SPRAY INTERACTION AND DROPLET COALESCENCE IN TURBULENT AIR-FLOW. AN EXPERIMENTAL STUDY WITH APPLICATION TO GAS TURBINE HIGH FOGGING

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Abstract
The paper describes results of experimental study on performance of high and inlet fogging water nozzles. Two different types of nozzles are examined. Droplet sizing measurements using a Malvern sizer were performed at various points and different conditions such as injection pressure, air velocity and the angle of injection. It was shown that the droplet size distribution reduced with the increase of air velocity. The droplet size reduction is a consequence of two effects, increase of a Weber number of large droplets exposed to the fast moving airflow and thus the occurrence of a forced droplet break up, and additionally decreased probability of coalescence between the large droplets near to the nozzle. It was also demonstrated that the droplet size distribution reduction depends on the angle of injection. Perpendicular injection relative to the airflow, appeared to have stronger impact on the droplet size reduction than the parallel injection. This is thought to be due to the large difference in Weber number for the two cases of the water injection. Droplet sizing measurements were also conducted on a gas turbine equipped with a high fogging nozzle rack. Results of these measurements showed very uniform droplet size distribution when compared to the laboratory experiments with injection into the still air. This was explained by the influence of the airflow. Additionally, these results shown no evidences of coalescence of sprays produced from neighbouring nozzles.

1. Introduction

Injection of water into the inlet duct of gas turbines (GT) is nowadays well-established tool of power augmentation [1]. This technique is commonly known as inlet fogging. The fine mist of water droplets, often referred to as “fog”, is injected into the air intake by a nozzle manifold, usually mounted downstream of the air filters. By injecting less water than is required for saturating the intake air, all the fog evaporates before reaching the compressor [2,3]. On the other hand, if more water is injected (high fogging, over fogging or wet compression), water will enter the compressor in the form of droplets, which evaporate during the compression. This in turn increases the air cooling effect and thus the air density will be increased. Since the volumetric airflow does not change with the fogging, the air mass flow simply increases due to the increase in air density. If the air to fuel mass ratio of the gas turbine combustor is kept constant, more mass flow of air requires more fuel to be added to the system and hence, power of a gas turbine is boosted [4]. The power boost of gas turbines is especially attractive during peak hours. The rule of a thumb is that each percent of the water mass relative to the inlet air generates at least 5% power increase [5]. With the current maximum of 2% of the water which can be injected, a realistic 10% power boost of the turbine is achievable.

Key difficulties associated with the water injection are potential detrimental effects on compressor stability and possible erosion of compressor blades due to liquid impact. Most of the authors [1-5] agree that the if the droplets entering a compressor are smaller than 30-40 microns, the erosion is almost certainly avoided. On the other hand, the airflow before entering the compressor is exposed to sudden change of direction and strong acceleration, where the intake duct turns into the compressor bellmouth. The large water droplets present in the airflow, do not follow this direction change and they end up at the bottom of the intake, where they are drained through the drainage lines. Therefore, some amount of water is pumped around without actually being used for the air cooling, representing a pure loss in the final energy balance. Molis et al. [5] demonstrated an introduction of a large droplet eliminator to the GT intake, showing that nearly 30% of the spray was drained out and actually not being used for the high fogging purpose. This clearly indicates the importance of producing fogging sprays in the GT intake with droplet size distribution not larger than 40 microns. In addition to these problems, evaporation rate strongly increases with decreasing droplet size, meaning that the droplet size also determines how many stages of compressor operate in the two-phase flow regime.

The original droplet size distribution produced by a single nozzle depends on the type of nozzle in consideration and operating pressure and water temperature. On the other hand, if individual nozzles are arranged in a nozzle rack injecting into the high-speed turbulent airflow, the resulting droplet size distribution can be significantly changed. This change of droplet size distribution can be caused by an effect of air turbulence on the droplet break up and/or by the interaction of neighbouring sprays and flow induced droplet coalescence in highly turbulent airflow. To assess these effects an experimental study is being conducted where droplet size distributions of different nozzles and nozzle arrangements injecting into ambient and moving air have been measured and compared. To compare these experimental results with the realistic GT conditions, measurements of the size distribution at the intake of a GT have been also performed and results were compared with the laboratory conditions.

2. Experimental set-up and procedures

TEST RIGS

Atmospheric test rig is used to investigate the droplet size spectrum of sprays injected into still air. The nozzles are supplied with partially de-mineralised and filtered water. The nozzles are mounted on the traversing system, allowing for measurements in different spray positions. The water is sprayed into the tank. The tank is purged by an auxiliary blower which is installed at the bottom of the tank. In this way the droplets are carried away by a very low airflow (1.5 m/s), keeping the laser system dry. The test rig allows accurate control of the water pressure and mass flow rate through the frequency regulated pump and a by pass system at the pump exit.

For investigation of the influence of air velocity and the interaction of sprays on the droplet size distribution, a wind tunnel with optical access (2) and water supply is used (Figure 2). The wind tunnel has a large cross section area (800x800 mm) allowing multiple nozzles to be tested in a nozzle rack arrangement. The air in the wind tunnel is transported using a frequency-controlled blower (7) which pushes the air in a semi-closed loop through the whole tunnel. Maximum velocity in the wind tunnel is 20 m/sec. The nozzles are mounted in the first measuring section (6) directly after two arrays of honeycombs used to eliminate the swirl caused by the blower. This provides a uniform air velocity field. The partially de-mineralised water is pumped to the nozzles, using a similar pump as described in the atmospheric test rig. Injection pressures and flow rates are controlled using a by-pass pipeline. The droplet sizing device is traversed along the measuring section allowing measurements at different axial and radial distances from the nozzle. During the testing, condensed excess water in the system is drained out through different drainage holes in the tunnel.

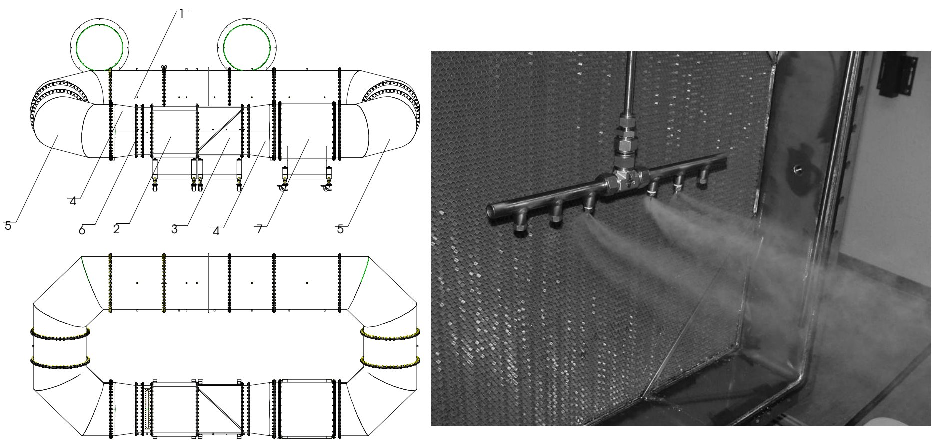

Figure 1. Left: The wind tunnel facility, Right: spray visualisation of a nozzle rack

NOZZLES

In most cases, inlet fogging or high fogging systems are equipped with impact pin or pressure swirl type of nozzles. In experiments conducted here, both types of the nozzles were investigated. Droplets were measured at different locations in the spray (see Fig 1), different injection pressures (70 and 140 bar) and different air velocities.

INSTRUMENTATION

MALVERN SPRAYTEC droplet sizing device is used for measuring the droplet size spectrum. The device is based on laser diffraction, where large droplets scatter light at smaller angles and vice versa, small droplets scatter at larger diffraction angles. The measuring zone lies within the laser beam, some 300 mm from the receiver, for the specific lens of focal length of 200 mm used in the experiments described here. A comparison of results obtained by Phase Doppler Particle Analyser and SPRAYTEC was performed with the data obtained from the atmospheric test rig, and the agreement between the two techniques for the SMD was within 10%. This was found to be acceptable and for the reasons of simpler alignment procedure, especially in the case of the wind tunnel (where the laser system had to be moved, rather than the spray), all the measurements were performed with the laser diffraction method.

Additional instrumentation used in test rigs includes pressure transducers, which are always located close to the nozzle, magnetic water mass flow meters, humidity and temperature probes and a DANTEC hot wire system which is used to measure air velocities in the wind tunnel.

TEST PROCEDURE

For all measurements performed at the laboratory, at least three different samples of the same nozzle were tested. Goof repeatability of the tests was provided by allowing droplet sizing duration of at least 5 minutes, which is in accordance to the recommendations for the standard measuring procedure as suggested by [6] Results shown in the following section represent the averaged values of repeated tests. Standard deviation of the measuring results did not exceed 5%.

3. Results of the nozzles characterisation

As described above, nozzles were tested injecting into still air and into moving air at different velocities. Droplet sizing measurements were performed at different sampling positions from the tip of the nozzle having a complete scan through the spray plumes. The most important characteristic diameters in characterising sprays for the application of high fogging, are D_{32} and the $D_{[v.90]}$. The first diameter is of importance to the determination of the evaporation rate, hence determining how much water and of which droplet size will enter the compressor. The other diameter, which describes the droplet size from which 90% of the droplets are smaller, gives the information on the largest droplets in the spectrum entering the compressor. The droplet sizes are function of various factors such as sampling position in the spray, injection pressure or air velocity. Therefore, any comparison of e.g. different nozzles, or different air velocities should be done keeping the other two boundary conditions constant. Typical air velocities in the intakes of the gas turbines range from 5 to 25 m/s, depending on the part of the intake. For example, in the inlet fogging application, nozzles are placed near to the filter house, and are exposed to lower air velocities, e.g. 5 m/s. On the other hand, for the high fogging applications, nozzles can be mounted in a part of the intake which is exposed to higher air velocities, such as 25 or even 30 m/s. Finally, GT can operate in different conditions, idle or full load, which in turn alters the intake air velocity in the same range as mentioned above.

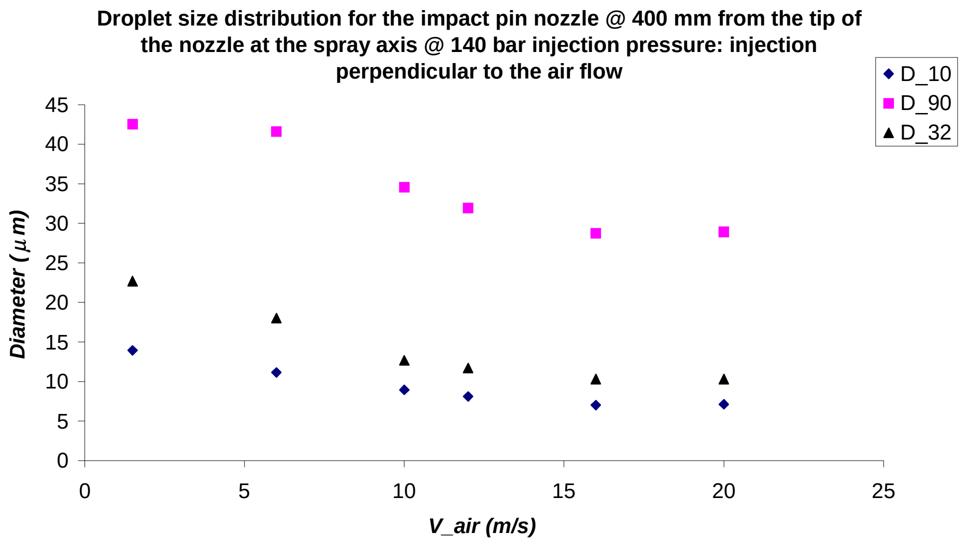

Figure 2. Influence of air velocities on the droplet size distribution for the perpendicular spray injection

The above mentioned influence of the different air velocities to the droplet size distribution are taken into account and results, applied on an impact pin nozzle are shown in the Fig 2. From this Figure, one can see that the droplet size significantly reduces with the increase of the air velocity. Droplet size distribution of a spray measured at the atmospheric test rig (air velocity of 1.5 m/s), represented with $D_{[v.10]}$ = 13.94 μm; D_{32} = 22.69 μm and $D_{[v.90]}$ = 42.54 μm reduced to the distribution represented by $D_{[v.10]}$ = 7.12; D_{32} = 10.31 μm and $D_{[v.90]}$ = 28.93 μm for the same spray exposed to the air velocity of 20 m/s. This change appears to be the most dramatic in the case of the $D_{[v.10]}$, which represents the lower tail of the droplet size distribution. It is also interested to note saturation in the droplet size reduction at around 12 to 16 m/s. This agrees well with [6], who reported a decrease of a droplet size distribution of the similar nozzle type in airflow characterised with air velocities of up to 12.7 m/s.

Results presented in Fig.2 are obtained for the nozzles mounted in such a way that the airflow was perpendicular to the injection plane (Fig 1 right). From Fig 1 (right) it can be seen that the spray plume bends under the influence of air and shortly after it emerges from the nozzle it fully follows the airflow. In the spray region near to the nozzle, before the plume bends, droplets are travelling perpendicular to the airflow and their relative velocities, at a constant injection pressure, depend on the air velocity. Since the Weber number increases by the square of relative velocity, probability of large droplets breaking up into smaller ones is increased at higher air velocities. Higher rate of the droplet break up is one of the possible reasons for the decrease of droplet sizes at increased air velocities. On the other hand, in the spray region near to the nozzle, there is high probability of droplet coalescence, due to the high density of droplets and their large Weber numbers (high initial droplet velocities and large diameters, even presence of ligaments). By exposing them to the strong airflow, spray is diluted and this probability of coalescence is lower. Hence the droplet size distribution is decreased by the increase of air velocity. To quantify this effect, tests with a spray injected parallel to the airflow were conducted. By injecting the spray parallel to the airflow, droplet relative velocity of the spray is smaller than in the case of perpendicular injection, and the effect of the spray dilution can be quantified. The difference in Weber numbers for two cases can be illustrated on the following example. In the case that the droplet initial velocity is 90 m/s (as measured by PDPA), and it's diameter is 40 μm, and if it is injected perpendicular to the airflow of 20 m/s, the resulting Weber number is 6.4. The same droplet, injected parallel to the air, has a relative velocity of 70 m/s and the Weber number equals to 3.9. According to [6], for a large range of Ohnesorge number critical value of Weber number is 6, and hence the same droplet injected at a different angle relative to the airflow may or may not break up.

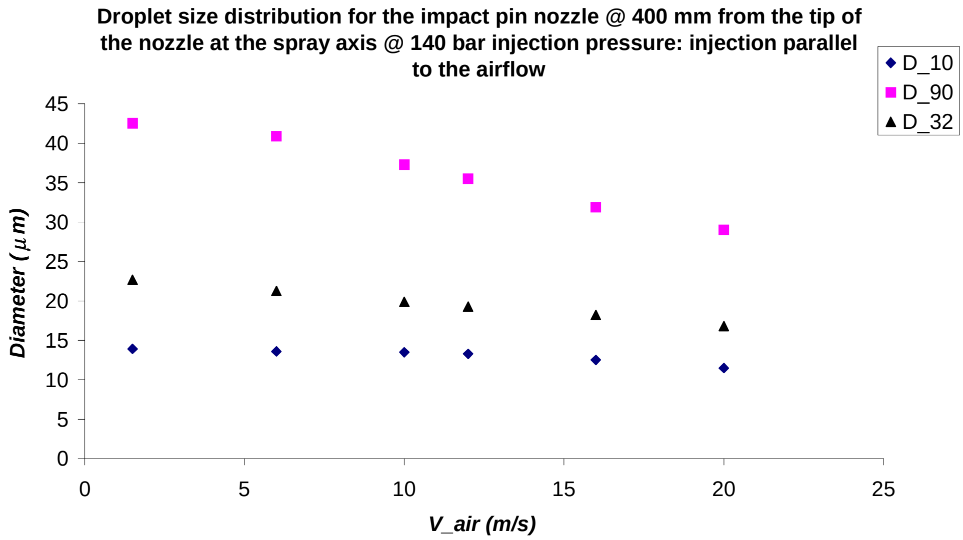

Figure 3. Influence of air velocities on the droplet size distribution for the parallel injection

From the Fig.3, one can see that the droplet size reduces with the increase of the air velocity, but at a much lower rate than in the case of perpendicular injection of spray. This difference is quantified in Fig.4, which shows a direct comparison between the two cases. It is clear that the angle of injection relative to the strong airflow significantly changes the number of droplets that break up. Therefore, one can say that the injection should be perpendicular in order to have finer mist and avoid possible damage to the compressor blade. On the other hand, sometimes it is not possible to arrange nozzles at 90 degrees relative to the airflow, since they may hit the near wall or the next pipe in the nozzle rack. Therefore, a compromising solution could be injection at e.g. 45 degrees, and a further work examining the optimal inclination is a subject of our current research. Results similar to the ones shown here have been obtained with pressure swirl nozzles. Also, same trends appear at different sampling positions.

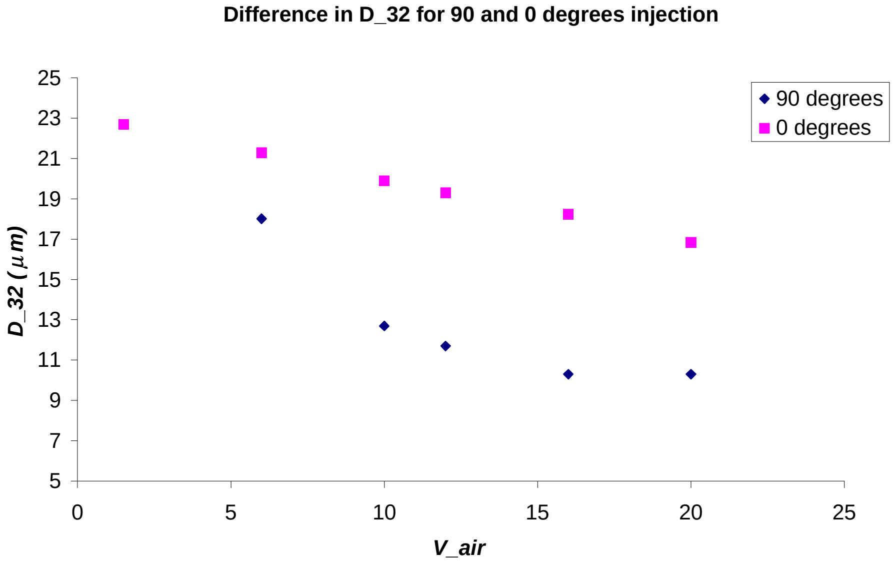

Figure 4. Comparative results of droplet size reduction at different injection angles

4. Droplet sizing measurements on the gas turbine

Measurements were performed using a Malvern sizer on gas turbine equipped with a high fogging nozzle rack, placed just upstream from the compressor bellmouth. The air velocity during the tests was set to 20 m/s and nozzles used were pressure swirl type nozzles. The main problem when performing such sensitive measurements directly on the gas turbine was in vibrations present on the machine. Therefore, Malvern sizer device was mounted to the construction independent from the inlet duct, thus providing vibration free operation of the system as well as preventing a possible misalignment during the measurements. To provide an optical access for measurements, two opposing holes were drilled on the intake duct of a gas turbine, 400 mm underneath the high fogging rack. Figure 6 shows a view through the observation glass on the gas turbine intake duct. Figure 7 shows comparison of droplet size histograms from the engine and laboratory conditions using the same nozzle but without the airflow.

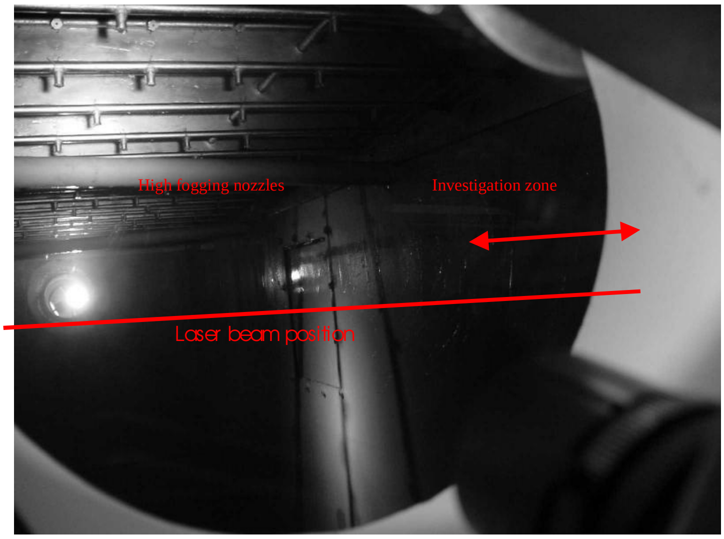

Figure 6. High fogging nozzle rack in the intake duct of a gas turbine

From the Fig 7, one can see that the uniformity of the droplets is much lower in the laboratory conditions (no airflow) than in the case of the turbine measurements. The spread of droplet sizes in laboratory conditions (water injected into single air, by a single nozzle) is from cca. $D_{[v.10]}$ =17 to $D_{[v.90]}$ = 66 microns, compare to turbine conditions where this spread was from 30 and 44. The possible explanations of these differences could be related to the difference in airflow (velocities above 20 m/s in the case of GT intake, and 0.5 m/s in the atmospheric test rig). Intensive airflow helps breaks up of larger droplets and enables quick evaporation of the small ones. On the other hand, due to the absence of a high airflow in the laboratory conditions, the large droplets would not break up, thus shifting a measuring sample towards the larger $D_{[v.90]}$. For the same reason of lack of airflow, the smaller droplets would simply not evaporate, and thus stretching the droplet size distribution towards the smaller $D_{[v.10]}$. Finally, measurements with the same pressure swirl single nozzle in the wind tunnel with the same air velocity of 20 m/s revealed the same results as in the case with multiple nozzle rack in the gas turbine. Therefore no increase of the droplet size was detected in an actual turbine due to the interaction of neighboring cones suggesting that the coalescence may not be an issue. However, further research is ongoing to clarify this effect.

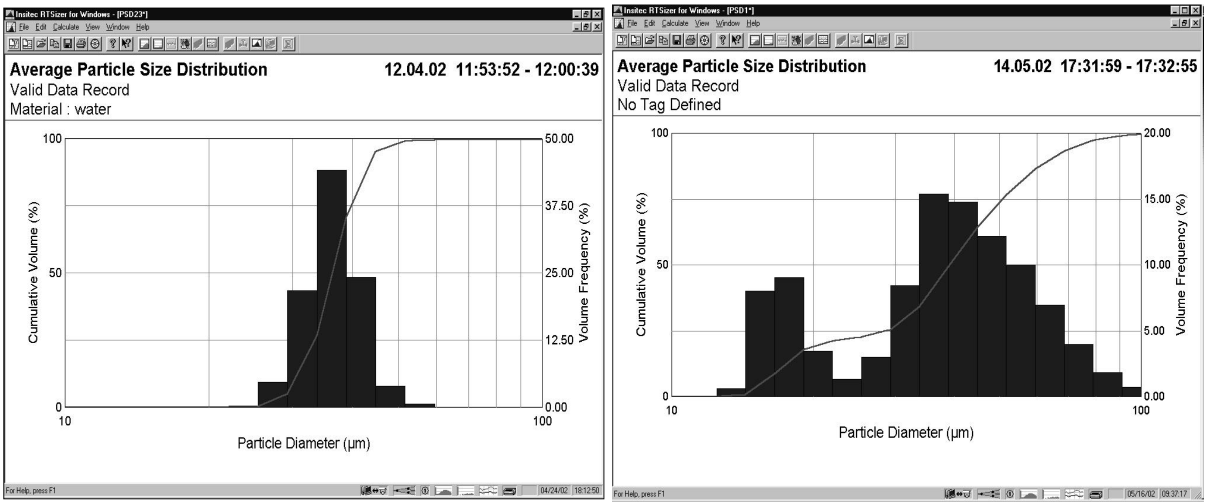

Figure 7. Comparison of engine results (left) and laboratory data (right)

5. Conclusions

Experimental study reported here revealed the importance of the correct nozzle arrangement for the inlet or high fogging applications. Results with varying air velocity and injection angle showed that the droplet size of a resulting spray can be significantly reduced by injecting the water perpendicular to the airflow, or in case where this is not possible, perhaps injecting at an injection angle between 0 and 90 degrees. An optimization of the injection angle can be a subject of further research. It has also been shown that the increase of air velocity more than 15 m/s does not reduce the resulting droplet size. Therefore, to explore the full benefit of the additional droplet break up process, it is enough to install the nozzle rack anywhere in the inlet duct, providing that the air velocity is higher than 15 m/s. It was also shown that the strong airflow can prevent the coalescence of droplets very near to the nozzle. This results in the smaller overall droplet size than when the spray is injected into a still air. On the other hand, measurements on the turbine and their comparison with results obtained at laboratory showed no evidences of the droplet coalescence of the spray cones from the neighboring nozzles. This can mean that the number of nozzles which are implemented in the intake duct is not limited by the spray width, but rather with pressure drops which a nozzle rack can cause to the inlet air flow. Further research to validate this claim is still necessary.

Nomenclature

D_{32} Sauter mean diameter
$D_{[V,90]}$ 90% of the water volume is in droplets less or equal to this diameter
$D_{[V,10]}$ 10% of the water volume is in droplets larger or equal to this diameter

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