problem, as has been demonstrated nebulizing a 5% vol. glycerol-water mixture. However, it has to be considered that the atomization rate drops dramatically as viscosity is increased.

Acknowledgements

This work has been partially funded by the Secretariat of State for Research of the Spanish Ministry of Science and Innovation under project ENE2008-03137.

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