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Production of Artificial Fog in the PAVIN Fog and Rain Platform: In Search of Big Droplets Fog

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Abstract

In fog, visibility is reduced. This reduction in visibility is measured by t meteorological optical range (MOR), which is important for studying hum perception and various sensors in foggy conditions. The Cerema PAVIN & Rain platform is capable of producing calibrated fog in order to better analyses it and understand its consequences. The problem is that the drop produced by the platform are not large enough to resemble real fog. This can have a major impact on measurements since the interaction between electromagnetic waves and fog depends on the wavelength and diameter o droplets. To remedy this, Cerema is building a new platform with n equipment capable of generating fog. This study analyses different no and associated usage parameters such as the type of water used and the pressure used. The aim is to select the best nozzle with the associated parame for producing large-diameter droplets and therefore more realistic fog.

Keywords

Fog, Physical Simulation, Droplets Size Distribution, Meteorological Optica Range

1. Introduction

Fog is defined as the suspension of very small (usually microscopic) water droplets in the air. Fogs of all types originate when the temperature and dew point of the air become identical (or nearly so). Fog is then a concentration of water vapor in the atmosphere that forms a cloud near the ground. Fog can greatly impact transportation systems, causing safety issues and reduced mobility. The economic impact is significant, on a scale comparable to that of tornad [1].

When fog is present, visibility is reduced, which leads to an increase in accidents, particularly at night, and doubles the number of fatalities per 100 accidents [2], [3]. This reduction in visibility is measured by the Meteorological Optical Range (MOR), which is the distance at which a beam of light's intensity is reduced to 5% of its original value when passing through fog [4]. Fog is considered to be present when the MOR is below 1000 meters. This MOR measurement is important for studying human and device perception in foggy conditions

There are different types of fog with different formation mechanisms [5]. This can be classified into two big classes: advection fog and radiation fog. Other kinds of fog also exist, such as steam fog, ice fog, stratus-lowering fog, precipitation fog or upslope fog [6]. In order to take into consideration a large majority of cases, it is possible to focus only on radiation and advection fog types, which will be the case in this paper.

Radiation fog (RF) is a consequence of radiative cooling of the surface under the clear sky, the ground emits long wave radiation that causes an inversion of the temperature and allows air to reach its dew point. This type occurs during nighttime, frequently in continental climates. Advection fog (AF), or moist, occurs when warm air is flowing over water with different temperature. This type occurs frequently in coastal regions, as an example is shown in [7], results showed that radiation fog dominates at CYOD (Colt Lake airport) in summer while precipitation, advection and cloud-base-lowering fog mostly occur in fall and winter.

Beyond the formation mechanism, the fog is mainly characterized by the Droplet Size Distribution (DSD), which can vary in size from a few tenths of a micron to a few dozen microns [8] [1]. Advection fog contains droplet diameters higher than radiation fog [9]. The average particle size diameter (D_{mean}) can vary from 2 microns to 27 microns for natural fog, according to the literature [10].

As it has been said above, fog affects the perception of the environment and then becomes an issue to safety and mobility. It is therefore important to work towards a more precise understanding of the interactions between fog and electromagnetic waves. Fog droplets affect light transmission in the 350-2400 nm range, which can impact sensors that operate within this wavelength range [11]. Lidars, which often use wavelengths between 905 nm and 1550 nm, can be affected by fog, interpreting droplets as obstacles rather than the actual objects behind them. In particular, advection fogs with low visibility (V < 30 m) show the highest impact in the near-infrared range (1000 nm - 2400 nm). In practice, in dense fog, the behavior of lidars is affected because they detect the fog as a barrier in front of them.

Although many test campaigns have been performed [12] [13] [14], the major problem is that nowadays, it is still difficult to predict fog generation and therefore difficult to perform tests under controlled fog conditions. Some existing databases use data from artificial fog, unfortunately, it is rarely a calibrated one corresponding to actual realistic fog, for example in the databases NTIRE [15].

The Cerema PAVIN Fog & Rain platform is able to produce realistic calibrated fog. Today, however, the Cerema platform is only capable of producing fog with droplets of a maximum average diameter of around 8 microns [10]. However, as described above, advection fog can contain droplets up to 30 µm in diameter.

In order to compensate that, a new research and development platform called PAVIN Adverse Weather [16], with funding from the Auvergne-Rhône-Alpes region (France), will be built by Cerema.

This innovative platform will be capable of generating artificial fog and rain conditions, as today's platform. However, the internal thermal conditions will be particularly stable, enabling a very homogenous atmosphere crucial for fog generation and control. Its dimensions (50 m length and 7 m width) will be particularly adapted for setting up complex road scenarios and testing various sensors at the same time. One of the main objectives of the new PAVIN platform will be the ability to generate and control various types of fog in an even more realistic way than the current platform. This also results in a DSD that is also closer to that of natural fog. The new PAVIN platform will aim to generate fogs with droplets up to more than 20 microns, without increasing the total number of droplets. Ideally, it is the number of droplets with an average diameter of less than 5 microns that should be reduced.

In practice, for Cerema, this means finding the best configuration between the type of nozzle, the operating pressure and the type of water used. All of these parameters have already been studied over the years but never together in the field of fog. In fact, there is some work in the literature concerning the testing of different nozzle types and the impact on the distribution of the generated water droplets [17]-[26]. However, these works do not concern fog, but rather fire countermeasures [17], light rain [18], or anti-covid misting [19]. There is some work in the literature comparing fog nozzles and their DSD [20]: they tested different opening diameters and different pressures for a large number of nozzles and tried to draw conclusions about the impact of these parameters. However, in this study, the influence of water type was never tested. Cerema had conducted previous studies on the subject but with a single nozzle tested [21] with different water pressures or different types of water [22] [23]. Finally, there are works looking at the chemistry's impact on droplet size [24] in the field of agriculture for example [25] [26], but in these cases, the water is not pure and droplet size is larger than that of the fog (100 microns).

This article proposes the comparative study of six nozzles used with different opening diameters, water pressures and two different types of water. For each configuration, the DSD was analysed. More specifically, in coherence with what has been said above, the number of big droplets (average diameter D_{mean} greater than 20 microns) was analysed.

Firstly, the protocol and experiment are presented. Then the results obtained from the experiment will be shown. The analysis will initially cover all the nozzles studied and will then gradually focus on the nozzles with the best results in terms of quantities of big droplets. Finally, a conclusion is made on the best configuration between the type of nozzle, the pressure applied and the type of the water to produce bigger fog droplets in the next PAVIN platform.

2. Protocol and Experiment

In order to check the various parameters that have an impact on the size distribution of the droplets produced by the nozzle, it is necessary to plan a vast protocol. Firstly, the influencing parameters identified are the following ones: the opening diameter of the nozzle, the pressure applied to water going through the nozzle, and the type of water itself. All of these combinations need to be analysed in order to check the cumulative aspect of the parameters.

Six different nozzles from different brands were selected. They were chosen from a range of manufacturers and particular attention was paid to selecting nozzles with different opening diameters. Indeed, it is generally considered that there is a correlation between opening diameter and droplet size: the larger the opening diameter, the larger the droplet size produced by the nozzle [21]. The nozzles are renamed (nozzle 1, nozzle 2, nozzle 3, nozzle 4, nozzle 5 and nozzle 6) during the experiment, their characteristics are given in Table 1.

The pressure applied to water going through the nozzle is tested according to two configurations: the minimum and the maximum admissible pressure given by the manufacturers. More configurations could have been tested but would have had an important impact on the campaign test duration and were silenced then. Two types of water were tested, in accordance with the literature [22] [23]. Finally, 24 configurations were tested, as shown in Table 2.

Table 1. Nozzles characteristics (according to manufacturers)

Nozzle id	Opening diameter (mm)	Minimum admissible pressure (bar)	Maximum admissible pressure (bar)	Anti-drip valve
1	0.20	15	85	Yes
2	0.23	20	50	Yes
3	0.25	20	75	No
4	0.35	15	85	Yes
5	0.40	20	75	Yes
6	0.51	15	60	No

Table 2. Different combinations of setting protocol.

	Nozzle	Pressure	Water	Total
Parameters	Nozzle 1, Nozzle 2, Nozzle 3, Nozzle 4, Nozzle 5, Nozzle 6	Minimum, Maximum	Tap water, demineralised water	
Number of parameters	6	x2	x2	=24

Concerning the instrumentation part, different devices were used in order to measure the MOR and the DSD. The MOR, which gives macroscopical information on fog density, is measured continuously inside the tunnel of the PAVIN Fog and Rain platform thanks to a Degreane Horizon TR30 transmissometer (called MOR device then). This device involves passing a beam of light from a transmitter to a receiver. The attenuation of the luminous flow on the travel due to fog diffusion and absorption effects gives the MOR value. The fog DSD is measured thanks to the Palas PROMO 2300, a Particle Size Analyser (PSA device) which has a measurement range in droplet diameter from 0.6 µm to 40 µm. This range is consistent with the objective of analysing which combination of parameters produces the largest droplets (droplets are considered large enough when their diameter exceeds 15 µm).

For each configuration, 6 identical nozzles are arranged on the same horizontal ramp, generating fog within a large volume. The MOR device measures fog through a thickness of about 11 meters, while the PSA device is placed in the centre of the volume to limit edge effects. The PSA and the MOR devices are placed at the same height, 1.2 m from the ground. The whole test configuration is illustrated in Figure 1.

Once produced, fog was maintained at a stable density in the volume shown within schema 1, in order to get several measurements with the PSA and the MOR devices. Several stable densities were applied successively. Then, the dissipation process allowed us to obtain MOR until 100m (it is too difficult to maintain a stable fog at such a MOR value without too important variation). As the DSD measurement is difficult, the frequency of measurement was set to 0.1 Hz (time step of 10 s). The transmissometer gives the MOR measurement at the same time thanks to a temporal synchronization of the two devices.

The first experiment started the 05/23/2022 and the last one was the 06/06/2022. At the end of the test, 3611 data rows were obtained. However, as the measure is sensitive, a lot of filters were applied in order to only keep the

Figure 1 Schema of the experiment, and pictures of the facility.

most relevant data.

3. Data Pre-Processing

Firstly, a theoretical MOR value was calculated using the measured DSD and the Mie theory [10], in addition to the MOR measured with the transmissiometer. The following ratings are given for the rest of the article: V_{REF} (reference visibility), is the MOR directly measured by the transmissometer and V_{DSD} is the MOR calculated from the DSD measurements. In this way, data where the reference MOR and the one calculated from the DSD with a ratio bigger than 2 are filtered according to Equation (1) below. Indeed, as DSD is a complex and precise measurement, it can be very sensitive to local heterogeneities of fog. This filter enables to reduction of what can be considered as noise.

$$\frac{1}{2} \leq \frac{V_{DSD}}{V_{REF}} \leq 2 \quad (1)$$

It was also chosen to retain only data corresponding to a MOR between 10 and 100 m, as shown in the following Equation (2). Fogs with a MOR above 100 m are particularly difficult to keep stable and homogeneous, the corresponding data were also removed in order to reduce noise in measurement.

$$10\text{ m} \leq V_{REF} \leq 100\text{ m} \quad (2)$$

Finally, to retain the data where the MOR was stable enough for 10 s, another last filter on the standard deviation of the MOR was applied. The average and standard deviation on the MOR are calculated as a moving average on 10 s. Only data for which the standard deviation of the MOR was less than 10% of the mean were retained, according to Equation (3) below.

$$\frac{\text{std}(V_{REF})}{\text{mean}(V_{REF})} \leq 0.10 \quad (3)$$

After all the above described pre-processing operations were applied, 820 data points were kept. For all these data points, the V_{REF}, V_{DSD}, the DSD itself, the type of nozzle and the pressure according to Table 1 are available.

The data are globally spread correctly with more data for small visibility as shown in Figure 2. In fact, the thickest fogs were favoured as they are the most used in the PAVIN platform studies. However, there is a disparity according the nozzles. Indeed, Due to the poorer quality of the data obtained for certain test configurations and pre-processing operations putting aside some data, nozzles 3 and 5 are less represented than others in the dataset. The analysis of these nozzles is therefore only partial.

With the aim of finding a nozzle that produces larger droplets, other DSD-derived parameters were calculated: Ntot, the total number of produced droplets expressed in particles × cm^3 and the mean diameter Dmean expressed in microns. These last two parameters have already been shown in a previous study that there are more discriminating [10].

Finally, the total number of droplets with diameters between 2 and 5 µm and

Figure 2 Data distribution according to the visibility (MOR) and different set of parameters. (a) is showing the amount of data corresponding to the combination of tap water and the minimum pressure allowed by the nozzle. (b) is with tap water and the maximum pressure. (c) is with demineralised water with minimum pressure combination. (d) is with demineralised water with the maximum pressure parameter that have been chosen

between 15 and 40 µm was counted. They are respectively called Nsmall and Nbig. The two droplet diameter ranges were chosen to highlight the small and large droplets of the DSD. Indeed, in the literature on natural fogs, droplets are considered "big" when they have a diameter between 20 to 50 µm, while droplets are considered small when their diameter is around the micron. Moreover, as the biggest droplets reachable by the current PAVIN platform have a modal diameter centre on 8 µm [10], it has been chosen to avoid on purpose this diameter range because these droplets are in fact medium droplets for natural fog.

After this first part of the global analysis on ad hoc and filtered data, a second analysis nozzle by nozzle is carried out for a more in-depth study. For this purpose, a different approach is used: the MOR is still filtered between 1000 m and 1 range of visibility but the data are not filtered anymore in order to have more data point. Then, to ensure that the observations and analysis made on the results are valid whatever the MOR, the data were divided into 12 sets of the same size (MOR quantiles) and averaged for each set. This second analysis enables us to determine which nozzle would be the most relevant to produce big droplets and also to better understand the cross-impact of water type and pressure type on each nozzle. To do this, it is suggested to look at the change in the Dmean from tap water to demineralised water. This is done thanks to the calculation of the Dmean discrepancy that respect the following Equation (4) below where x represents one of the three other pressure type/water type combinations.

$$\Delta D_{mean} = D_{mean,x} - D_{mean,\text{tap water}/\text{max press}} \quad (4)$$

This analysis of the Dmean discrepancy is represented for all the combinations available. In this way, if the Dmean discrepancy is positive, this would mean that there was a gain (bigger droplets) compared to the nominal condition considered with tap water and maximum pressure. This would allow us to quickly visualize which is the best combination for each nozzle.

Finally, in the last part, the DSD of the most relevant nozzles, water type and pressure type combination will be presented and compared.

Now the method has been presented, this one is applied in the database, and the obtained results are shown in the next section.

4. Results

The data analysis will be in two parts. To start, a general study of the parameter is suggested. This will aim to draw a conclusion on the big tendency of the available parameters (type of water, type of pressure, nozzle) before digging the response of each nozzle. This study per nozzle will come in a second time.

4.1. Global Influence of Pressure and Water Type

Firstly, it is interesting to check the influence of the type of water and pressure on the DSD obtained for each nozzle. Indeed, on the actual PAVIN platform nozzles (nozzle 2), [10] has shown that demineralised water allowed bigger droplets diameter (8 microns vs 1 microns) than tap water for a maximum pressure, that while keeping the same nozzle.

Figure 3 shows Nsmall depending on Nbig for all the nozzles. In this figure, all the nozzles and MOR are plotted without distinction. A dense fog (MOR = 10 m) will then be placed in the right-up corner of the figure (a lot of droplets, of any size). Contrary to a light fog (MOR = 100 m) which will be placed on the left

Figure 3 Nbig depending on Nsmall for all the nozzles with different combination of water and pressure.

bottom corner of the graphic. Thanks to Figure 3, a first conclusion can be made on the fact that using the minimum pressure is generally the best way to produce bigger droplets: the blue and orange scatter plots present a lot of big droplets for the same number of small droplets. Then the figure shows that the use of demineralised water with the minimum pressure is the second way in order to produce bigger droplets (orange scatter plot vs. blue scatter plot). After this first global analysis, it is interesting to check which nozzles are the most persistent for the production of large drops.

4.2. First Selection of Nozzles

From now on, it is possible to globally check which nozzles may be the most relevant. Figure 4 shows Ntot according to Dmean for all the nozzles. The data were sorted by nozzle, the type of water and pressure but not on the MOR. On this figure, dense fog points correspond to big values of Ntot and Dmean. On the contrary, the lightest fogs are generally obtained for small Ntot and Dmean values. The most relevant nozzles are the ones that produce fog containing big droplets, according to this results representation so it is when Dmean is big independently of the Ntot.

From a general point of view, without carrying the difference linked by the type of water or the type of pressure, the nozzle 4 can be identified as less relevant as it produces only small droplets. On the contrary, the nozzles 1, 2, 3, 5 and 6 seems to be more relevant. The nozzle 4 is then excluded for the rest of

Figure 4. Ntot depending on Dmean for all the nozzles with different combination of water and pressure respectively the minimum pressure and the maximum pressure. Meanwhile (c) and (d) are the same combination than (a) and (b) but with demineralised water instead of tap water.

this study.

Then, doing a focus on the impact of the type of water and pressure, some discussions can be made. First of all, the combination allowing the highest values of Dmean is tap water with the minimum pressure for the nozzles 1, 3, 5 and 6 and demineralised water with the maximum pressure for the nozzle 2. The latter is the nozzle type installed on the current platform PAVIN, then this result is coherent with previous studies [14] [23] [22] [10] [21]. The tap water and maximum pressure combination never allows to production of bigger droplets whatever the nozzle used. The water type seems not to have a big impact on the nozzle 1. Due to a lack of data on the nozzles 3 and 5, it is not possible to conclude on the impact of the type of water. On one hand, the demineralised water passage allows the production of bigger droplets for the nozzle 2 and the maximum pressure. On the other hand, the demineralised water passage seems to reduce the droplet size at minimum pressure for the other nozzles. The type of water does not have an impact on the other cases. Finally, the pressure is the parameter that seems to have the biggest impact on most of nozzles. Reducing the pressure generally allows for an increase the droplet size, this result is coherent with previous studies. It can also be noted from this analysis that the diameter of the orifice and the anti-drip valve does not allow the nozzles to be sorted according to the size of the droplets produced. The brand of the nozzle and its design has probably more influence on the size of the produced droplets. Nozzles 2 and 4 behave differently, even though their orifice diameters are in the same range as those of nozzles 1, 3, 5 and 6 (nozzles are numbered in order of orifice diameter, from smallest to largest).

After this global and synthetic study over the nozzles, the type of water and pressure, it is necessary to check in detail for which combination the biggest droplets are obtained. As the water and pressure influences are not the same for each nozzle, an analysis of the impact nozzle by nozzle is made. The main objective is to identify the differences in behavior between nozzles 1, 3, 5 and 6, and nozzle 2 in particular (as a reminder, nozzle 4 was excluded as it produces only small droplets).

4.3. Choice of Water Type and Pressure for Each Nozzle

The purpose of Figure 5 is to see how the change in the type of water and pressure affects the droplet size produced by each nozzle. Thus, Figure 5 shows the evolution of Dmean, compared to the reference condition. The reference condition chosen is the maximum pressure and tap water, as this is currently the option present in the current PAVIN platform for the production of small droplet fog. The idea here is to check if a diffuser would be able to produce both a small droplets fog and a large droplets fog, by changing the type of water and/or the pressure only. So, such a diffuser, with a large gap between two settings, would be able to produce two types of fog in the platform.

According to Figure 5, for all nozzles except nozzle 2, the minimum pressure

and tap water are the best combinations to maximize the mean diameter of the DSD. For these same nozzles, using demineralised water presents no added value, compared to apply the minimum pressure. For the nozzles 1 and 6, using demineralised water even produces a decreasing of the Dmean, which goes in the opposite direction of the desired objective. The demineralised water is very interesting with the nozzle 2 because it allows to increase the size of the droplets. It should be noted in the current PAVIN platform, bigger droplets fogs are obtained by switching from tap water to demineralised water (nozzles 2 are used in both case). This result is then coherent with previous studies [10], but it is actually a quite specific behavior observed only for the nozzle 2 in this study. One potential explanation could be a particular internal design of the nozzle 2, indeed it is a brand with no other representative in this study.

The nozzles 1, 3, 5 and 6 are more interesting in producing bigger droplets with the combination of minimum pressure and tap water. The nozzle 2 with the maximum pressure and demineralised water produces bigger droplets, but the impact is less important than low pressure for nozzles 1, 3, 5 and 6. If we are looking at the nozzles for which the difference in droplet size is the most important according to the applied parameters, the nozzle 1, 5 and 6 are those for which the diameter evolves the most by changing the pressure. This is interesting because for the future application in the platform, the idea is to be able to change the type of fog, without having to use two sets of nozzles. A nozzle that has a large droplet size evolution when changing the pressure is therefore better from this point of view.

It is now important to check which nozzles produce the largest droplet diameter, for their best set of parameters (water type and pressure). Then, for the rest of the paper, the data are filtered once again as they were in the beginning of the article.

4.4. Final Choice of Nozzle

The standard use in the platform to obtain the fog with big droplets is the combination of the nozzle 2 with demineralised water and maximum pressure. This nozzle will serve as a reference for future analysis, the aim being to select a diffuser with better performance in terms of the presence of large droplets.

Figure 6 shows the DSD curve obtained with the best configuration (water type and pressure at minimum or maximum value) previously seen for each nozzle in order to produce the biggest droplets. Each sub-graph corresponds to a different MOR range, all of them being between 10 and 100 m.

The first result is that there are significant differences among the different MOR ranges, to go further the best nozzles in terms of big droplet production are not the same according to the MOR. So, it is important not to only focus on one MOR but to have an overall view on the tendency of the nozzles. With that point in mind, the nozzle 1 looks like the best nozzle within the (a), (b), (c), (d) and (f) graphs, especially for droplets with a mean diameter superior to 15

Figure 6. DSD for all satisfying nozzles for different MOR ranges. (a) represents the 16–19 m range, (b) the 19–21 m range, (c) the 21–25 m range, (d) the 29–35 m range, (e) the 35–41 m range, (f) the 41–50 m range, (g) the 50–68 m range and (h) shows the 60–100 m range.

microns. In the same way, the nozzle 2 used as reference here seemed to be the nozzle producing the smallest droplets. A second way to analyse Figure 6 can be made by observing the nozzles doing fewer small droplets (with a diameter under 10 µm). In this way to analyse, the nozzle 1 is still the best nozzle producing fewer small droplets than any other nozzles whatever the MOR range. As a last observation, we can see that the results of nozzle 1 are very good for dense fogs (MOR inferior to 50 m, sub-graphs (a), (b), (c), (d), (e) and (f)) but for lighter fogs (MOR between 50 and 100 m, sub-graphs (g) and (h)) all the nozzles produce droplets of similar mean diameters.

In the end, all the nozzles in their best configuration are better than the nozzle 2 currently in use, insofar as it is possible to find a configuration that allows the production of larger droplets. However, the results show that the production of bigger droplets depends on the MOR even if the nozzle 1 is globally better. As the study in the previous section (Figure 5) showed nozzle 1 also has the advantage of having a large difference in droplet sizes depending on the pressure, it is this nozzle that is selected in the end. The next part proposes a final comparison between nozzle 1 (future use) and nozzle 2 (currently in use) to see in more detail the potential gains obtained for the future platform.

4.5. Final Comparison between the Actual Nozzle and the Future Nozzle

Figure 7 shows the DSD for the nozzles 1 and 2, each one used for two different configurations. One configuration corresponds to the production of a fog with the biggest droplets possible, the other corresponds to the production of a fog with smaller droplets. They are respectively entitled "Big" and "Small" within the legend of the graph. In the case of nozzle 2, these 2 configurations are obtained by changing the type of water between tap water and demineralised water, whereas for nozzle 1, the DSD changes are obtained by changing the pressure. Figure 7 proposes different sub-graphs in order to show the comparison for different MOR ranges.

The first observation is that for some MOR ranges and for nozzle 2, there is not a significant difference between the biggest droplet configuration and the smaller one. In contrast, the two configurations obtained with nozzle 1 have very distinct curves, especially when the MOR is up to 50m: the "big droplets" fog configuration has much larger droplets than the "smaller droplets" configuration. For a MOR beyond 50m, all the combinations produce similar fog DSD. To be noted, in these high MOR cases, the number of big droplets in only between 1 and 10 per cm3. Figure 7 also shows that nozzle 1 produces a "smaller droplets" fog similar to that obtained with nozzle 2. Nozzle 1 then produces the same "small droplets" fog as nozzle 2, while producing a "biggest droplets" fog with many more large droplets.

In order to better quantify these results, an analysis of the mean diameter of the different DSDs obtained as a function of MOR is proposed. Figure 8 shows

Figure 7. DSD for nozzle 1 (selected as best nozzle) and nozzle 2 (currently used nozzle) for different MOR ranges. For both nozzles, the "biggest droplets" and "smaller droplets" fog configuration DSD curves are shown. (a) represents the 16 - 19 m range, (b) the 19 - 21 m range, (c) the 21 - 25 m range, (d) the 29 - 35 m range, (e) the 35 - 41 m range, (f) the 41 - 50 m range, (g) the 50 - 60 m range whereas (h) shows the 60 - 100 m range. SD for all satisfying nozzles for different MOR ranges. (a) represents the 16 - 19 m range, (b) the 19 - 21 m range, (c) the 21 - 25 m range, (d) the 29 - 35 m range, (e) the 35 - 41 m range, (f) the 41 - 50 m range, (g) the 50 - 68 m range and (h) shows the 60 - 100 m range.

Dmean as a function of MOR range, for nozzle 1 (selected nozzle) and 2 (currently used nozzle) with their biggest and smaller droplets configuration settings. In Figure 8, the small droplets fogs produced by nozzle 1 and 2 are very similar, with an almost constant Dmean of 3.0 microns on average for nozzle 2 and 3.2 microns on average for nozzle 1. Conversely, nozzle 1 achieves an average Dmean of 7.8 microns for a MOR below 50m for the biggest droplets configuration, compared to only 5.0 microns for nozzle 2. This represents a gain of 56% on the average mean diameter of the DSD thanks to the new identified nozzle.

Figure 9 shows the change brought about by nozzle 1 compared with nozzle 2

Figure 8. Dmean for nozzle 1 (selected nozzle) and nozzle 2 (currently used nozzle) for different MOR ranges. For both nozzles, the 2 fog configurations, that of the biggest droplets and that of the smaller droplets, are shown.

Figure 9. The number of big droplets, Nbig, for nozzle 1 (selected nozzle) and nozzle 2 (currently used nozzle) for different MOR ranges inferior to 50m. For both nozzles, the 2 fog configurations, that of the biggest droplets and that of the smaller droplets, are shown.

in terms of the number of large droplets per cm³, Nbig. Thus, for MOR below 50 m, Nbig goes from 50 particles/cm³ for nozzle 2 on average to more than 100 particles/cm³ for nozzle 1, this represents a very important gain, with a number more than double.

5. Conclusions

We have proposed a comprehensive protocol to seek to produce a variety of artificial fogs that are representative of reality. As there are naturally fogs containing small droplets (1 micron), and fogs with much larger droplets (>20 microns), it is important for Cerema to be able to reproduce this variety. For this, we have identified in the literature that the type of nozzle (orifice diameter, brand), the pressure or even the type of water (tap or demineralised) can lead to produce droplets of different diameters. We then set up a complete protocol, with 6 nozzles of different orifice diameters and brand, two pressures and two types of water. This protocol used a PSA, in order to obtain the DSD of the fogs obtained for all the MORs over the 10-100 m range. This range of MOR is indeed usual for the tests within the PAVIN fog and rain Cerema platform.

Among the conclusions, it is confirmed that the pressure and type of water have an impact on the DSD obtained by certain nozzles, although this impact is not always the same depending on the nozzle. The type of nozzle itself also has an impact on the DSD: the nozzle brand and design seem to have as much impact as the orifice diameter alone. For all the nozzles, the combination of parameters tap water and maximum pressure never allows the production of big droplets. For the nozzles 1, 3, 5 and 6, the smaller the orifice diameter, the larger the droplets produced. Moreover, for these nozzles, the pressure is the parameter that has the biggest impact: putting the pressure down generally allows the production of bigger droplets. The nozzles 2 and 4 behave very differently from the others. The nozzle 2 is the one used in the current PAVIN platform and was then kept as a reference in the study as the objective was to find a better configuration. On the contrary, the nozzle 4 was quickly excluded as showing not interesting results. A detailed study of the impact of pressure and type of water confirmed that it was possible to generate two very different fogs with a single set of nozzles.

Finally, the nozzle 1 seems to be the best one according to the different results, in order to produce both big and small droplets fog. With this nozzle, we can produce a fog of small droplets similar to that which can be generated in the current platform. On the other hand, nozzle 1 can still generate a fog with droplets whose average diameter (Dmean) is 56% greater than in the big droplets fog generated by the current platform. This result seems to go against the literature, however, it can be explained by the process used in the platform. Indeed, the smaller the orifice, the lower the water flow rate injected and the longer the production time. Then, regular production allows to maintenance of a high number of large droplets. This is particularly true for MOR below 50 m, however, above 50m, all nozzles seem to produce similar droplet sizes.

For a future study, it would be interesting to test different PSA in order to counterbalance the complex measurement. For that purpose, developing a universal method on radiative transfer to come back to the mean DSD would be a good approach to explore. In order to explore the relationship between the nozzle and DSD in a different way, a study on the modelling of nozzle microphysics could be interesting in order to validate the impact of pressure on droplet size. Finally, to improve DSD control for all fogs, even the lightest with a MOR greater than 50m for example, it could be useful to do micro injections of fog in order to add big droplets regularly. Similarly, exploring nozzles with even smaller orifices, or reducing the number of nozzles to inject water more often could be good ideas.

Author Contributions

Conceptualization, P.D. and S.L.; methodology, P.D., S.L. and M.FF; software, P.D., S.L. and M.FF; validation, P.D. and S.L.; formal analysis, P.D.; investigation, P.D., S.L. and M.FF; resources, P.D., S.L. and M.FF; data curation, P.D., S.L. and M.FF; writing—original draft preparation, P.D. and M.FF; writing—review and editing, P.D., S.L. and M.FF; visualization, M.FF; supervision, P.D.; project administration, P.D.; funding acquisition, P.D. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement

The data and code presented in this study will be openly available in 2025.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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