INTERACTION OF NEIGHBOURING HIGH FOGGING SPRAYS: INFLUENCE OF NOZZLE PLACEMENT AND AIR VELOCITY ON DROPLET COALESCENCE

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ABSTRACT

The paper describes results of an experimental study on performance of high fogging water nozzles. Tests were performed in a wind tunnel facility and an atmospheric test rig, where 2 identical single-hole pressure swirl nozzles were tested in different arrangements to investigate the effect of nozzle placement and air velocity on droplet coalescence between interacted sprays. Direct comparison between rack arrangements and single nozzle tests was performed and conclusions on droplet size distribution were allowed.

Results revealed that under tested nozzle placement and air velocities, droplet coalescence did not occur. On-line measurements using a Malvern Spraytec system showed that once a second spray is introduced and interaction of the two sprays occurs, the droplet size distribution in the interaction region remains unaffected. To verify results from Malvern Spraytec, image-based techniques were applied to the sprays using a SprayMaster laser system by LaVision. Qualitative and quantitative information of the interaction region of the sprays is provided in this paper, which coincides, with results from Malvern Spraytec.

1. INTRODUCTION

High fogging (also known as wet compression, spray inter-cooling) is a technique used for gas turbine (GT) power augmentation, where the power boost of the GT is achieved by evaporative spray inter-cooling of the air during compression. Water, in the form of finely atomised droplets, is introduced in the intake duct of the GT using high-pressure nozzles, usually organised in a high fogging rack. The water then enters the GT compressor, where it evaporates during the compression process. This evaporation reduces the temperature rise in the compressor, thus reducing the power needed for compression. In this way, it is possible for each percent of injected water (per mass of air) to increase the GT power output by 5-7%.

The injection location inside the intake duct and the resulting droplet size distribution of the fog are of crucial importance for the safe operation of the GT. The driving parameter is the droplet-size spectrum produced by each high-pressure fogging nozzle. The spectrum is influenced by nozzle design, operating pressure and flow-induced fragmentation or coalescence of droplets in the highly turbulent airflow of the intake duct.

The original droplet size distribution produced by a single nozzle at a specific operating pressure is provided by the nozzle manufacturer or can be found by experimental studies. However, if individual nozzles are arranged in a nozzle rack injecting into high velocity turbulent airflow, the resulting droplet size distribution is not known. Previous studies [1] revealed that air turbulence has a significant impact on droplet break up, which causes the droplet size distribution to change. Furthermore, change of droplet size may be caused by interaction of neighbouring sprays and flow induced droplet coalescence in highly turbulent airflow [2,3].

To quantify these effects, an interaction between the two sprays was assessed. Two nozzles were placed at different distances from each other, but always close enough to allow spray overlapping. Measurements, using laser diffraction and image-based Mie scattering and PIV techniques were focused on the region of spray interaction. Measurements were conducted in such a way, that nozzles were firstly individually tested in the regions of spray overlap (one of the nozzles closed at the time) and then compared to combined injection of both nozzles (both nozzles opened), without changing the laser beam or camera position. In this way, it was possible to provide one-to-one comparisons of droplet size distributions between single and combined sprays. All tests were performed both in a wind tunnel, operating at GT inlet conditions (velocity from 20-25 m/s) and in quiescent air. Results obtained, allowed to assess the effect of air velocity on the spray-spray interaction.

2. EXPERIMENTAL SET-UP

2.1 Test rigs

As described above, tests were performed in quiescent air and medium airflow in atmospheric rig and wind tunnel respectively. Both experimental rigs are shown in Figure 1. Partially de-mineralised water pressurised up to 140 bar was used in experiments. A transducer located close to the nozzle rack monitored the pressure injection during tests. Additional instrumentation included a magnetic mass flow meter placed after the water pump and a thermocouple located close to nozzles. To provide standard conditions for safe and clog-free nozzle operation, various water filters were placed in the pipe system.

The wind tunnel had a large cross section area (800x800 mm) with an optically accessible region of the spray interaction. The air was transported using a frequency-controlled blower that pushed the air in a semi-closed loop. Nozzles were mounted directly after two arrays of honeycombs used to eliminate the swirl caused by the blower and provided a uniform air velocity field. Additionally, the honeycombs were used as separators or water condensers, preventing re-circulated water to enter the measuring section.

In the atmospheric rig, nozzles were injecting into still air and mounted on a traverse system, measurements were allowed at different spray positions. The water was sprayed inside a tank, which was purged by an auxiliary blower installed at the bottom. The droplets were carried away by a very low airflow (1 m/s), keeping the laser system dry.

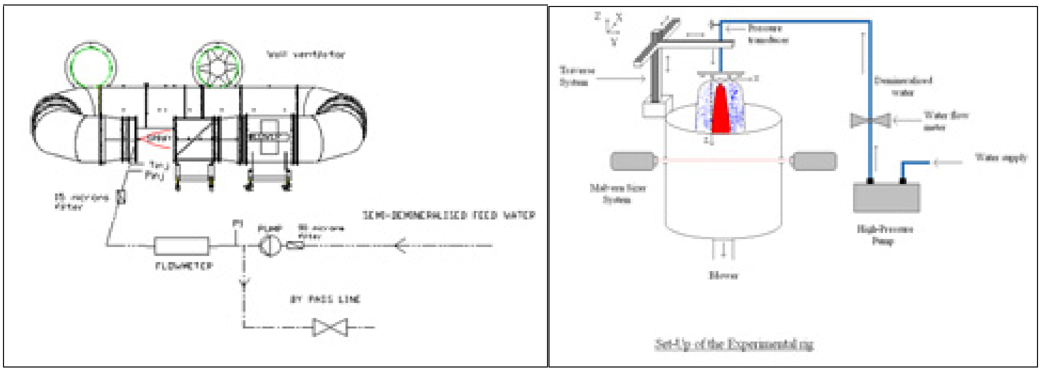

Figure 1. Left: The wind tunnel facility, Right: The atmospheric test rig

2.2 Nozzles

The nozzle type used was a single-hole pressure-swirl nozzle producing 30 Kg/h mass flow rate. Two (2) nozzles were mounted in the wind tunnel in two different rack configurations. Nozzles were placed 10 and 15-cm apart and Malvern measurements were performed with the laser beam crossing perpendicular to the overlap spray region. PIV and Mie laser sheet measurements covered the entire spray interaction region. In the atmospheric rig, the nozzles were placed 12-cm apart. Droplets were measured at different locations in the spray and injection pressures. All configurations are depicted in Figure 2.

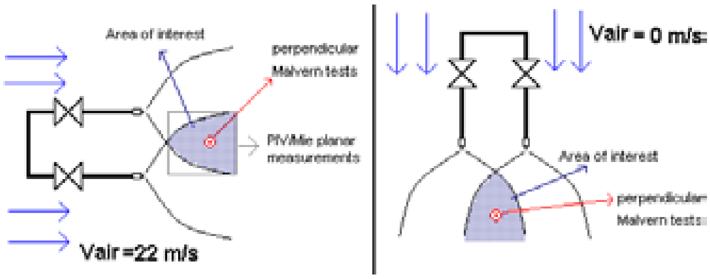

Figure 2. Nozzle rack arrangements (left in wind tunnel, right in atmospheric test rig)

2.3 Instrumentation

Laser diffraction spray analyser (Malvern sizer SprayTec) is based on Fraunhofer diffraction evaluating method. The principles of operation are based on the fact that the angle of the light scattered from the edges of a particle depends on its droplet diameter. The scattered light is collected by the use of a Fourier lens, which focuses the light beams scattered at the same angle onto the same ring on the detector, regardless of the position of the droplet (source of a scatter). The detector is divided into a number of diffraction rings, which detects a light of a corresponding scatter angle. The latter is then related to a droplet size. The larger droplets scatter the light at smaller angles and vice versa. 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. Additionally, Lorenz-Mie correction of scattering intensity was used for the detection of multiple scattering phenomena.

The SprayMaster measurement device allows advanced spray analysis based on laser light sheet imaging. The optical source used for the SprayMaster is a Tempest Nd: YAG laser. During measurements reported here two different laser wavelengths were used (355 and 532 nm) that allowed two imaging techniques to be performed. To characterize and visualize the spray plume, elastic scattering (Mie) and 2-dimensional Particle Image Velocimetry (PIV) were performed.

3. RESULTS ON LASER DIFFRACTION

To identify any coalescence phenomena, nozzles were tested at different injection pressures. At lower injection pressures the atomisation performance of the nozzles is decreased and thus larger droplets are formed with higher probability of coalescence.

Droplet sizing measurements were performed at different sampling positions from the tip of the nozzles, allowing complete scanning of the spray plumes. During wind tunnel tests, sprays were exposed to 22m/s air velocity, similar to actual GT intake conditions for high fogging systems. The influence of injection pressure on the spray-spray interaction is shown in Figure 3. Variation of characteristic diameters D_{32} and D_{v90} (for definition see [1]) for all three test cases, namely the upper nozzle and the lower nozzle (with respect to the laser system) individually tested and both nozzles when the two sprays were overlapping is presented.

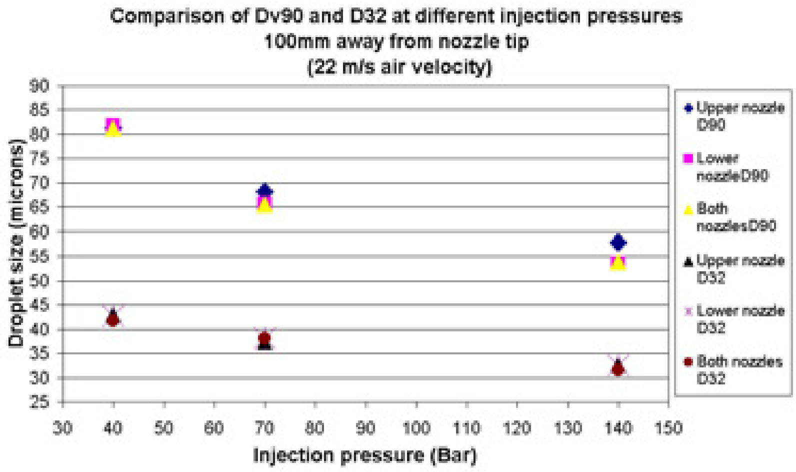

Figure 3: Variation of Dv_{90} and D_{32} on injection pressure effect when nozzles are placed 10-cm apart. Measurements were taken 100mm away from nozzle tip at middle plane between the two nozzles

Figure 4 shows results of the spray-overlapping region at constant injection pressure for different distances from the nozzle tip. The droplet size distribution in the interaction zone of the two nozzles remains unaffected by the spray-spray interaction. There is some variation of the representative diameters between the two nozzles, which is a consequence of an uneven flow characteristic of the nozzles (7.9 and 8.6 g/s respectively due to manufacturing tolerances) but once both sprays were on, the representative diameters remained between the values of diameters recorded for the individual nozzles. This indicates that droplet sizes did not increase when neighbouring sprays have interacted and thus larger droplets have not been formed. Similar results were recorded at different axial and radial distances in the spray.

A representative way of the overall behaviour of the droplet size distribution between individual and interacted sprays exposed to different air velocities is shown in Figure 5. The actual droplet size distributions are depicted on same graphs. The spray behaviour of individual sprays is very similar. Minor deviations are attributed to difference of nozzle mass flow and the asymmetry of the produced sprays. Droplet size distribution produced at the interaction of the sprays “falls” between distributions by individual sprays. Similar observations are seen at different nozzle distances for all tested arrangements. No droplet size increase is seen that would suggest possible droplet coalescence phenomena.

By allowing each nozzle to be tested under the same conditions, results can be comparative and accurately reflect any change in the droplet size due to coalescence effect. The spread of results from the three sets of configurations (upper nozzle, lower nozzle and both nozzles) was below 3%. This spread is within the measurement error of the laser system. From this it follows that the coalescence of droplets does not occur or it can be neglected at any of the tested conditions.

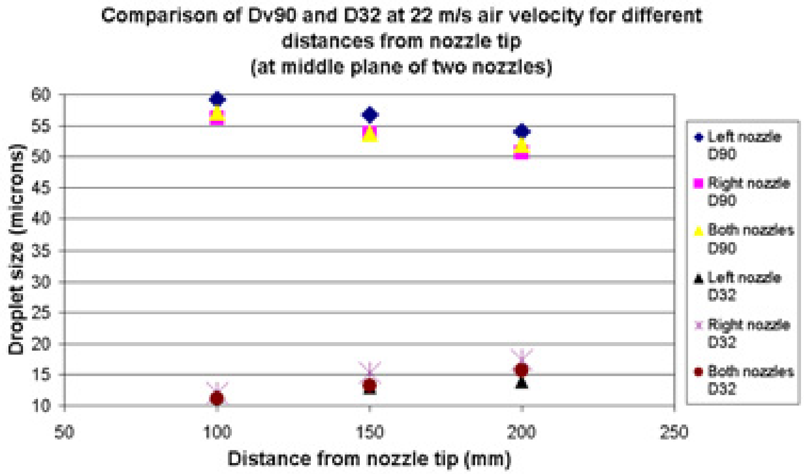

Figure 4: Variation of Dv_{90} and D_{32} at different sampling positions from the nozzle tip

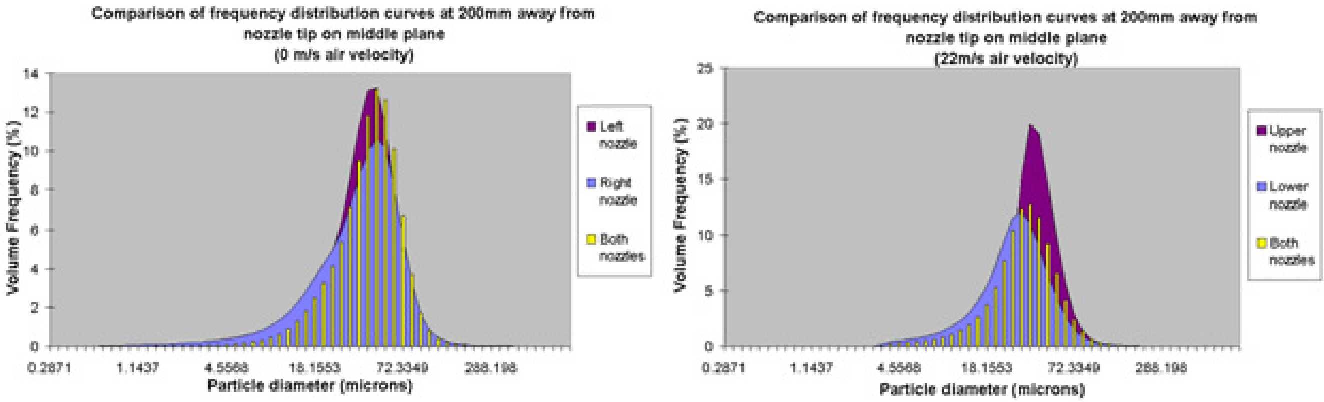

Figure 5: Variation of the droplet size distribution of different sprays tested in the atmospheric rig and the wind tunnel

4. RESULTS ON IMAGE BASED TECHNIQUES

<u>MIE imaging results</u>

Averaged and RMS results for the spray-spray interaction are seen in Figure 6. The scale of counts on the right of each image relates to the droplet surface area. More counts indicate a higher surface spray area. If sphericity of water droplets is assumed, then more counts indicate a dense spray area. The scale on images is in mm and covers an area of 160x130mm. Areas of high intensity (and thus high spray concentration) are seen at the central axis of each spray. Fewer droplets appear in the interaction region of the two sprays where the probability of droplet coalescence is expected to be higher due to opposed droplet trajectories. This is attributed to the effect the surrounding air has on the spray pattern that causes it to collapse along its central axis and reduces the number of droplets in the interaction zone. Studying the RMS images, fluctuations are present in the central core of the sprays where most of the spray volume is seen. However, on the interaction area of the two sprays no fluctuations appear.

In Figure 7, an attempt to visualize the earlier statement on reduced coalescence probability in the interaction region is made. Using the average image and taking a circular profile in the interaction region the intensity profile is seen. Clearly the range of counts in that region (between 5-25 counts) is much smaller than values obtained at the middle of each spray, which is in the region of 100 counts. Relating the intensity (counts) to droplet presence, fewer droplets appear to exist in the interaction region. This is explicitly seen from the 3D profile of the sprays where the effect of accelerated air causes the spray patterns to deform and restrict the distribution (spreading) of the majority of droplets around the central axis of the spray.

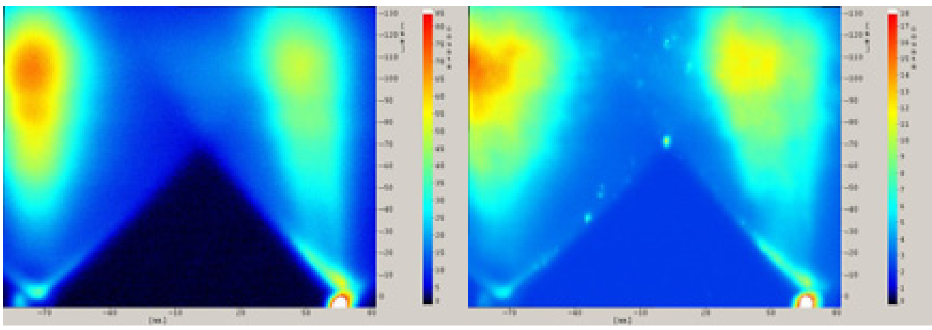

Figure 6: Average and RMS images of both nozzles

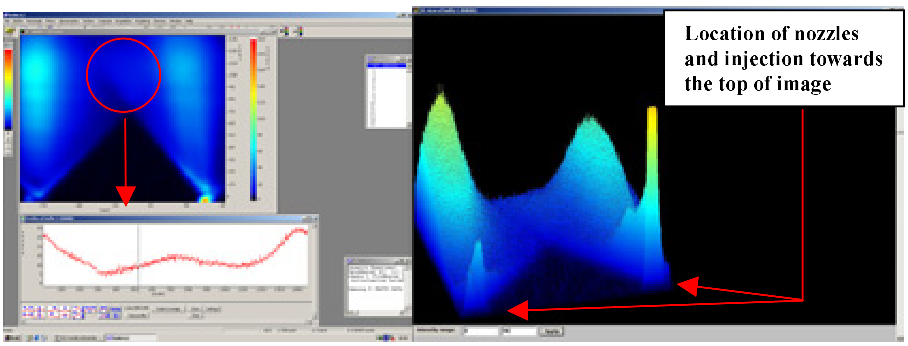

Figure 7: 2D and 3D Profile along interaction region

PIV results

For PIV tests, the time between image exposures (dt) is an essential pre-test variable that determines the accuracy of the vector field. In theory, the higher the velocity, the lower the dt. Normally, particle displacements should be smaller than 5 diameters between them in the two images taken by the camera [4]. Based on airflow field investigations in the wind tunnel, the dt was found to be 20 μs and results are shown in Figures 9-11.

Studying the vector field of all tests, the highest velocities are recorded at the edges of the spray. However, the velocity profile is not uniform but reduces as the distance from the nozzle tip increases. It is known that the maximum droplet velocity is at the nozzle exit but as the droplets travel downstream, with the effect of co-current accelerated air, their relative velocity is reduced until they become airborne. The initial droplet momentum is reduced further away from the nozzle exit and due to surrounding airflow, the spray collapses in the middle as it is also seen in Mie images.

Using post-processing routines in PIV environment, the statistics of each vector field image are summarized below:

	Left nozzle (Figure 9)	Right nozzle (Figure 10)	Impact velocity (Figure 11)
Absolute Velocity (m/s)	47.3	45.8	64.5
D32 (microns)	36	32	34
Weber Number	1.4	1.2	2.5

The impact velocity is the vector sum of the absolute individual velocities and based on Figure 8 that indicates the droplet collision velocities the PIV results coincide with theory.

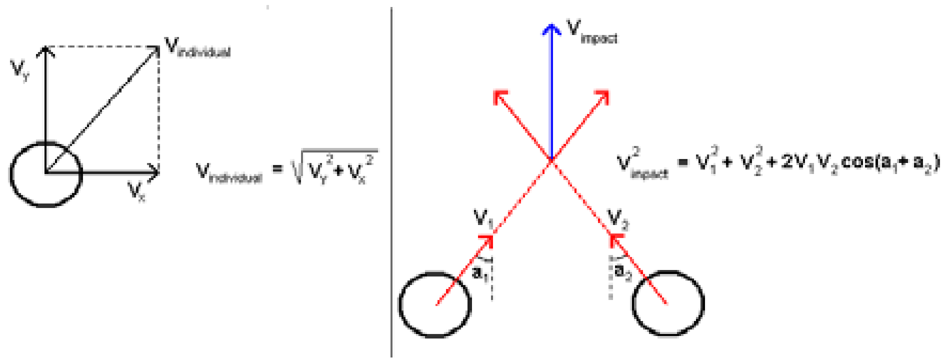

Figure 8: 2D and 3D Profile along interaction region

In all above cases the Weber number is always smaller than 8, which according to [5] is a cut-off limit above which coalescence occurs. At such low Weber numbers the kinetic energy of the droplet is insufficient to overcome the surface energy and cause coalescence. The thin air film between the liquid surfaces cannot be expelled by the action of the dynamic forces and therefore droplet bounce occurs. Results presented here coincide with [6] where droplet bounce occurs at Weber numbers lower than 3.6.

It should be noted here that an important parameter in droplet interaction process is the impact parameter, which is the distance from the centre of one droplet to the relative velocity vector placed on the centre of the other droplet. However, due to the fact that the droplets produced by the two nozzles are injected at a fixed angle, the impact parameter is constant for all tested cases and thus not considered here.

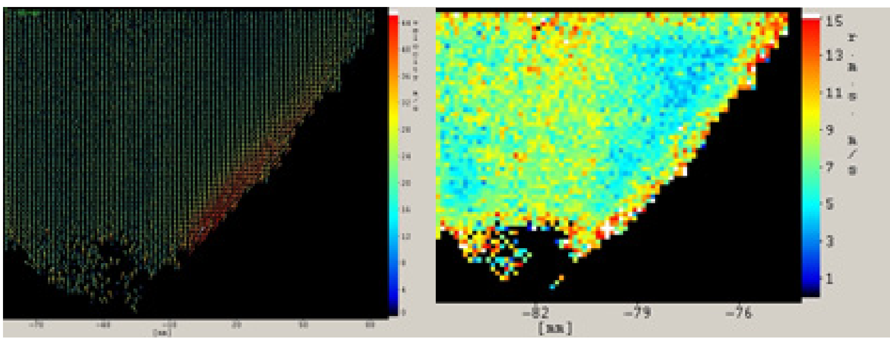

Figure 9: Average and RMS velocity for left nozzle

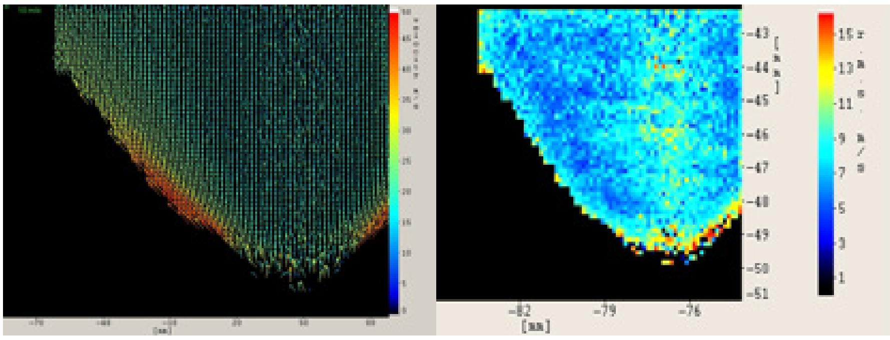

Figure 10: Average and RMS velocity for right nozzle

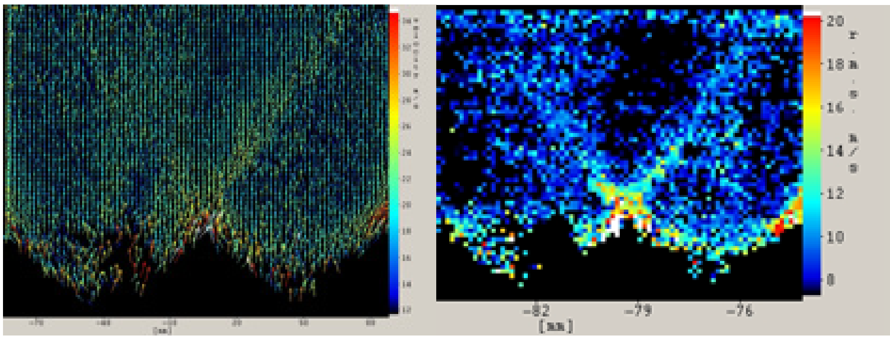

Figure 11: Average and RMS velocity for both nozzles

5. CONCLUSIONS

Results revealed that at tested conditions (given nozzle placement and air velocities) droplet coalescence did not occur. On-line measurements using a Malvern Spraytec system showed that once a second spray was introduced in the tested area and interaction of the two sprays occurred, the droplet size distribution in the interaction region remained unaffected. The only parameter which was changed, was the volume concentration of the spray that has doubled. Using 2D PIV tests the velocity vector field was calculated and it was seen that droplets at cone edges of individual sprays, reduced their absolute velocities after the impact, from cca. 60 to cca. 40 m/s. The collision under tested conditions contributed to the loss of kinetic energy of droplets and has led to the droplet bounce, but it did not affect the original droplet size distribution.

Findings of this study assist the selection of design rules for fogging racks. Nozzle placement, which is an important design parameter in racks, showed that spray-to-spray interaction under realistic gas turbine–nozzle rack geometric restrictions does not affect the droplet size distribution. Nozzles should be placed on racks based on parameters such as intake pressure drop, geometrical restrictions, avoiding the wetting of intake structures e.t.c and not on coalescence effects which were believed to be promoted from the interaction of the sprays.

Further investigation on interaction of sprays can be conducted aiming to define when coalescence occurs. Nozzle injection angles and placement should be investigated. In this way an overall view of the coalescence phenomena could be made and could assist in defining of the conditions for an onset of the coalescence.

NOMENCLATURE

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

REFERENCES

[1] Savic, S., Mitsis, G., Khaidarov, S. and Pfeiffer, P., "An Experimental Study with Application to Gas Turbine High Fogging", ILASS 2002, Saragossa Spain.

[2] Molis, S. J., Levine, P., and Frischmuth, R., "Capacity Enhancement for Simple and Combined Cycle Gas Turbine Power Plants" *Power-Gen International,* September 1997.

[3] Savic, S. and Kippax, P., "Advanced Gas Turbines: Fogging Dynamics Solved", Power Engineering International, May 2003, pp29-31.

[4] Keane, R.D., Adrian, R.J., "Optimisation of Particle Image Velocimeters, Part I: Double-Pulsed Systems", Meas. Sci. Tech. Vol. 1, pp.1202-1215.

[5] Gunn, K., "Collision Characteristics of Freely Falling Water Droplets", Science Vol. 150, pp.888-889, 1965

[6] Orme, M., "Experiments on Collisions, Bounce, Coalescence and Disruption", Progress in Energy and Combustion Science Vol. 23, pp.65-79, 1997.