

# DEVELOPMENT OF A SPRAY BAR SYSTEM FOR THE SIMULATION OF SUPERCOOLED WATER DROPLETS IN THE NIDF CLIMATIC WIND TUNNEL

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**Abstract.** *The Climatic Wind-tunnel of NIDF/COPPE/UFRJ was built in order to simulate extreme atmospheric cloud conditions, i.e., low temperature and high velocity turbulent flows under controlled humidity conditions. This paper presents the development of a spray bar system designed to simulate supercooled water droplets for ice-accretion investigation purposes. The spray bar system comprises six independently controlled nozzles, which are driven by separate compressed-air and liquid supply lines. Droplet diameter distribution and liquid water content inside the wind-tunnel can be varied through changes in the air pressure and liquid flow rate. The spray bar system was installed in a settling chamber located immediately upstream of the wind tunnel contraction. To investigate the uniformity of the simulated ice cloud a rectangular grid composed by 6mm diameter rods was installed in the middle of the 2m long test section. The droplet size distribution was measured under different flow velocities, temperatures and humidity. Mean flow and turbulence were measured with the aid of a PIV (Particle Image Velocimetry) system. The supercooled large droplets were characterized through a Shadow Sizer system. The wind tunnel temperature was monitored with a set of thermocouples and a humidity sensor. A special sampling probe was developed for the measurement of the liquid water content, which is an important parameter for the prediction of ice accretion on aircraft wings and empennages. This experimental database establishes the operating envelopes of the Climatic Wind-tunnel of NIDF and quantifies its capability to produce large droplet icing clouds. For general icing investigation purposes, the wind-tunnel results are compared with FAA icing certification criteria.*

**Keywords:** *Icing wind tunnel, droplet size distribution, turbulence.*

## 1. INTRODUCTION

Structures exposed to severe temperature and humidity conditions are susceptible to different kinds of problems. However, there are specific environmental conditions where it is possible to have ice accretion on those structures, creating a bigger concern about safety and energy efficiency development. Nowadays, the aeronautic and energy industries are the most interested on studying the ice formation in different kinds of products and they acknowledge that scientific research related to this topic is a necessary step to achieve new technological solutions. Climatic wind tunnels are being used as an important tool on this investigation, since it can easily create an extreme condition (i.e. high velocity, low temperatures) in a controlled, safe and not so expensive way for different kinds of tests, including tests involving ice accretion.

It is possible to observe different types of ice formation, depending on the meteorological condition. The society of Automotive Engineers (SAE) has elaborated a series of tables describing patterns to determine each kind of accretion and also listed the measure techniques mainly used to acquire one of the most important parameters on this subject: the droplet diameter. Super-cooled large droplets (SLD) are the simplest yet critical parameter on this topic due to its hazardous nature to aircrafts, for example. A SLD makes larger ice shapes that spread faster than tiny droplets.

The climatic wind tunnel of NIDF/COPPE/UFRJ, located at the Federal University of Rio de Janeiro is the only climatic wind tunnel from the southern hemisphere and it is capable of reaching -12C and 27m/s with droplets around 192um of diameter. The droplet size was acquired with the Shadow Sizing technique and further details are presented through this article.

## 2. EXPERIMENTAL SETUP

The wind tunnel works as a closed circuit. The air gets into the cycle through the fan and passes by the evaporator, located at the top part of the tunnel. The air, which is circulating with a pre-determined velocity between x and y, becomes cooler than the refrigerant, reaching temperatures close to -20°C. Continuing the cycle, the air passes through a curve, reaching the bottom part of the wind tunnel. At this point, the air must pass through a mesh grid to make the flow less turbulent and then comes the contraction, a critical point of this circuit, since it controls the level of turbulence inside the wind tunnel. Finally, it reaches the test section: a 2m long and 0.3m wide glass section, where most of the data is collected.

At this section a NACA airfoil with hydrophobic properties was installed and the results can be seen at Froening et al. (2016). After the test section come the diffuser followed by a curve and an “S” shaped curve that leads the air back to the fan.

Besides the evaporator, the refrigeration system is based in two compressors working separately in automatic mode or manual mode. The automatic mode works together with the thermostat. Two set points can be chosen previously as minimum and maximum temperatures and the compressors will start or shut down automatically in order to keep them at the setpoint. A schematic image of the climatic wind tunnel can be seen at Figure 1.

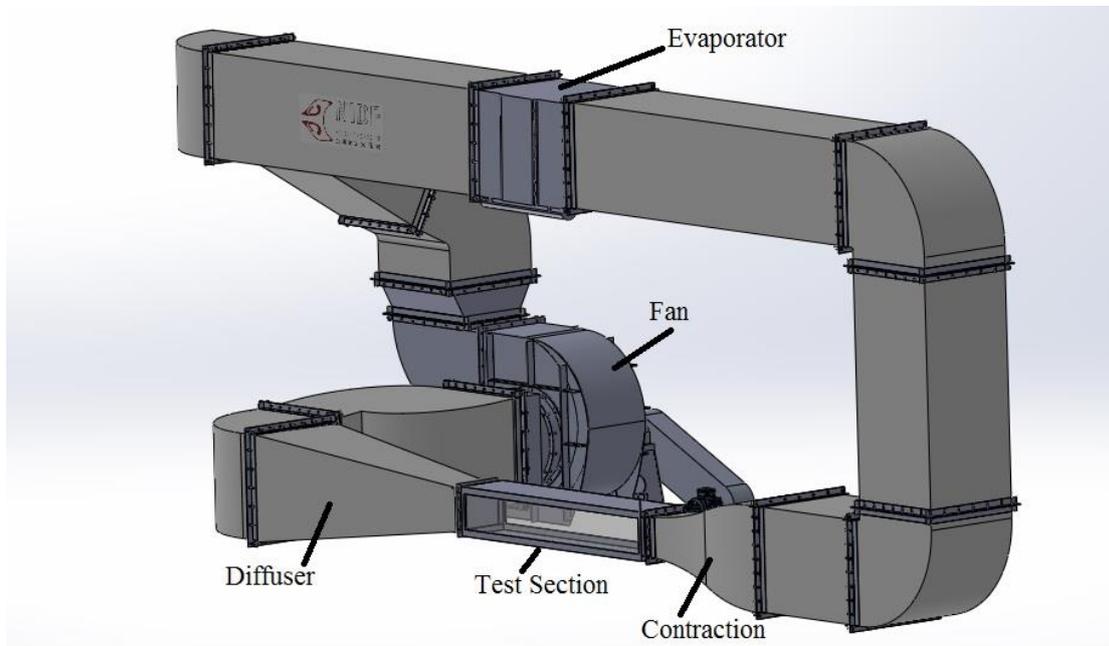


Figure 1: 3D tunnel representation.

The climatic wind tunnel is thermally insulated with glass wool, PVC plates and refrigeration tape. The junctions are isolated with rubber foam and the test section wall is made of two vacuum separated glass layers. At the roof, an acrylic plate was placed so it would be possible to have three transparent walls at this section, allowing the use of image based measurement techniques. Over the tunnel extension there are three points electrical resistance. The first one is at the test section with the main objective of defog the glass walls. The second one is located after the diffuser and the last one at the evaporator, to prevent the water from freezing and causing damage. With this configuration, it was possible to reach  $-12^{\circ}\text{C}$  with low humidity and velocity (i.e. 10% RH and 90 rpm fan rotation).

## 2.1 Spray bar system

In 2015 a study began in order to develop a way to add water droplets through the tunnel's flow. The motivation towards this idea was to improve the possibility of creating an environment that would correspond in a more realistic manner the atmospheric conditions. Hence, it was necessary to implement a system capable of generating a water cloud containing large droplets (around  $100\mu\text{m}$ ).

The spray system is made of 5 commercial pulverizing nozzles (Spraying Systems Co. 1/8JJAU + SUJ16-Q) located just before the contraction section. The nozzles were installed in 3 fixed bars. Bar number 1 and 3 contains 2 nozzles each separated of 5cm whilst bar number 2 contain only one centralized element (Figure 2(a)). This configuration was chosen to maximize the target area, concentrating the sprinkling both at the middle and periphery. Each nozzle has 3 different inputs: air, liquid and actuation. The hoses are connected in a control panel located outside where it is possible to manage each spray separately, giving the opportunity to try different set-ups, depending on the experiment. At this panel, three pressure gauges are located indicating the water, air and actuation pressures. The standard air pressure used is 2 bar and the water pressure is 3 bar. The control panel and the pressure gauges are shown on Figure 2b.

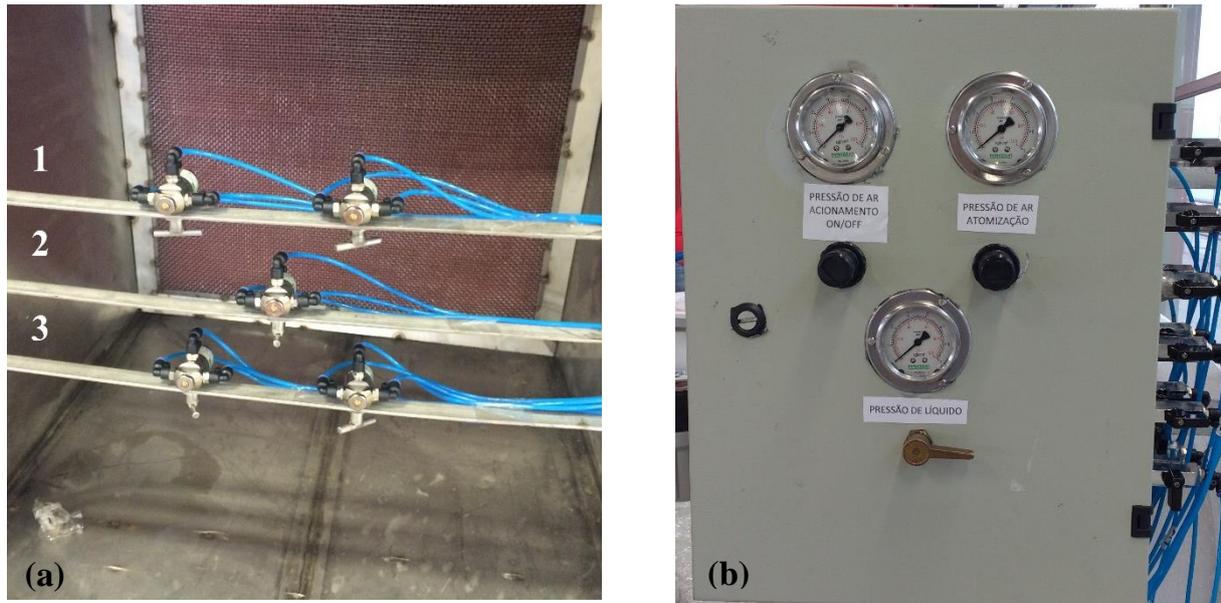


Figure 2: (a) Spray bar system; (b) Atomization control panel.

The nozzle performance data can be seen on Figure 3. As it shows, the nozzle used at the stated conditions has approximately 2.36gph in liquid capacity and 0.56scfm in air capacity. The nozzles are, however, susceptible to obstruction after certain amount of time. The spray system should run in room temperature before any test takes place so it can be cleansed. Water particles and even ice from previous tests on low temperatures can prevent the system from working correctly.

PERFORMANCE DATA		WIDE ANGLE ROUND SPRAY															*At the stated pressure in psi.					
Spray Set-up No.	Spray Set-up Consists of Fluid and Air Cap Combination	Liquid Capacity (gallons per hour)* and Air Capacity (standard cubic feet per minute)*															Spray Dimensions					
		Liquid Pressure																				
		10			20			30			40			60			Air*	Liquid*	A (in.)	B (in.)	C (in.)	D (ft.)
Air Press.	gph	scfm	Air Press.	gph	scfm	Air Press.	gph	scfm	Air Press.	gph	scfm	Air Press.	gph	scfm	Air Press.	gph	scfm					
SUJ16	Fluid Cap J2050 + Air Cap J67-6-20-70°	8.0	1.41	.36	14.0	2.10	.42	22	2.36	.56	30	2.53	.68	44	2.95	.81	10	10	5-1/2	7	9	5
		10.0	1.14	.43	16.0	1.90	.50	26	2.02	.69	34	2.23	.81	48	2.72	.94	20	20	6	7-1/2	9-1/2	6
		12.0	.79	.50	18.0	1.68	.56	30	1.61	.83	38	1.90	.94	55	2.30	1.20	34	30	6-1/2	8	10	7
		14.0	.45	.60	22	1.17	.71	36	.91	1.07	46	1.10	1.26	65	1.50	1.60	42	40	6-1/2	8	10-1/2	9
		-	-	-	26	.55	.90	40	.43	1.25	50	.69	1.45	75	.65	2.05	60	60	7-1/2	9	12	13

Figure 3: Performance data for the nozzle used. Font: Spraying Systems Co. Catalog page B26.

## 2.2 System operation

The wind tunnel operation consists in two important control systems. The first one is the tunnel itself. It can be controlled manually or automatically as explained on section 3. The automatic control works keeping the compressor on while the previously determined temperature is not reached. The temperature is measured by a thermostat located just before the contraction section and it is programmed to shut down the compressor as soon the tunnel's temperature reaches the desired condition. The manual control let the operator decide whether or not the compressor should stop. All the operations are made at a control shown on fig. 4.

Another important operation is the water aspersion. It could be seen at fig. 2 the control panel where the operation takes place. Everything is controlled manually what makes difficult to achieve certain parameters. The most critical situation is to repeat the water pressure every time an experiment is made. The water supply is the same as domestic ones, being stored at tank and pumped to the panel. To let the water flow to the sprays, a valve must be opened manually what makes extremely difficult to work since the pressure varies easily. Turn the water supply an automated process is one of the most important changes that will be done in the future.



Figure 4: Control Panel

### 2.3 Data acquisition

The Shadow Sizing technique was used to obtain the water droplets diameter with the 200mm lens. The camera is placed in front of the NACA airfoil while the light source (LED) stays right opposite. The shadow image of the object is captured by the camera and it is sent to the computer where these images will be analyzed with the proper software. At fig. 5, the schematic configuration is shown.

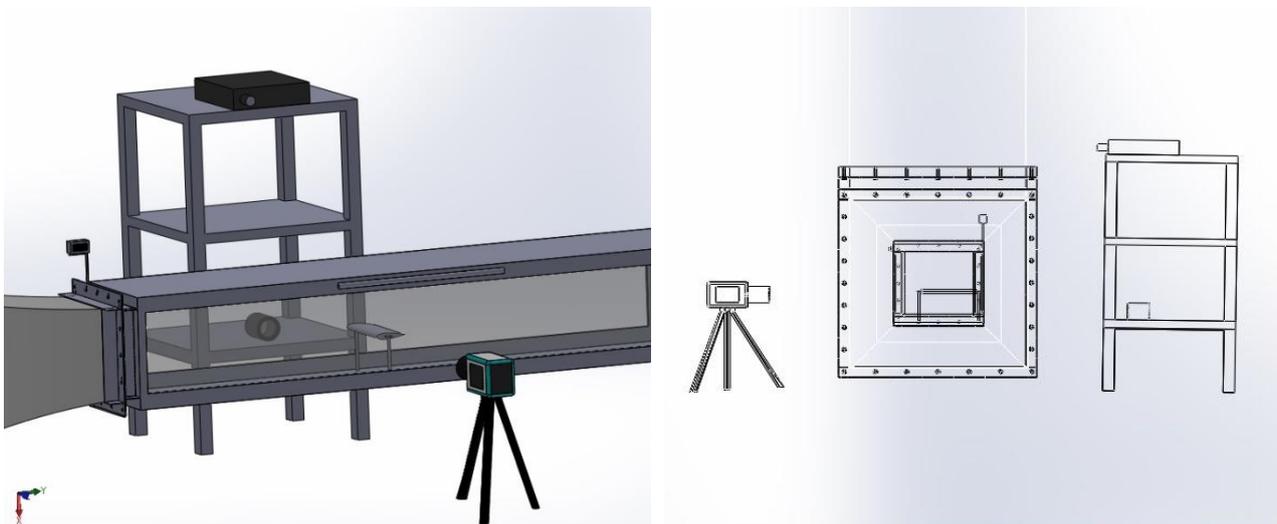


Figure 5: Schematic configuration.

This technique requires a safe environment since all equipment is extremely fragile and susceptible to damage. The lighting should be controlled so the lens doesn't get too exposed. To avoid any problem, a structure was built around the setup and a blackout evolved all the equipment.

### 3. RESULTS

In this section the results containing the droplet diameter, the aspersion homogeneity and the velocity and temperature reached will be shown. Those are good parameters to investigate the wind tunnel capacity, the spray bar system operation and characterization.

#### 3.1 Velocity

A climatic wind tunnel has the objective to achieve high velocities while keeping low temperature, so it was important to understand the tunnel's capability before getting further information. The velocity was measured using a Pitot tube located at the middle of the test section (1m after the contraction, following the flow direction) and in 3 different heights shown as A (235mm above the tunnel floor), B (155mm above the tunnel floor) and C (75mm above the tunnel floor). As fig. 7(right) shows, the pitot wasn't at the middle of the x axis of the graph. It happened due to problems with the pitot tube installation at the tunnel's floor. However, it still brings important results for this matter.

At fig. 7(left) there is a graph showing the flow velocity at different fan speeds.

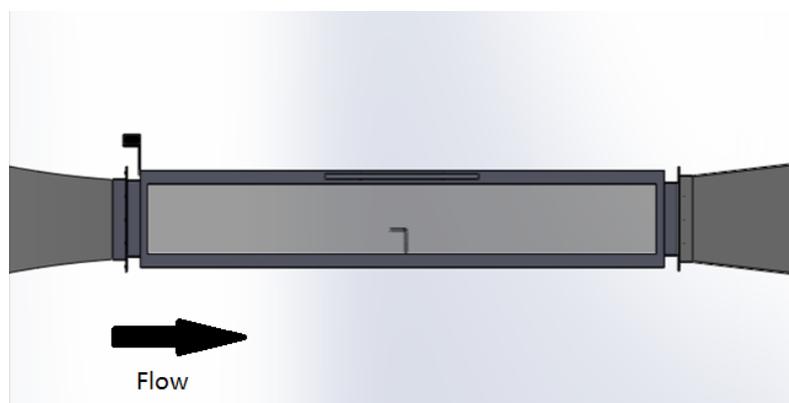


Figure 6: Pitot tube inside test section schematic view.

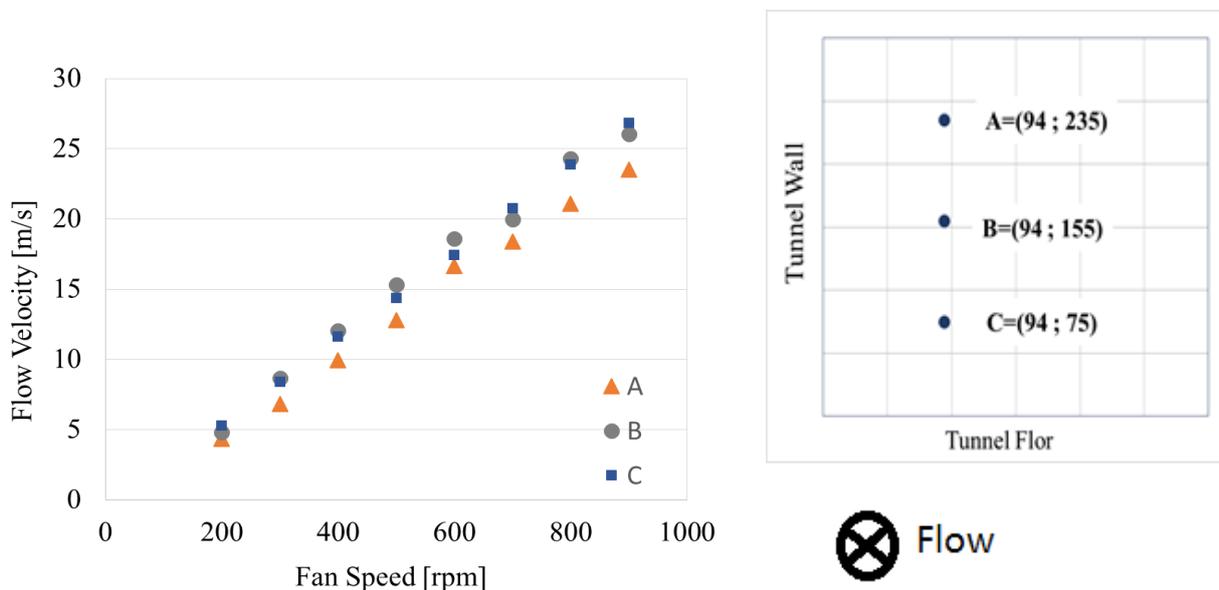


Figure 7: (Left) Flow velocity: variation on fan speed. (Right) Measurement points (all in the same axial position, at middle of the test section).

The pitot tube was connected with a manometer. Alcohol 46% was used in the process. The height difference obtained in the manometer is part of the equation below used to calculate the velocity. The alcohol density  $\rho$  was 0.788kg/L, while the air density  $\rho'$  was considered 1.183 kg/m<sup>3</sup>. The angle  $\alpha$  is related to the manometer inclination which was 21°.

$$v = \sqrt{\frac{2\Delta p}{\rho'}} \quad (1)$$

Where  $\Delta p = \rho \cdot g \cdot \Delta h \cdot \sin(\alpha)$

The results for the velocity distribution are similar to those obtained by Souza, (2014).

### 3.2 Ice accretion distribution

To observe the aspersion homogeneity is important to help finding out the best position for the nozzles. A qualitative research was made to comprehend the system's operation. A grid was positioned in the middle of the test section and received directly the water droplets pulverized by the nozzles. The first test was made with a simple grid at 500rpm and -1°C and, as can be seen on fig. 8, it seemed to have a constant deposition of ice, being concentrated in the middle. The spiked look shows that the water got at the grid in liquid state and drained through the previous ice accretion.



Figure 8: First ice distribution test. 3x3 grid.

The second test was conducted with a different grid and at this time it was easier to understand the ice distribution. The picture in Fig. 9 shows that the ice accretion occurred slightly more on the left side. The nozzles were probably not well aligned with the tunnel's section, since the nozzles do not have proper mobility. At this experiment, the temperature was kept at -8°C and 11.7 m/s was the velocity inside the test section. The use of 5 nozzles proved to be an excess, so from this moment, the nozzle located at the 2<sup>nd</sup> bar was always kept off.

A third test was made with only 4 nozzles from the configuration and it showed to be more effective at ice distribution.

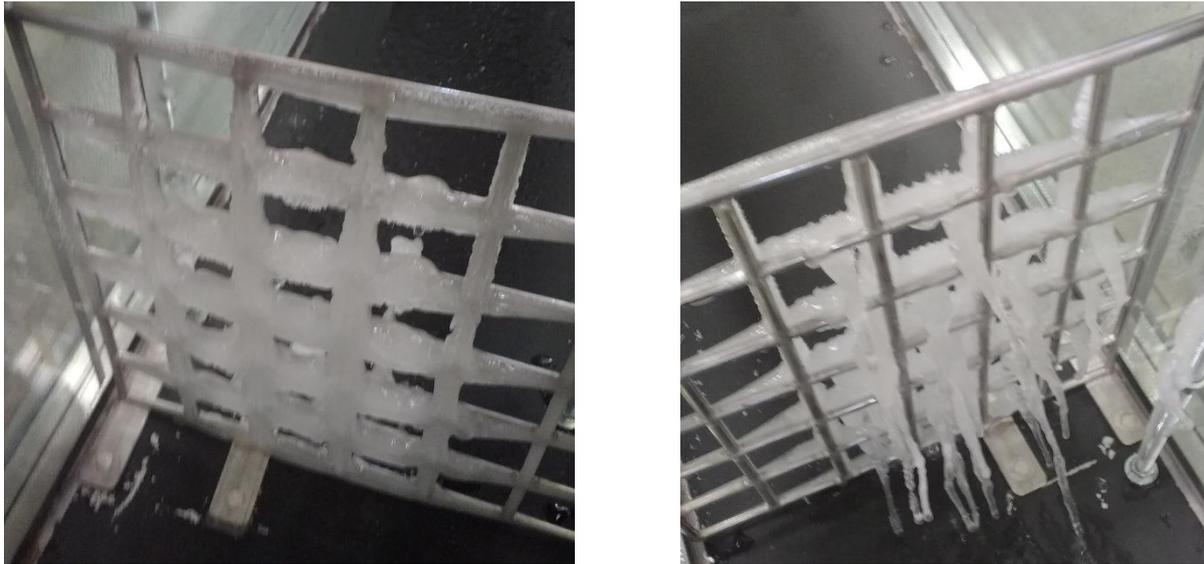


Figure 9: Ice accretion on 6x6 grid.

### 3.3 Droplet diameter

Using the Shadow Sizing technique, the water droplets diameter could be measured. The nozzles were working under room temperature (20°C) and air velocity at 11.7m/s. The air pressure was kept at 3.2 bar while the water pressure was 1bar. 25 photos were taken where 634 droplets could be identified. The median diameter was 0.196 mm with standard deviation of 0.043 mm, which is a positive result since a 100 µm diameter droplet can be considered large according to Wendisch et al. (2002). Also, some parameters such as the water and air pressures can be changed to get even larger droplets as seen on Miller and Addy (2005). Fig. 10 below shows the results obtained.

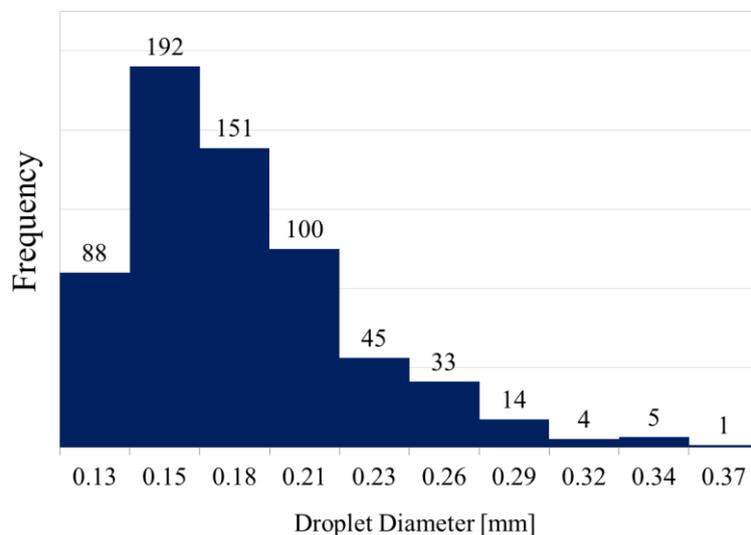


Figure 10: Droplet Diameter Histogram.

## 4. FUTURE MODIFICATIONS

Some modifications should be done in order to improve the tunnel capacity. Firstly, a better thermal insulation must be installed to reduce the temperature variation, what will bring more accuracy to future experiments and will avoid compressor related problems.

The water pressure control should be automatized due its importance for the median droplet diameter. While the operation occurs without a well-regulated pressure, some diameters cannot be achieved.

Each nozzle has only one position option turning it impossible to test different configurations that can produce better results on the tests made. Another complication is the difficulty of access. A study must be done to assess the possibility of installation of a hatch on the tunnel wall (close to the spray bars) to make it easier to reach the spray system without the need to open the contraction section, what takes too much time and effort. A hatch or a door, however, will create turbulence, hence, this project may not be pushed forward.

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