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KEY PARAMETERS FOR THE PERFORMANCE OF IMPACTION-PIN NOZZLES USED IN INLET FOGGING OF GAS TURBINE ENGINES

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Abstract

Application of inlet air fogging to gas turbine engines for power augmentation, has become common practice, with more than a 1000 installations worldwide including a large number of advanced gas turbines. In this paper an experimental investigation and empirical analysis of key operating parameters on the performance of impaction pin nozzles will be investigated. To this date no such correlation is available for impaction pin nozzles, which are currently used in about 75% of this type of applications. The correlations are developed from a series of experiments conducted in a wind tunnel equipped with the Malvern Spraytec droplet size measurement system. The conducted analysis covered a wide range of the relevant parameters. Mainly the water flow rate from the nozzle orifice was (0.00126 $l.s^{-1}$ to 0.00063 $l.s^{-1}$: 0.02 gpm to 0.1 gpm), the operating pressure was (34.5 bars to 204.1 bars: 500 psi to 3000 psi), the airflow velocity was (1.5 $m.s^{-1}$ to 15.2 $m.s^{-1}$: 295 fpm to 3000 fpm), the distance between the nozzle orifice and the location of measurement was (0.0127m to 0.508 m: 0.5” to 20”). Other parameters such as the plume spray cone angle and the surrounding ambient psychrometric conditions, which may affect the droplet size for impaction pin nozzles is also discussed.

Introduction and Background

Gas Turbine output is significantly impacted by the temperature of the ambient air, with the power output dropping by 0.54% to 0.90% for every 1 C (1.8°F) rise in ambient temperature. One approach to overcome the loss of gas turbine power output during periods of high ambient temperature (high demand period) is to cool the inlet air. While there are several inlet air cooling technologies available, high pressure inlet fogging has become increasingly popular over the past decade due to its low cost and its effective power augmentation.

A direct evaporation effect is derived by using fog droplets generated by high-pressure pumps and atomizing nozzles installed in the inlet duct downstream of the inlet air filters. The fog evaporates in the inlet duct and cools the air down to the wet bulb temperature.

A review of the basic principles of fogging technology can be found in Chaker and al [1, 2, 3, 4], Meher-Homji and Mee [5, 6], and Bhargava and al [7]. Early papers on fog intercooling and wet compression started to appear in the late 1940s and include Hill [8], and Utamura et al [9].

There are two types of nozzles commonly used in inlet fogging systems: impaction pin nozzles and swirl jet nozzles. In both types, the difference in nozzles’ configurations may lead to differences in the atomization process and consequently in droplet sizes. It is therefore important to provide all details regarding the nozzles under test. This paper studies the behavior of impaction pin nozzles designed and implemented by Mee Industries in various gas turbine inlet fogging applications as shown in Figure 1.

Due to the use of swirl nozzles in some applications such as the atomization of fuel in gas turbine combustors, there are a number of studies characterizing this type of nozzles and summarized by Lefebvre [10]. His work includes a number of empirical formulas regarding the parameters which influence the size of the droplet from this type of nozzles.

Several papers have been published to measure the droplet size from impaction pin nozzles [11,12]. However, to our knowledge, no paper exists in the open literature which provides empirical relations of droplet size as a function of critical parameters affecting it. These equations are very useful in showing the importance of each parameter and gives the users a tool in order to estimate rapidly the droplet size based on the value of the applied experimental parameters. This paper makes a systematic study and analysis of the different parameters that influence the droplet size and provides an empirical correlation between the droplet size and each of these parameters.

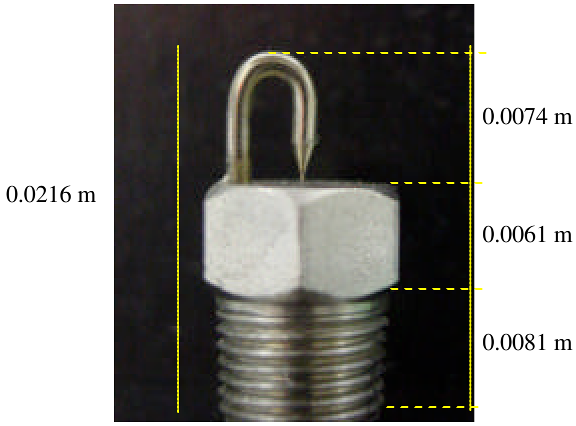

Figure 1, Impaction pin nozzle

Experimental Setup

In order to measure the droplets' size in conditions similar to those found in gas turbine inlet ducts, a variable speed wind tunnel was built, as shown in Figure 2.

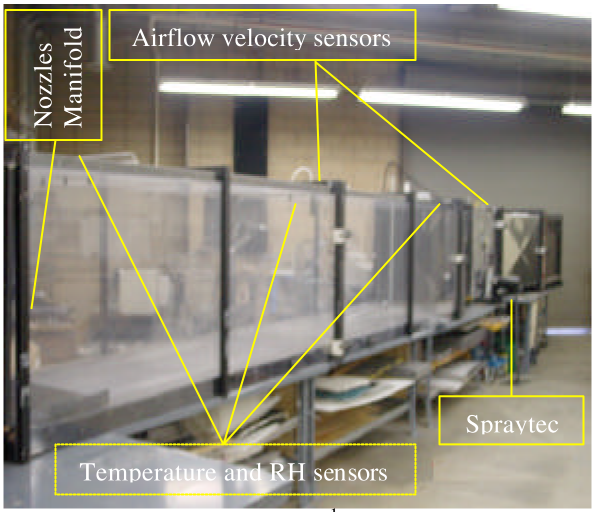

Figure 2, 11 m long 25 m.s^{-1} velocity wind tunnel

A brief description of the wind tunnel is given below and more information regarding its configuration and instrumentation may be found in Chaker [1,3].

Fog is generated in the wind tunnel by forcing high-pressure, filtered and deionized water through the small orifice nozzles. In the experimental setup, a variable-speed-drive, positive-displacement, ceramic-plunger pump is used to generate water pressures up to 207 bars (3000 psi).

The wind tunnel is equipped with a high-speed data acquisition system, which consists of a DAS 1200 board with up to 16 input channels and 2 output channels. Daisy Lab software was used to manage the data acquisition. The DAS 1200 monitors:

Temperature and Relative Humidity of the air in several locations
Air velocities
Water flow

The position of the sensors in the duct is shown in Figure 2 and Figure 3.

Droplet size measurements, at different locations in the spray plume and for different airflow velocities, and operating pressures were done with nozzles located in the constricted section of the duct, where the highest airflow velocities are attainable. Measurements were taken at different locations in the spray plume using a Malvern Spraytec RTS5114 laser particle analyzer, as shown in Figure 3. The Malvern system is based on a laser diffraction technique [13, 14]. This is a spatial sampling system; consequently it allows the sampling of a large number of droplets instantaneously with a frequency up to 2500 Hz.

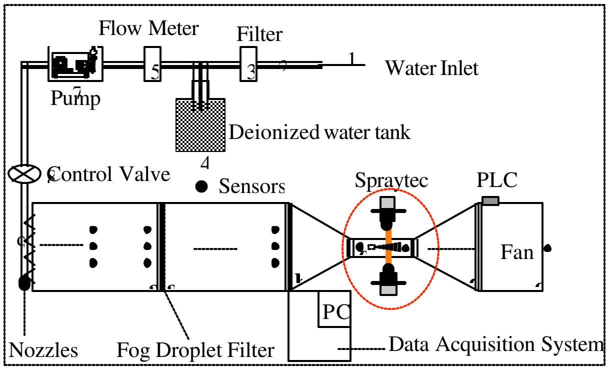

Figure 3, Wind Tunnel experimental setup

A nozzle manifold, installed at the inlet of the duct, was turned off when measurements were taken at ambient conditions. For measurements with a saturated airflow these nozzles were turned on, Figure 4, and a fog droplet filter was used, as shown in Figure 3, to remove any un-evaporated droplets. Droplet size measurement locations is shown in Figure 5.

Figure 4, Fog nozzles manifold

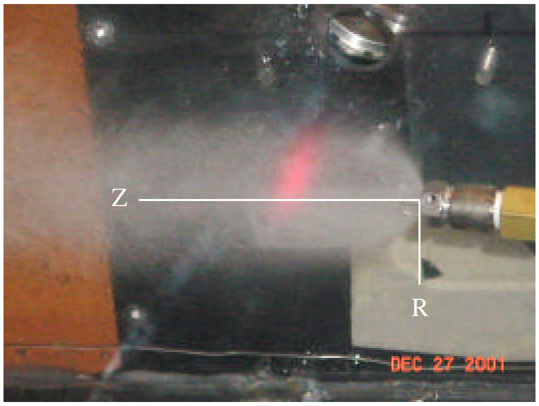

Figure 5, Droplet size measurement in the wind tunnel

Experimental Results

The Spraytec unit outputs a value for Concentration Volume (CV). The results from each measurement position are based on the relative mass flow of water at that particular position and use the concentration volume value as a weighing coefficient. This technique mitigated errors that would have resulted from the fact that droplets in the center of the spray plume tend to be much smaller than droplets at the edges of the plume, while mass flow is much greater at the edges.

The most important variables that affect the water droplet size produced by impaction pin nozzles are: the water supply pressure, the airflow velocity in which the water is atomized, the flow rate of the water from each nozzle, the distance between the measurement position and the nozzle's orifice. Other parameters, namely the plume cone angle and consequently the width of the plume, as well as the ambient psychrometric conditions, have less impact on droplet size. Their influence will be analyzed in later sections.

Two characteristic diameters, employed in the gas turbine inlet air fogging industry, were used to study the droplets size: the first is the Sauter Mean Diameter (SMD) or D_{32} which gives a droplet diameter that represents the ratio of volume to surface area of all the drops in the spray plume and, consequently is important in showing the evaporation rate which occurs at the droplet-air interface. The second is DV90, which is a droplet diameter where 90% of the volume of water in the fog is made up of drops with diameters smaller than or equal to the given diameter. A small DV90 diameter indicates that a very small volume of larger droplets is produced. That minimizes any potential erosion effects on compressor components should these droplets be carried over into the compressor.

Either D_{32} or DV90 may be written as function of the above-cited most important parameters following the equation:

$$Diameter = \kappa \frac{\dot{m}_w D^{\delta}}{\Delta P_w^{\pi} V_a^{\varpi}} \qquad (1)$$

Where k is constant of proportionality, $\dot{m}_w$ is the water flow rate in liter per second, D is the distance between the nozzle orifice and the measurement position (m), ΔP_w is the differential pressure applied on the liquid (bar), and V_a is the airflow velocity (m.s^{-1}). $\propto$, δ, π, and ω are power constants.

1. **Effect of applied pressure:**

Figure 6 shows the effect of the operating pressure on the droplet size for different airflow velocities (from 1.5 m.s^{-1} to 15.2 m.s^{-1}). It shows that as the operating pressure increases droplet size decreases. This decrease is important when the water is under an increasing operating pressure from 34.5 bars to 138 bars (a nozzle is typically operated at 138 bars in gas turbine inlet air fogging), however becomes insignificant when the operating pressure increases from 138 bars to 207 bars.

The variation of DV90 and D_{32} as function of the applied pressure follows the empirical formulas:

$$DV_{90} \propto \Delta P^{-0.16} \qquad (2)$$

$$D_{32} \propto \Delta P^{-0.23} \qquad (3)$$

From Figure 6, we can also see that the droplet size decreases when we increase the airflow velocity. Figure 7 shows this variation at different operating pressures.

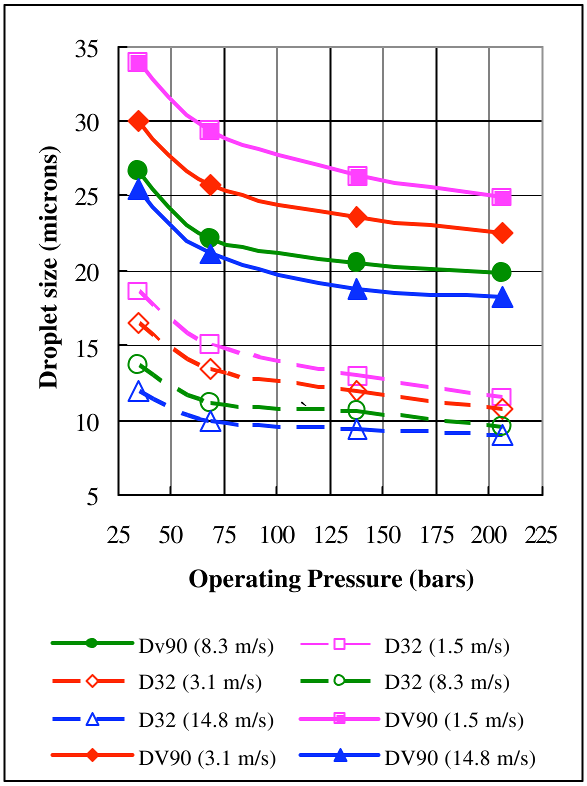

Figure 6, Variation of droplet size as a function of the operating pressure and the location of the measurement in the spray plume. The distance between the nozzle orifice and the measurement position is 0.075 m

2. Effect of airflow velocity:

The airflow velocity was varied from 0.46 m.s^{-1} to 15.24 m.s^{-1}. As can be seen in Figure 7, a decrease in droplet size occurs as the airflow velocity increases. This decrease is important between 0.46 m.s^{-1} and 5 m.s^{-1} which is the typical airflow velocity at the location of nozzle manifolds installed in gas turbine inlet ducts upstream of the silencer. For the other nozzle manifolds position, downstream of the silencer with an airflow velocity varying between 10 m.s^{-1} and 20 m.s^{-1} depending on the gas turbine inlet duct configurations, the decrease in droplet size is much smaller and eventually levels out.

In still air, and close to the nozzle orifice where the density of the droplets is high, a coalescence phenomenon may occur due to the high probability of collision between droplets of different sizes, and therefore different penetration velocities [4].

In high-velocity air streams the coalescence effect is greatly diminished as the airflow acts to separate droplets of different sizes, thus reducing the potential for collision.

Measurements made at ambient conditions, where fast evaporation of smallest droplets occurs, and at saturated air conditions, where no droplet evaporation occurs, exhibit no difference in size increase due to this coalescence phenomenon.

The variation of DV90 and D_{32} as function of airflow velocity follows the empirical formulas:

$$DV_{90} \propto V_a^{-0.14} \qquad (4)$$

$$D_{32} \propto V_a^{-0.11} \qquad (5)$$

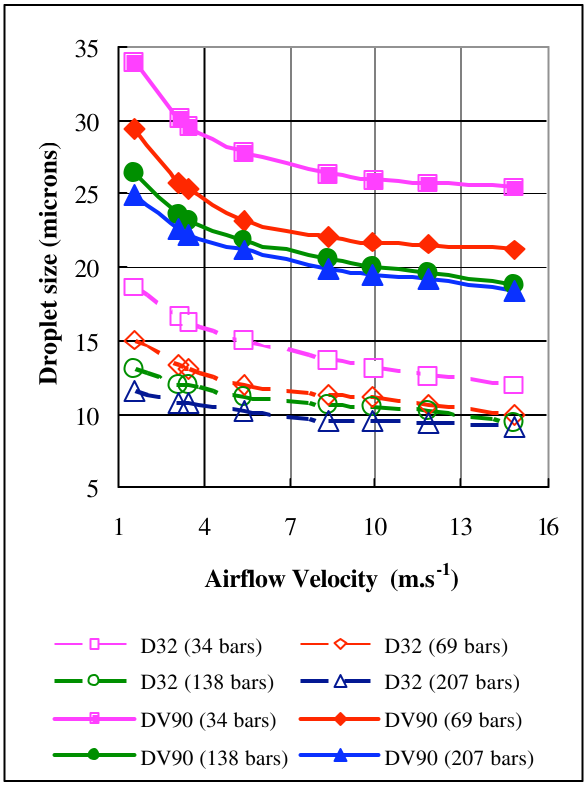

Figure 7, Variation of the droplets size as function of the airflow velocity, at 30°C and 40% RH. The distance between the nozzle orifice and the measurement position is 0.075 m

3. Effect of the measurement distance

By increasing the distance between the nozzle's orifice and the measurement position, an increase in droplet size may occur due to two reasons: The first is due to the coalescence and the second is due to the fast evaporation of the smallest droplets.

Figure 8 shows the effect of the measurement distance between the nozzle orifice and the position of measurement on the droplet sizes. The upper two lines on the chart show the DV90 diameters, while the lower two lines show the D_{32} diameters. In studying these curves, one can see that the dashed lines (which representing the droplet size under non-saturated conditions), start to separate away from the solid lines (which representing the droplet size under dry air conditions), as the fog moves away from the nozzle orifice. That separation shows the very small effect of evaporation.

In order to experimentally quantify the effect of rapid small droplet evaporation, measurements were taken at two airflow velocities, 3 $m.s^{-1}$ and 13 $m.s^{-1}$ (590 fpm and 2560 fpm), and for two sets of air conditions: 30°C (86°F) with 40% RH represented by dashed lines and defined as ambient in the chart, and 20 C (68°F) with close to 100% RH represented by the solid lines and defined as saturated.

The results of the experiments (Figure 8) show that the effect due to coalescence is much higher than that due to evaporation for the given distances of measurement. Figure 8 shows also the effect of the airflow velocity on the reduction of the coalescence effect. At 13 $m.s^{-1}$ (the blue lines) the coalescence leads to an increase of DV90 of 4 microns where as for an airflow velocity of 3 $m.s^{-1}$ (the green lines) the increase is 8 microns due to higher coalescence. The difference in droplet size increases also with increasing distance of measurement. D_{32} behaves similarly to DV90.

The variation of DV90 and D_{32} as function of the distance between the nozzle orifice and the measurement position follows the empirical formulas:

$$DV_{90} \propto D^{0.14} \tag{6}$$

$$D_{32} \propto D^{0.13} \tag{7}$$

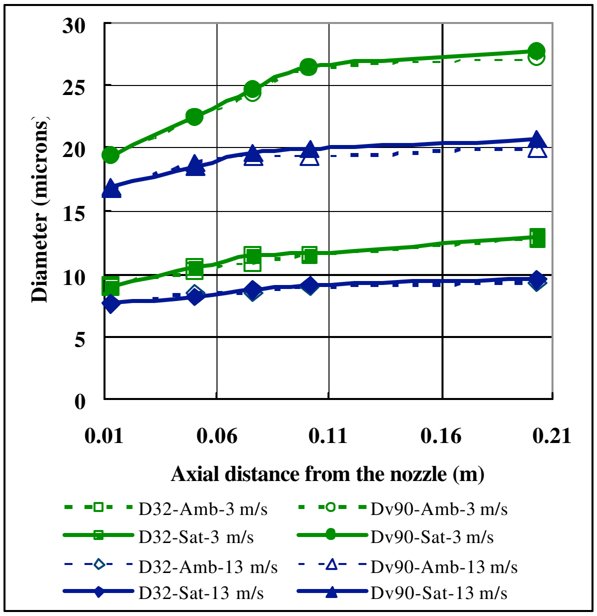

Figure 8, Effect of ambient humidity on droplet size at different axial distances from the nozzle at 38 bars (2000 psi) pressure

4. Effect of flow rate on droplet size

Figure 9 shows the effect of the flow rate on the droplet size for different airflow velocities and distances from the nozzles' orifice.

It confirms that within our range of flow rate, the droplet size decreases when airflow velocity increases, and the droplet size decreases when the distance the distance between the measurement position and the nozzles' orifice decreases.

The variation of the droplet size and the flow rate may be correlated as follows:

$$DV_{90} \propto \dot{m}_w^{0.23} \tag{8}$$

$$D_{32} \propto \dot{m}_w^{0.31} \tag{9}$$

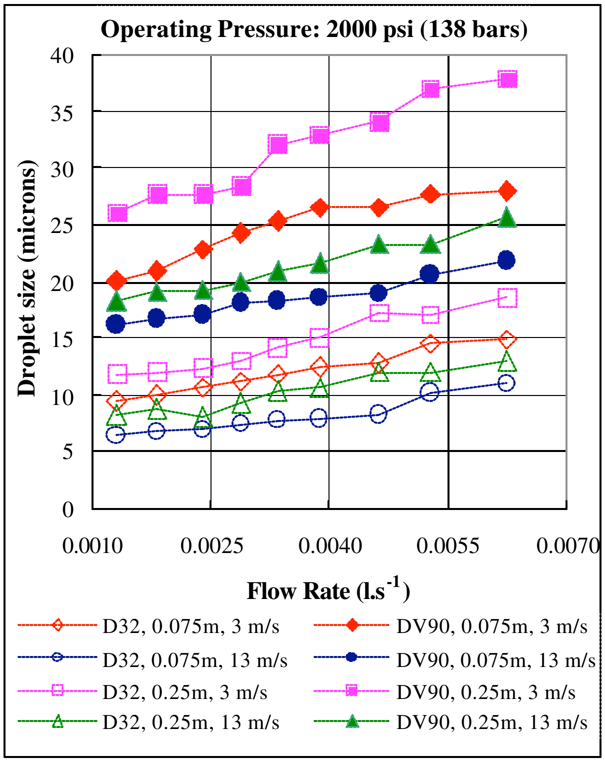

Figure 9, Effect of flow rate on droplet size

5. Effect of the plume cone angle

The major reason for droplets' coalescence within the plume is due to the high density of droplets close to the nozzle orifice. The collision between droplets in this region leads in general to their coalescence or bouncing because of a low Weber number [2]. By increasing the cone angle of the plume (by modifying the configuration of the nozzle) and consequently its width, the density of the droplets in the dense area decreases.

Two nozzles which operate at the same experimental conditions were tested (Figure 10) at 0.2 m from the nozzle orifices and for an airflow velocity of 0.2 m.s^{-1}. The first one had an initial plume width (at this distance) of 0.17 m (Red Plain circle), and the second had an initial plume width of 0.13 m (Red empty circle).

As can be seen in Figure 10, with the increase of airflow velocity, the plume width decreases from 0.17 m to 0.1 m for the largest plume, and from 0.13 m to 0.09 m for the smallest plume. At an airflow velocity of 0.2 m.s-1, D_{32} (blue lines) for both plumes has the same value while DV90 (Green lines) for the smallest plume has around 7 microns more than the one for the largest plume (size is around twice in volume). With the increase in airflow velocity, D_{32} decreases approximately in the same way for both plumes, while the decrease in DV90 is less important for the smallest plume. DV90 of both plumes decrease to around 20 microns at an airflow velocity of 13 m.s^{-1}.

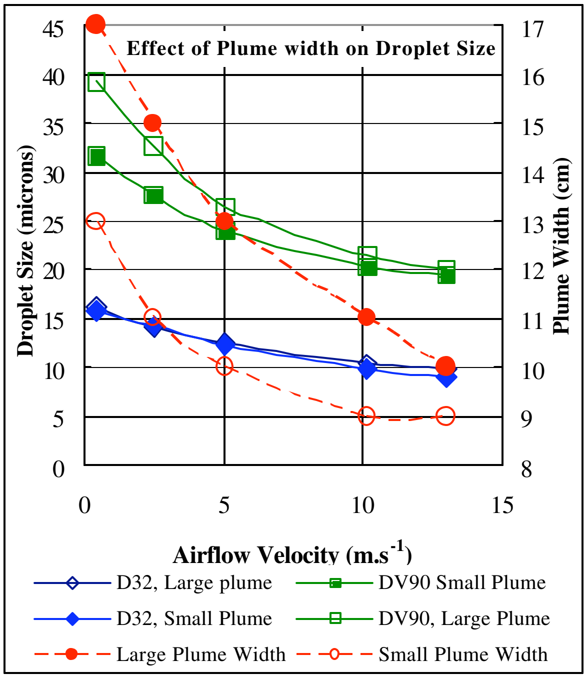

Figure 10, Effect of plume width on droplet size as function of airflow velocity

More experiments have to done to incorporate the effect of the plume size in the empirical formula given below.

Discussion and Conclusion

The combination of the experiments described above leads to the development of new empirical correlations between the Sauter Mean Diameter (D_{32}) and DV90 and the different parameters of influence, within the range of experimental values specified above. These empirical equations are:

$$DV_{90} \propto \dot{m}_w^{0.23} D^{0.14} \Delta P^{-0.16} V_a^{-0.14} \qquad (10)$$

$$D_{32} \propto \dot{m}_w^{0.31} D^{0.13} \Delta P^{-0.23} V_a^{-11} \qquad (11)$$

While the results of these empirical correlations give values close to the measured ones, more experiments need to be conducted to incorporate the effect of other parameters and to increase the precision and the range of the experimental values.

This paper provides new tools which may be used by gas turbine inlet air fogging users to estimate the droplet size from impaction pin type nozzles.

NOMENCLATURE

CV	Concentration Volume (ppm)
D	Distance between the nozzle Orifice and the measurement location (m)
DAS	Data Acquisition System
DV90	Droplet size number (∝m)
K	Constant of proportionality
$\dot{m}$	Water flow (l.s^{-1})
P	Operating pressure (bar)
SMD (or D_{32})	Sauter Mean Diameter (∝m)
T	Temperature (°C)
Va	Airflow velocity (m.s^{-1})
ΔP	differential pressure applied
Subscript	
W	Water
a	Air
∝, δ, π, ω	power constants

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