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Measurements of velocity and droplet sizing in industrial applications using non-invasive laser systems

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Abstract. Many industrial applications involve the measurements of the velocity and size for the design of the products. Examples of such products are kitchen ventilator, water pump, household appliances and industrial oriented nozzles for fire suppression and paint. In the area of industrial safety, validation of the face mask for leakage is also an important aspect of the mask design. Fire suppression, paint nozzle, and mask filter are items which we encounter and rely on in our daily life. The design of products of those items to provide the best and optimal outcome is a critical aspect of the research and development in many industries. This paper covers two laser based techniques, Phase Doppler Particle Analyzer (PDPA) and Particle Image Velocimetry (PIV), for the design of fire suppression nozzles, paint nozzles, and N95 filter mask. The results of velocity profiles and droplet size distributions provided the critical information to evaluate the design and to allow corrections of deficiency in the process. Both the PDPA and PIV are non-invasive laser based techniques which introduce no disturbance to the flow and particle fields to be measured, giving the true representation of the measurement results.

1. Introduction

The characteristics associated with droplet formation are of importance to many nozzle manufacturers. Sprays are applied in numerous circumstances, from internal combustion engines, paint application, fire suppression, and a multitude of other applications. Spray performance has significant impacts on daily life. As such, there has been a continual evolution in analytical tools and methods which evaluate spray attributes. A very comprehensive analysis of the various spray diagnostics given by [1] discussed the capabilities and deficiencies of those diagnostic techniques. The surveyed techniques included (1) Imaging systems, (2) Particle Imaging Velocimetry, (3) Phase Doppler Interferometry, and (4) Optical Patternators. It was concluded that a combination of results from those diagnostics techniques, complimented with numerical models, were all necessary to achieve the goal of completely understanding the spray.

The first technique applied to the spray was the Phase Doppler Particle Analysis (PDPA) system which offered highly accurate and well resolved simultaneous size and velocity droplet measurements. PDPA is an interferometric laser diagnostic technique that provides insight into several important spray properties, including drop size and velocity, number-density, flux, time-of-arrival statistics, and gas-phase velocity. Figure 1 shows the schematic diagram of a PDPA system. Crossed laser beams and slit aperture define a cylindrical measurement volume (typically 10s to 100s of microns in each dimension) with obliquely-angled ends. Within this measurement volume the crossing laser beams interact and generate an interference "fringe" pattern. Drops passing through this volume scatter light which is collected by an off-axis receiver. Scattered fringe spacing and frequency dependent on drop size and velocity and is measured by three detection regions in the receiver. An additional validation of drop size is provided by the measuring the intensity of the scattered light.

Many product design in the area of range hood ventilator, household appliance, water pump requires the validation of the flow output, hence an imaging based technique is ideal for such flow measurement because of its ability to provide a global flow field, giving the complete picture of the behavior of the product. Particle Image Velocimetry (PIV) is one of the most well established techniques to obtain instantaneous velocity related measurements and related properties of the fluids. In general the fluid flow (either air or liquid) is seeded with tracer particles that are very small and are faithfully follow the fluid flow. These tracers are typically illuminated by a planar, short duration high powered lightsheet, generated by a dual pulsed laser source. Each light pulse scatters off of the tracers and collected on either a CCD or CMOS camera. The scattered light, registered as intensity in the pixels of these cameras, identifies particle locations at each time instant. The measured particle displacement (either individual or specially averaged) of the resulting image pairs and time separating the laser pulses determine speed and direction of the velocity field of the flow being studied. The schematic diagram of a PIV system arrangement can be seen in Figure 2a while the principle of the velocity measurement is illustrated in Figure 2b. More information on the technique can be found in the following references [2, 3].

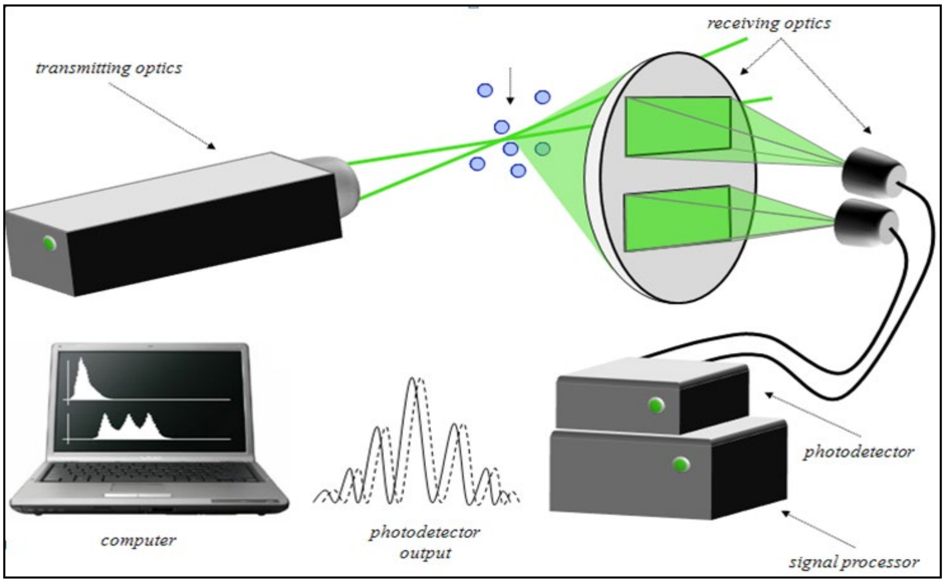

Figure 1. Schematic diagram of PDPA system arrangement

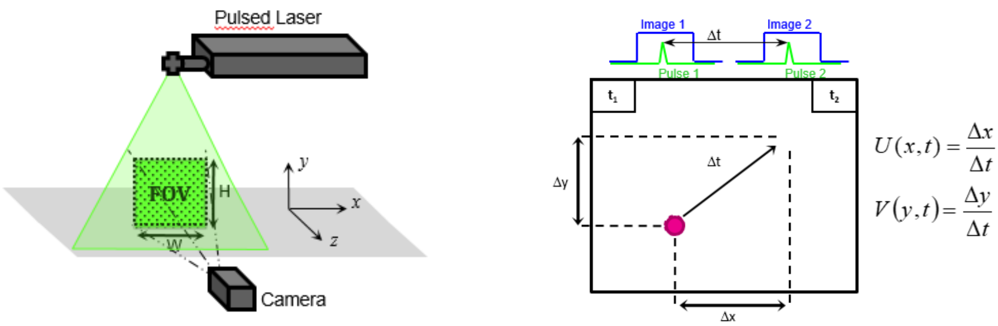

Figure 2. (a) Schematic of PIV system arrangement (left); (b) principle of velocity measurement (right)

The application of the PIV to spray analysis is straight-forward since there is no need to apply tracer particles to follow the flow. The typical droplet diameters found in sprays that are in the range of few to hundreds for microns act as particles and the scattered light is used to extract information about the spray velocity.

2. Simultaneous droplet size and velocity measurements

Simultaneous droplet size and velocity measurement is a critical factor for industrial to design the appropriate nozzles. Two types of applications, fire suppression and paint dispersion nozzles, are illustrated in this paper with the PDPA and PIV techniques.

2.1. Evaluation of Fire suppression nozzles

Characteristization of nozzle for fire suppression is critical to the effectiveness of the results. Not only that the amount of droplets has to be very high, the droplet size and velocity exiting the nozzle is also important. If the droplet size is too small, the droplet may have evaporated before it reaches to the high temperature environment (fire in this case). On the other hand, when the droplet is too large, it may never reach to the location because of the larger mass.

The PDPA system was used to characterize the output of a particular nozzle design as shown in Figure 3a and with results given in Figure 3b. As seen in the figure, the concentration of droplets was very high and with large divergence of the spray, allowing the droplet to cover a large area. These are all desirable characteristics for fire suppression nozzle. The velocity at the exit of the nozzle was measured to be about 8.5m/s which was considered to be sufficient to provide the necessary momentum for the droplets to reach to the high temperature environment. More importantly the measurements of the D10 (Mean diameter) and D32 (Sauer Mean Diameter) provided the important information of the droplets. The D10 of 109 µm was considered to be appropriate and the D32 of 132 µm (ratio of the volume and the surface area) was deemed to be very important for this fire suppression application.

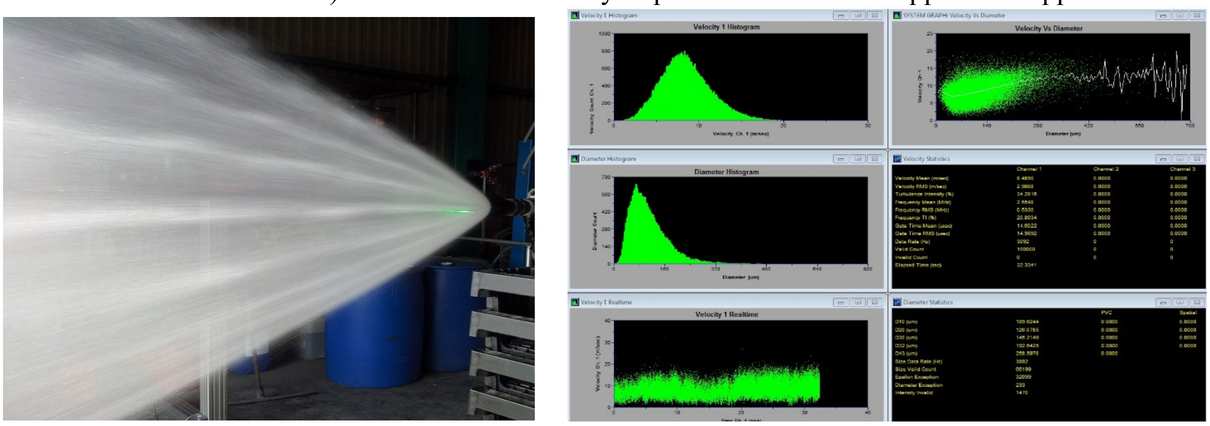

Figure 3. (a) Picture of the fire suppression nozzle (left); (b) Measurement results on velocity and droplet size (right)

Another type of fire suppression nozzle is the type which is installed on a ceiling of a room as shown in Figure 4a. The required characteristics for such nozzle is to provide the appropriate droplet size as well the large coverage area as shown in the figure. Figure 4a shows a test nozzle hung on a ceiling of a test laboratory and the coverage of the droplets downward from the nozzle. For this particular study, a PIV system was used to measure the velocity profile and the diameter of the droplets. Figure 4b provides the schematic diagram of the nozzle, showing the PIV system setup with camera and laser light sheet with respect to the nozzle. It is to be noted that the camera and light sheet optics were mounted on separate traverse mechanism such that different regions of the nozzle could be investigated.

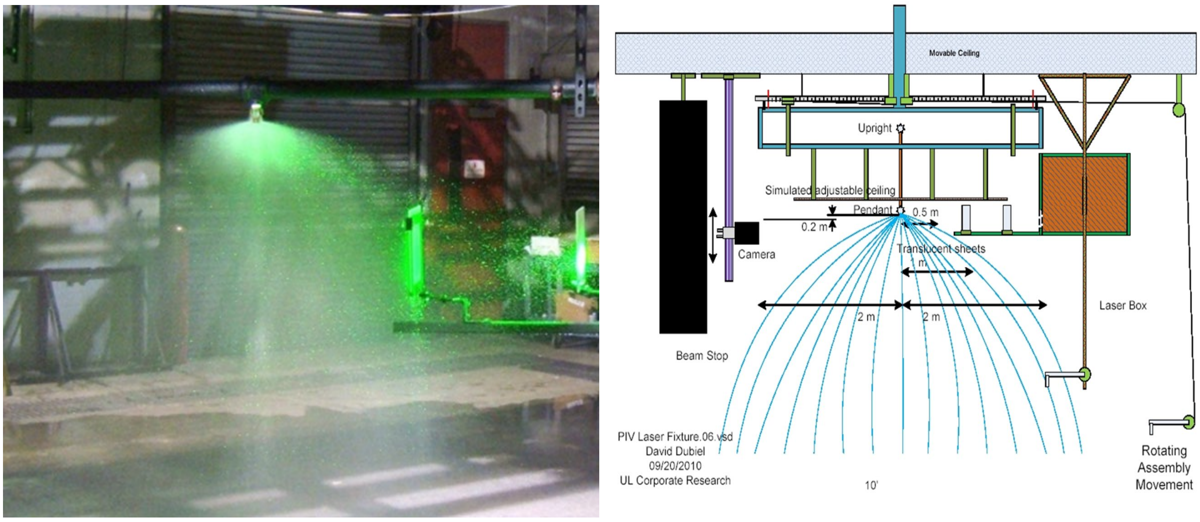

Figure 4. (a) Setup of the ceiling type nozzle (left); (b) Schematic diagram of nozzle and PIV system

Figure 5a provides the result of the velocity distribution from one of the PIV measurements, showing a maximum velocity close to the exit of the nozzle at about 10 m/s. As observed, the majority of the droplets had the maximum momentum when dispersed from the nozzle except the outer edge and the middle portion of the nozzle – referring to the highest amount of droplets exiting at about 45 degrees angle of the nozzle. Figure 5b shows the droplet size distribution with the mean droplet size of about 350 μm. However the important information is the cumulative volume plot showing the 50% of the volume was less than 1490 μm.

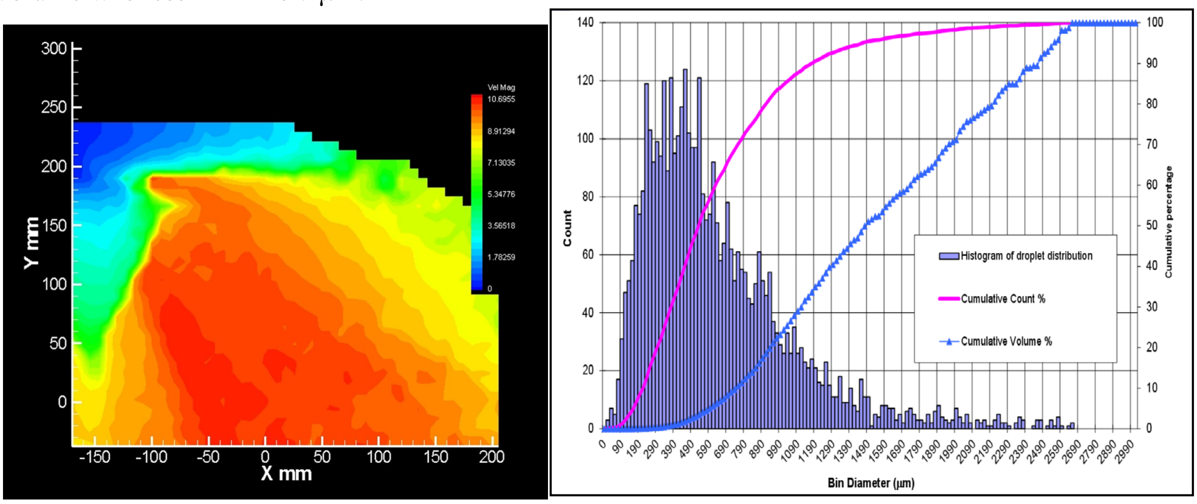

Figure 5. (a) Velocity distribution (left); (b) Droplet size distribution with cumulative volume (right)

2.2. Characterization of paint spray nozzles

For paint manufacturers, it is important to obtain the right paint chemical mixture and to test with different nozzles to get the best coating performance. The main task is to characterize the various behavior of different paint coatings: Clearcoats, Colors and metallic, emitting from various types of nozzles. The requirements for the characterization are (a) flux based giving the amount of paint per unit area and (b) the ability to measure forward/backward moving particles. The bounce-back and overspray were important to understand the transfer efficiency of the spray nozzle delivering the paint pigments. In addition the ability to measure all velocity range, from near zero to more than 30 m/s range. The ability to operate on paint with significant pigment presented, meaning the droplets could be opaque (non-transparent) is also important. Since it is necessary to quantify the nozzle design with different paint chemicals, the repeatability of the technique giving the same result is important.

PDPA system was used as the technique to characterize the paint spray as described above. The system setup in two different arrangements is given in Figure 6a and 6b. Both setup used the Powersight laser module with a separate Receiving probe for the velocity and sizing measurement. The setup in Figure 6a was used to evaluate the velocity and size for different paint pigments for a particular nozzle while the arrangement equipped with a traverse mechanism given in Figure 6b was used to measure the distribution of the velocity and size at different location of the nozzles. Measurements were also taken close a surface to understand the "bounce back" of the droplets.

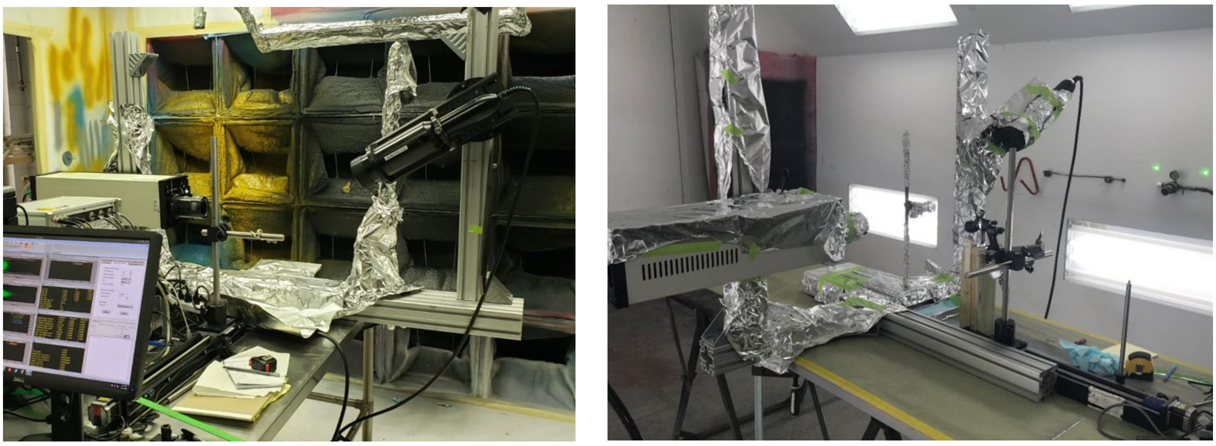

Figure 6. (a) System setup for paint pigment tests (left); (b) system setup for droplet size distribution along nozzle (right)

In the study, a number of spray nozzles were used, together with various types of paint pigments. Figure 7a provides the information of droplet velocity at different locations of the nozzle for a number of nozzles (total of 7 nozzle types). The purpose was to investigate the dynamic of the nozzles. The results show that all the nozzles came to a similar settling velocity of about 6m/s at the 12 inch location from the nozzle. Another observation was that the velocity increased with the operating pressure of the nozzle while the droplet size decreased, translating to about 65 to 70% reduction in D_{32} and DV_{50}.

When scan capture was performed on the one particular nozzle from the 12 to 105 mm along the nozzle center axis, the results of diameter, Velocity and concentration distribution are given in Figure 7b. It is shown that good diameter uniformity across swept area with D_{32}, D_{10}, DV_{50} with little variation along the nozzle with lower concentration, velocity, and flux near spray edge. The RMS component of velocity showed higher relative to mean velocity near spray edge.

Results of the droplet size for two paint pigment types, clearcoat and black, are given in Figure 8a and 8b respectively. The figures show the diameter changes along the nozzle axis from a number of nozzles investigated, with the group of graphs at the top showing the D_{32} variation and the bottom group of plots giving the D_{10} distribution. The D_{10} gives very similar behavior while the D_{32} changes differently for the different type of nozzles.

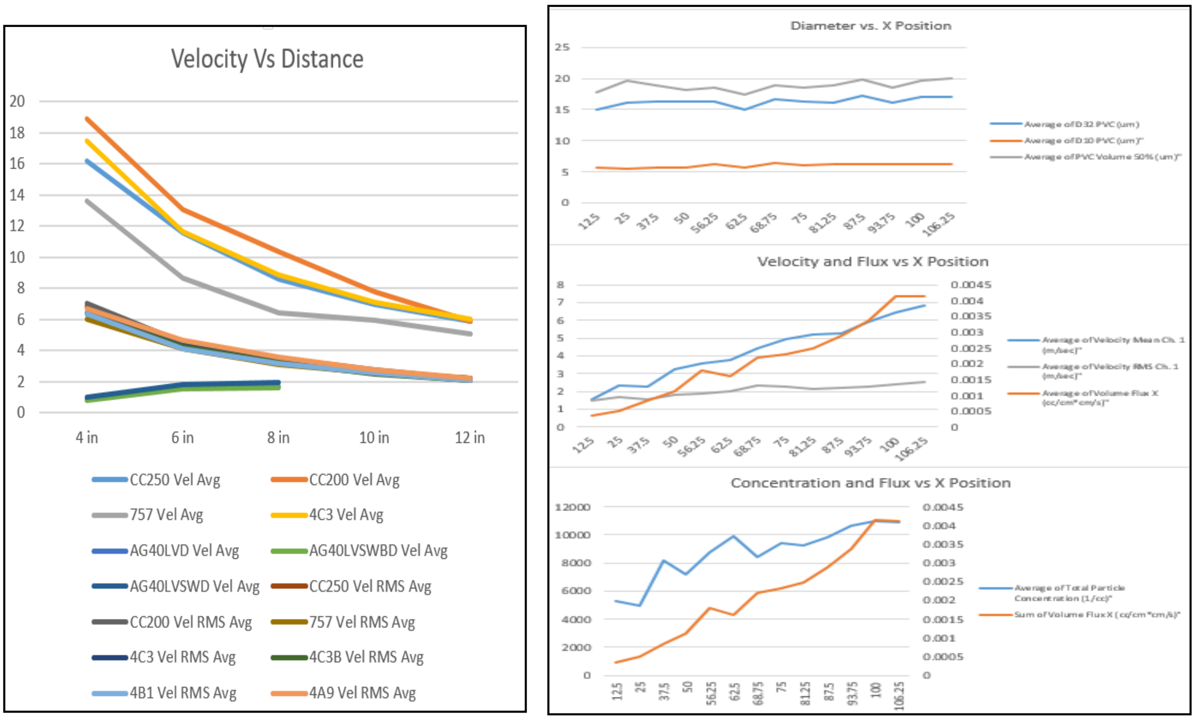

Figure 7. (a) Velocity distribution for 7 different nozzle types; (left); (b) Diameter, velocity and concentration along a nozzle (right)

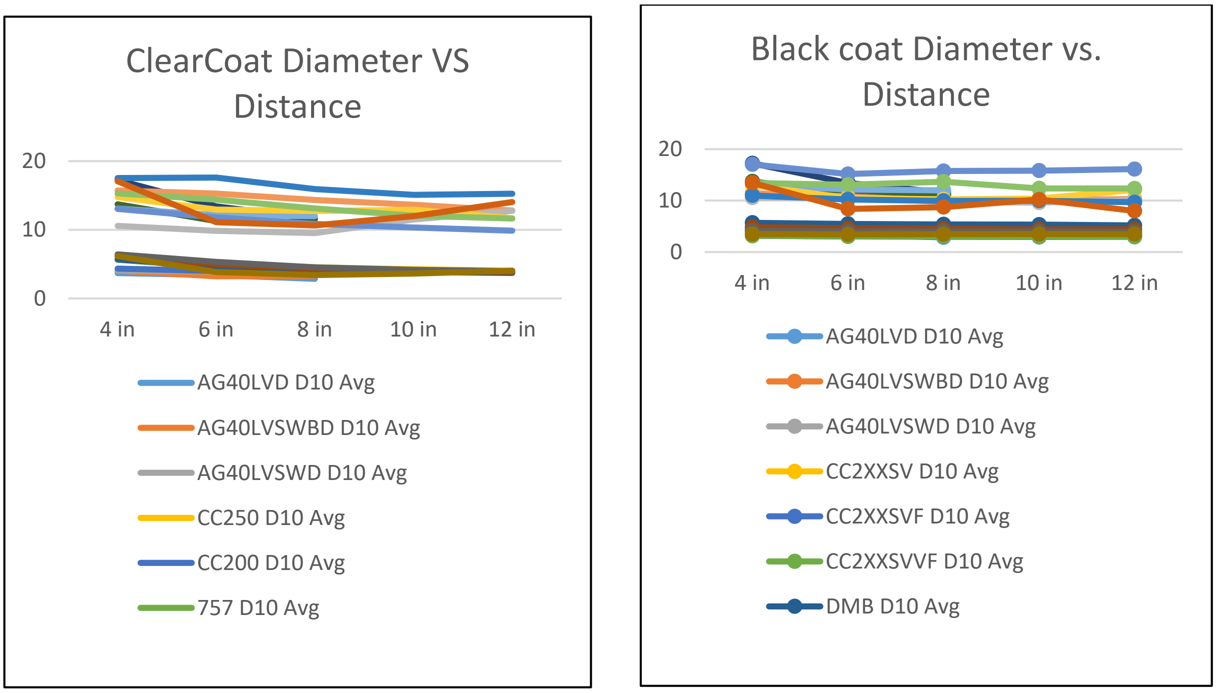

Figure 8. (a) Clearcoat pigment for different nozzle types (left); (b) Black coat pigment for different nozzle types

The various results from the PDPA measurements helped to validate the design of the nozzles for paint applications. Dependent on the requirements, the appropriate type of nozzle can be selected to provide the best performance in terms of paint coating.

2.3. N95 filter testing for leakage investigation

To evaluate the efficiency of N95 face mask, the typical method is to use particle counting technique based on comparative measurement -- Particles concentration inside the mask vs Particle concentration outside the mask. Such measurement tells us whether a leak exists, but not the type – leakage through nose bridge, chin cuff, jaw line, facial hair, etc. Using a Flow visualization diagnostics, such as PIV, could be useful to reveal location of a leak. The manufacturers of face mask can take advantage of such information for the better design of the mask to allow better fitting of the mask.

The PIV system was employed to investigate the flow around the mask to see where the leakage occurred. The experimental setup using PIV is given in Figure 9, showing the laser source, high speed camera and the mannequin. The mannequin can be controlled to provide “inhalation” suction through the mouth.

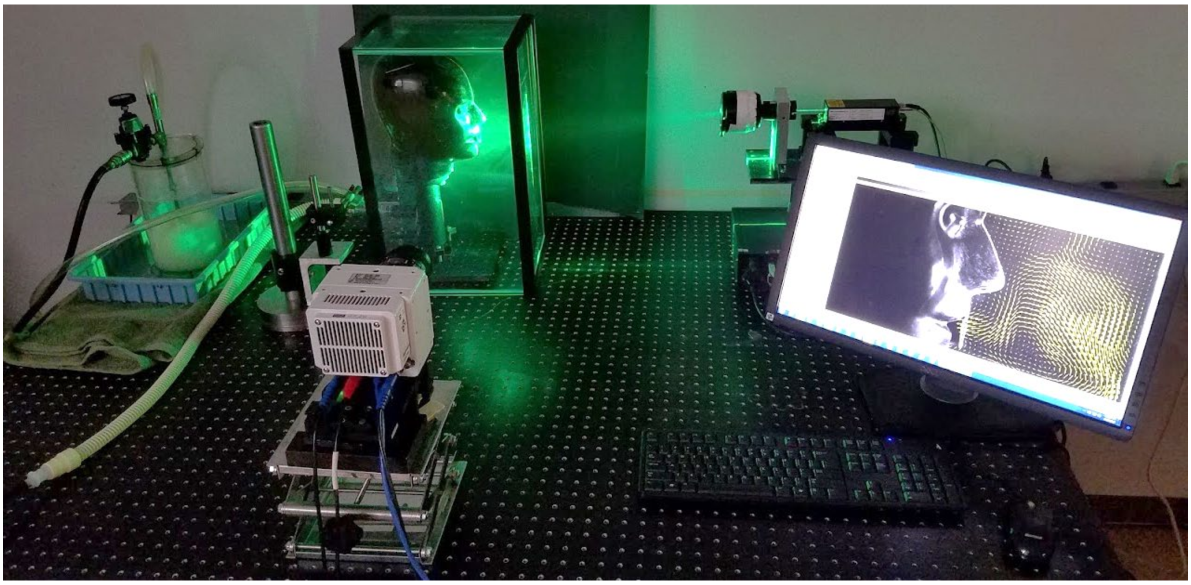

Figure 9. PIV setup for the investigation of leakage through N95 mask

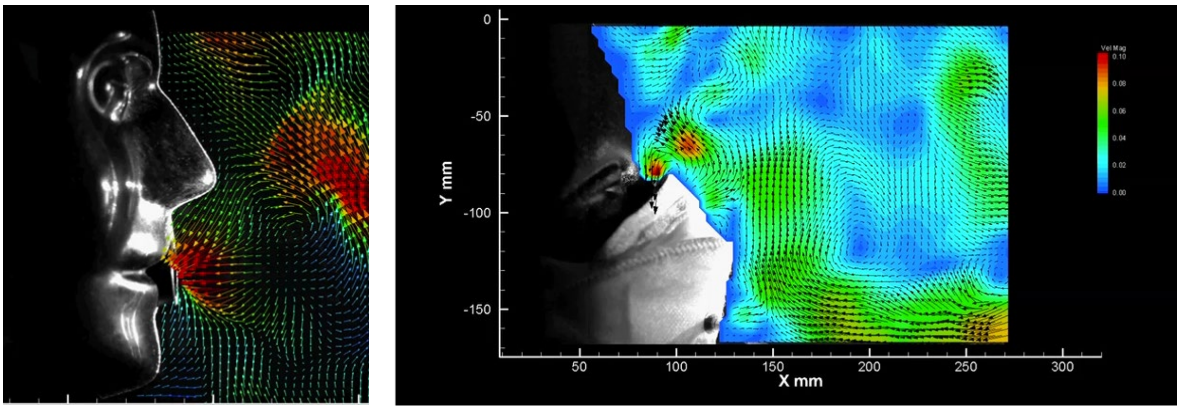

Figure 10. (a) Flow around the mouth region w/o mask (left); (b) flow getting through the nose bridge region with mask (right)

Results of the investigation are given in Figure 10a and 10b, showing the air flow distribution with suction from the mouth without a mask (left) and the air inflow through the nose bridge region when a mask was in place around the mannequin. The PIV system provided important information to the mask manufacturer on how to improve the design for a better fit.

3. Conclusion

A number of industrial products were evaluated using PDPA or PIV system to improve the product design. For fire suppression nozzles, results from PDPA and PIV provided the validation of the design for optimal coverage. In the study of paint nozzles, the PDPA technique was employed to characterize a number of nozzles with various paint pigments. Results gave the validation of the nozzle design for best coating performance. The PIV system was used to evaluate leakage area around a N95 face mask and helped the manufacturer to improve the design for a better fitting to human face.

References

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