Generation and droplets size distribution of propylene glycol/water dissolution used as tracer particle for PIV measurements in air

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ABSTRACT

This work proposes a simple alternative to current designs of liquid seeding generators into air, usually used in Particle Image Velocimetry (PIV), or other tracer particles based optical measurements. Air is injected inside a propylene glycol – water mixture through 0.5 mm discharging orifices bubbling in the solution. This fluid presents the advantage of being food-grade and harmless to health, according to literature. In addition, the characteristic time of evaporation of the residues is in the order of hours, so that lesser concern about cleaning or protecting delicate devices subjected to settling is needed, compared with other fluids like oil. Droplet size distribution at the outlet of the seeding generator is performed by means of a laser diffraction analyzer Malvern Spraytech®. Measurements reveal narrow-band, single distribution micrometric droplet sizes, suitable for seeding highly turbulent air flows. The study shows that the volumetric concentration of the tracer particles in the generated aerosol is almost independent on feeding air pressure, thus allowing to easily control the seeding density.

1. Introduction

In the last decades, Particle Image Velocimetry (PIV) has grown as a relevant and mature tool for globally measuring velocity in flows of industrial interest or to check prototypes suitability. Meanwhile, its ability to capture instantaneous snapshots of a certain flow field and its spatial resolution capability has wrought this measurement technique and its derivatives (e.g. Stereo-PIV, dual plane PIV, tomo-PIV, high resolution PIV, among others) into an appropriate instrument for testing the validity and accuracy of Computational Fluid Dynamics (CFD) numerical models.

Nevertheless, as many other optical measurement techniques, PIV is based on measuring the displacement of tracers spread in the flow under study, so that generation and control of particle tracer is of paramount importance in its application. As flow tracers, particles need to be light and small enough to fairly follow the flow field in order to reduce measurement errors. Various
studies summarize the behavior and motion of discrete particles embedded in a turbulent flow, offering considerations on tracer particles and seeding for PIV measurement in gases or liquids (e.g. Hjemfelt and Mockros, 1996; Melling, 1997). The size specifications for suitable tracer particles for PIV, particularly with respect to their flow tracking capability, are discussed in Melling, 1997. For air flows, the adequate particle size is in the order of the micrometer. With emphasis on gas flows, the latter reference reviews some methods of generating seeding particles and introducing the particles into the flow.

Solid particles generally present the advantage of withstanding high temperatures (e.g. TiO₂, Al₂O₃) thus being suitable for hot reacting flows such as combustion. They present the drawback of being hygroscopic materials. Thus they need dry air (or even N₂) for aerosol generation because of their tendency of agglomeration in presence of humidity.

For close-to-ambient temperatures, liquid droplets are more suitable for seeding the flow as their density is generally smaller than solid particles, thus following better the flow for the same size. In order to overcome the droplet evaporation in air, low vapor pressure liquids are generally used, such as vegetal oils. Kähler et. al, 2002 offers an ample review of different methods for generating almost mono-disperse distributions of micrometric droplets of vegetal oil. Most of them, more or less sophisticated, consist in injecting air through cylindrical orifice nozzles into the liquid contained into a vessel. Liquid droplets are teared from the bulk liquid downstream the exit of the nozzle. They are trapped inside large air bubbles migrating toward the free surface. The air bubbles filled with droplets then burst, eventually generating more droplets, and deliver the particles to the air above the liquid. The remaining kinetic energy of the air jets, after droplets generation and bubbles burst, maintain turbulence, eventually breaking the largest droplets into smaller ones and producing collisions. The main stream then exits the vessel in order to supply seeded air. Large particles settle, thus reincorporate to the bulk liquid. For the proposed geometry, this study reveals that the particle size distribution depends on the supplied air pressure and, to a lesser extent, on the distance between the nozzle and the free surface.

In addition to the low vapor pressure, another reason to find in the literature vegetal oils for liquid droplet tracers is that this material is not intrinsically harmful to health and preclude the experimentalist to breath toxic substances if exposed to the seeded air. Nevertheless, vegetal oils present the drawback of being sticky, which makes cleaning necessary after sedimentation. This turns to be especially difficult for computers and delicate devices, including optics. Solid surfaces of the model are spoiled when the seeded air flows around it. Moreover, especially when mixed with ambient dust, the oil can generate obstruction or even plug some experimental
devices, like honeycombs, grids and other devices commonly involved in flow seeding and conditioning.

In this work, a mixture of propylene glycol and water is investigated as a substitute to the widely used vegetal oils as liquid droplet tracers. In a concentration around 50% of propylene glycol (PG) in weight, the impregnating solution film tends to evaporate in the order of hours, so that lesser concern about cleaning or protecting fragile devices is needed. In addition, PG is in compliance with specifications for USP (United States Pharmacopeia), EP (European Pharmacopeia) and the FCC (Food Chemical Codex). The international regulations about PG USP/EP offers among the highest purity and most consistent quality available – with a specified purity of 99.8% or greater, making it food-grade or suitable as an excipient for pharmaceutical preparations. According to the referred sources, there are no known significant effects or critical hazards if inhaled, so it can be breathed as an aerosol, being harmless to health. Actually, solutions of propylene glycol, sometimes mixed with 10-15% glycerin, are often used as working fluid for fog emulation by mean of smoke generators (e.g. discotheques, theatrical representations ...). Finally, its price is reasonably accessible.

Section 2 of this paper describes the specific seeding generator design used in this work. Its layout is simple, aiming at being generic. The device can deliver a seeded flow amount suitable for being diluted in air flows up to ~0.1–0.2 kg/s. Some details are also given concerning the experimental technique used for particle size distribution measurements. Optical properties of the solution are also given in this section.

Section 3 presents the results on the particle size distribution varying feeding air pressure and the distance between nozzles and the free surface.

Finally, Section 4 offers a discussion about the suitability of the current design and the conclusions of this work.

2. Experimental set-up

2.1. Liquid droplets generator

A vertical stainless steel cylindrical vessel of 285 mm diameter and ~700 mm height can contain up to about 40 liters of solution. Figure 1 shows the general layout and dimensions of the particle generator. In the lower part it is closed by a welded hemisphere provided with a drain. In the upper part, a 13 mm thick plate forms a circular cover, which is fixed to the vessel by six
bolts. The sealing between the vessel and this cover is guaranteed by an O-ring. The cover plate is perforated allowing four 10 mm inner diameter tubes to penetrate into the liquid and ensure air supply. The submerged sections of the tubes are ended by a cap of 1 mm thickness walls, drilled with 4 clean holes of 0.5 mm diameter radially oriented. The choice of such a simple nozzle for liquid droplets generation is due to the fact that more complex arrangements, like the Laskin nozzle (Laskin, 1948) or suction nozzle with impactor ring (Kähler et. al., 2002), did not perform much better than the reference nozzle described above in terms of particle size distribution. This study also shows that high concentrations of particles with a narrow band size distribution and a mean diameter in the order of 1 !m can be achieved by means of these multi-hole nozzles under over-critical supply pressure conditions (>1 bar gauge) issuing from 4 nozzles per tube. Ø 0.5 mm drilled holes seemed a good compromise over the tested conditions.

In the present study, each air-feeding tube can be enabled or disabled individually by a quarter-turn valve for selecting seeding amount. At the center of the cover plate the air seeded with liquid droplets exits through a pipe (32 mm inner diameter). The exit pipe is also connected to the air supply in order to enable some air supply by-pass, if needed. The vessel cover is provided with a security valve to limit the inner pressure. A vertical transparent tube is connected to the vessel in order to check the liquid level inside it. Incidentally, this also allows to measure the distance between nozzles and the free surface. Fig. 1 depicts the detailed layout of the seeding generator design.

A pressure regulator allows to specify the vessel working pressure between ambient pressure up to 6 bar gauge. Upstream the regulator, the installation is provided with a filter so that compressor oil – that could interact with propylene glycol – is removed, as well as possible liquid water, although air supply is dry down to –20 ºC dew point. All the submerged parts of the generator are made of stainless steel in order to avoid corrosion, while most of the pneumatic connections are made of brass.

It is worth to point out that the dimensions of the present seeding generator are relatively large. Actually, the current design allows to properly seed up to approximately 0.1 kg/s of air. The phenomena involved suggest that the only relevant parameters are the nozzle dimensions and their distance to the free surface. Only a secondary effect can be expected for different distances to the walls where the nozzle jets may impinge, as the generated particles are small enough to effectively follow the flow.
2.2. Particle sizer

A flexible tube is plugged at the exit of the seeding generator toward the measuring device. Droplet size distribution at the outlet of the flexible tube is performed by means of a laser diffraction analyzer, Malvern Spraytech®. The analyzer emits a collimated laser beam (He-Ne) which is scattered by the liquid droplets seeding the air. A receiver, placed in front of the emitter, collects the beam plus the scattered light on a linear (log-spaced) detector array. Based on either Fraunhofer/Mie scattering theory and Beer-Lambert law, both particle size distribution and volumetric concentration, $C_v$, are obtained. The analyzer also incorporates a multiple scattering correction algorithm (Harvill and Holve, 1997) enabling measurement in high volumetric concentration condition or large path length integration, avoiding large measurement bias toward smaller particle sizes. With the current hardware and settings, the measurement dynamic range is $0.1 - 2,000 \ \mu m$, covering the region of interest of tracer particles in air flows.

The measured particle size distribution mainly depends on two variables: i) the scattered light pattern registered by the light sensor array; and ii) the complex refractive index $n_D$ of the liquid (accounting both for refraction and absorption). In this work, absorption is considered as
negligible for transparent liquid particles of few micrometers or less. The refractive index of the solution is obtained from the data of MacBeth and Thompson, 1951, as a function of the PG weight concentration of the solution, $y_{PG}$, and then has been fitted with a third order polynomial, as shown in Figure 2. The seeding particle characterization is performed very close to the particle generator outlet, where the mixing with ambient air does not start to evaporate the liquid water of the solution.

![Figure 2](image.png)

**Figure 2:** Real part of the refractive index of the propylene glycol – water solution as a function the weight concentration $y_{PG}$.

At $T = 25$ °C.

For PIV seeding applications it is convenient that the droplets do not evaporate too quickly. For that, test have been carried out at PG weight concentration fixed either at $y_{PG} = 60$ % or $y_{PG} = 100$ %. Under these conditions, the solution refractive index are $n_{D,60} = 1.398$ and $n_{D,100} = 1.432 \pm 0.1$ % at 25°C. Slight variations of the refractive index of the aqueous PG solution should be expected, so the measurements of particle size distribution were performed close to this temperature. Due to operating conditions or water evaporation the refractive index may experience variations. It has been checked that these variations do not significantly affect the measured particle size distributions values.

A volume of 5 l was carefully prepared so that the nozzles were at a depth $h = 60$ mm. For the case $y_{PG} = 100$ %, an additional depth has been tested in order to check its possible effect on
the droplet size distribution, $h = 200$ mm. The by-pass duct has been maintained closed during all the measurements.

3. Particle size distributions

The analyzer laser beam is located normal to the flow direction, at the outlet of a 32 mm inner diameter straight tube, with 2 m downstream length from the seeding generator own outlet. The seeded flow is discharging in ambient quiescent air. Fig. 1Fig. 3 shows both the droplet size distribution (log-scale) and the cumulative distribution, varying the feeding pressure from 1 to 4 bar gauge and for different values of the mass concentration of the solution.

![Figure 3](image)

Fig. 3: Droplet size volume distribution varying $y_{PG} = \{0.6 , 1\}$ and feeding pressure $P = \{1, 2, 4\}$ barg. $h = 6$ cm. Left: pdf distribution ; Right: cumulative distribution

For pure propylene glycol ($y_{PG} = 1$), particle size distribution is almost log-normal, presenting peaks between 1.5 and 2 $\mu m$, depending on the feeding pressure (dashed lines in Fig. 3). Actually, as feeding pressure increases, the distribution is shifted toward smaller diameters. For 4 bar gauge feeding pressure, 90% of the droplet volumetric fraction ($D_{90}$) is below 2 $\mu m$ ($\sim$ 2.4 and 2.8 $\mu m$ for 2 and 4 bar gauge, respectively).

For the 60 % solution ($y_{PG} = 0.6$), the trend is very similar as aforementioned, presenting almost the same peaks location. Nevertheless, the distributions are wider for the less concentrated propylene glycol solution. $D_{90}$ is significantly larger: $\sim$2.4, 2.8 and 3.2 $\mu m$ for (4, 2, and 1 barg feeding pressure, respectively).
In contrast with Fig. 3, Fig. 4 shows the influence of the depth $h$ of the feeding orifices below the liquid free surface and for pure propylene glycol. Two depths have been tested in this work: $h = 60 \text{ mm}$ and $h = 200 \text{ mm}$. The diameters peaks are almost at the same locations, regardless to the depth, depending mostly on the feeding gauge pressure. Nevertheless, the distributions for $h = 60 \text{ mm}$ are clearly narrower, thus presenting a smaller $D_{90}$ (less than 2.8 $\mu$m in all cases).
Fig. 5 summarizes all the tested cases in this study. Right vertical axes of the figure represent the Sauter mean diameter (open symbols), $D_{32}$, determined as follow from the volumetric particle size distribution:

$$D_{32} = \frac{\sum_{n=1}^{N} x_n D_n^3}{\sum_{n=1}^{N} x_n D_n^2}$$

(1)

Being $x_n$ the particle number fraction associated to a diameter $D_n$, and $N$ the total number of bin $n$ of the discrete histogram distribution.

This particular choice of mean diameter has been preferred to the arithmetic mean, as $D_n^3$ (volume) is related to inertial forces and $D_n^2$ (surface) to drag forces as well as scattering. The $D_{32}$ combination is usually referenced in seeding characterization in term of its capacity to follow the flow.

The trend of the measurement reported on Fig. 5 clearly indicates that $D_{32}$ decreases with feeding pressure. Smaller depths of discharging orifices seem advisable as it slightly reduces $D_{32}$. Moreover, this tendency is stronger as feeding pressure increases. 60% propylene glycol concentration seems to yield significantly smaller particles, especially for high feeding pressures.

In addition to $D_{32}$, the volumetric concentration, $C_v$, is also obtained from the measurement through the Beer-Lambert law of light extinction. For pure propylene glycol, and above 2 barg feeding pressure, $C_v$ is almost constant, although it slightly decreases. In turn, for the 60% dissolution, the volumetric concentration of particles is about half of the one with 100% concentration. If laser power is enough for particle image acquisition in PIV, and given that the number of particles is not significantly reduced, smaller volumetric concentrations at smaller mixture contain, is an advantage in terms of total propylene-glycol consumption and emission.

4. Conclusions

This work proposes a simple alternative to current designs of droplet seeding generators into air, usually used in Particle Image Velocimetry (PIV), focusing on delivering seeded air for main air flows up to 0.1 kg/s under normal ambient conditions. Droplet size distribution at the outlet of the seeding generator is performed by means of a laser diffraction analyzer Malvern Spraytech®. Measurements reveal narrow-band, single distribution micrometric droplet sizes, suitable for seeding highly turbulent air flows. Two propylene glycol–water mixtures have
been tested at different gauge feeding pressures, revealing that droplet sizes decreases significantly with increasing supply pressure.

Less concentrated propylene glycol solutions present smaller Sauter mean diameter, although distributions are wider and $D_{50}$ generally larger. For 6 barg feeding pressure and 60% weight concentration of propylene glycol, sub-micrometric Sauter mean diameter have been achieved.

The influence of the discharging orifices depths does not seem very relevant in terms of mean particle diameter, although it tends to widen the distribution.

The study also shows that the volumetric concentration of the tracer particles in the generated aerosol is almost independent on feeding air pressure, thus allowing to easily control the seeding density.

Future work can be directed on the effect of the orifice diameter and number, trying to increase the throughput.

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