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**DEVELOPMENT OF HYDRO JETTING NOZZLES FOR INSULATOR  
WASHING**

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**Abstract.** *The activities of insulator washing are crucial to ensure the maintenance of the electricity supply, avoiding power outages due to malfunctioning of the insulators caused by salt spray deposited, especially in coastal regions, also due to environmental pollution. During the development of an intelligent system for washing distribution network insulators, it was observed the need for studying the hydro jetting nozzles to be used in the washing fluid outlet, in order to ensure the achievement of the desired requirements in the cleaning procedure. The objective of this work is to present the development, evaluation, and selection of hydro jetting nozzles. To characterize the nozzles, a performance simulation was carried out with a range of opening diameters, pre-selected from the literature. From the manufacturing of nine designed nozzles, bench tests were performed aiming to verify the jet behavior for each of them, concerning the monitoring of the working system pressure, spray opening, impact force measurement and flow rate. The results indicate that there is an increase in the pressure and flow rate as the passage diameter increases. To define the best nozzle for use, insulator washings were performed and the efficiency of each nozzle was evaluated, considering the visual aspect and its respective water consumption.*

**Keywords:** *hydro jetting, insulator, insulator washing, nozzle.*

## 1. INTRODUCTION

Insulators are important components of the electric power transmission and distribution systems. Their characteristics are significant for the safety and reliability of distribution networks. The accumulation of pollution on the surface of insulators can result in failures due to the flashover phenomenon, which consists of partial discharges caused by the corona effect that occur in transmission and distribution power lines. In order to minimize these failures, insulators are washed preventively (Nader et al., 2022).

Regions, especially coastal areas, where insulators are exposed to the deposition of saline pollution, require greater attention regarding their maintenance. During dry periods, saline pollution tends to accumulate on insulators, creating a path between the energized and non-energized parts, making the insulator ineffective in its function (Moutinho, 2021). Besides being a nuisance for power utilities, the general population is also negatively affected by such failures. The consequence of this is the compromise of electricity supply, leading to interruptions in various areas of development and impacting society.

With the development of an intelligent system for washing electrical insulators in distribution networks, the relevance of studying hydro jetting nozzles in washing applications has been realized, both in terms of the parameters that influence the process and the development of models for physical testing.

To deepen the understanding of the phenomenon of high-pressure water jet formation and trajectory in the insulator washing process, a study was conducted in conjunction with literature on the subject. This study aims to characterize the hydraulic system and nozzles of a high-pressure washing system, compare the behavior of nozzles with different diameters, considering velocity, pressure, and trajectory, and select the nozzles with the most suitable behavior for the system.

Research conducted in the literature shows that in recent decades there have been several studies related to fluid dynamics in hydro jetting nozzles, whether for cutting or washing purposes. The current knowledge regarding washing hydro jetting is mostly derived from experiments, especially due to the complexity of the viscous interaction of the water jet with the air, which is difficult to reproduce through analytical and numerical modeling (Urazmetov et al., 2021).

According to Eggers and Villermaux (2008), a good understanding of fluid jet dynamics is crucial for the design of hydro jetting nozzles, adapting them to the desired application. It is necessary to initially define the type of application. With this in mind, the concepts of fluid dynamics can be related to the geometry of the nozzle, considering its diameters and angles, as a starting point.

It is known that there are four regions in hydro jetting: the flow in the nozzle, occurring in a closed duct and turbulent regime; the initial region (referred to as the potential core region), where the water jet has a continuous flow; the main region, which consists of a mixed zone of water jet and water droplets due to contact with the air, generating a region of droplets and another of mist, with negligible velocity; and the final region (diffuse droplet region), which represents the water jet completely broken into droplets with negligible velocity, making it useless for the washing process. In the main region, the closer the jet flow distance is to the centerline, the bigger the water droplet size and consequently the higher the concentration of the droplet flow. This results in a gradual expansion of the jet flow section and a reduction in velocity and pressure (Leu et al., 1998) (Rajaratnam and Albers, 1998).

Thus, it is evident the dynamic relation between the characteristics of washing nozzles and the type of jet each one can provide, necessitating the adaptation of this dynamic to the desired application and optimizing it in order to minimize resource waste and increase system efficiency.

The remainder of this article is structured as follows. Section 2 discusses the numerical approach used for the design of the washing nozzles. Section 3 focuses on the development of the nozzle models. Section 4 presents the obtained and discussed results. Section 5 concludes the paper.

## **2. NUMERICAL APPROACH**

### **2.1 Literature reference**

Due to the jet structure, mentioned in Section 1 and illustrated in Figure 1, Leu et al. (1998) state that the optimal cone for the washing process is contained within the main region of the jet, where sufficient velocity, spray opening, and pressure can be found for effective washing.

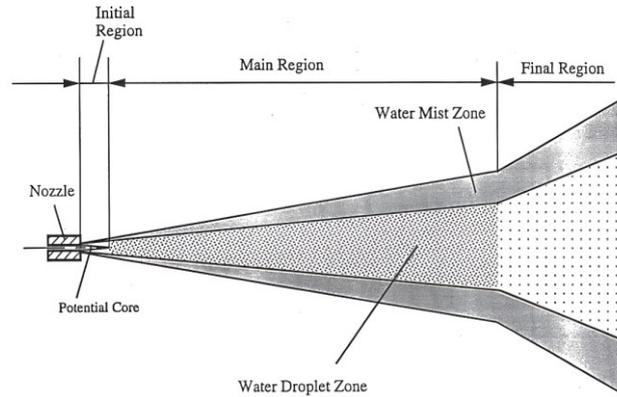


Figure 1. Stages of high-speed water jets in air. Leu et al. (1998).

The stagnation pressure of the jet is defined by the central pressure line on the target object. According to Leach et al. (1966), regarding the pressure distribution of a target positioned at a distance from the washing nozzle, the jet pressure decreases as the distance from the working surface to the nozzle outlet increases, which means that depending on the required force, pressure, and distance for washing, the procedure may become ineffective.

The concept of critical washing distance is defined as the shortest distance from the nozzle outlet at which the jet loses its ability to remove material from a surface. This concept also demonstrates the dependence of this distance on parameters such as nozzle diameter, jet velocity at the nozzle outlet, and water pressure generated by the pump. Within this context, the nozzle diameter is directly related to the mass flow rate (Leu et al., 1988) (Rajaratnam et al., 1994).

The impact pressure distribution of the jet and critical washing distance can be observed in the schematic diagram in Figure 2.

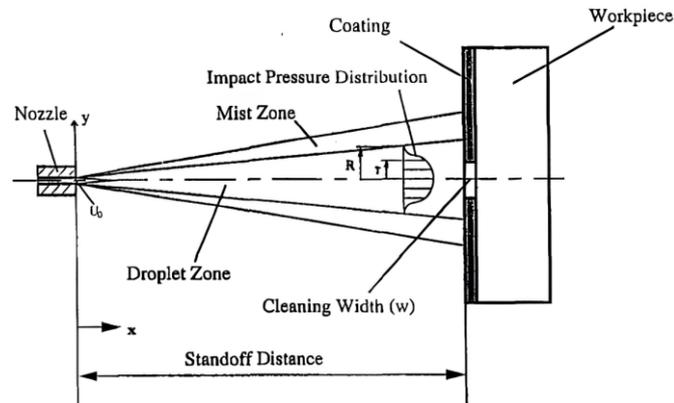


Figure 2. Water jet cleaning scheme. Leu et al. (1998).

The spray opening of the jet is inversely proportional to the jet pressure at a specific point, as an increase in the spreading cone radius leads to bigger contact between water and air, resulting in a less concentrated flow in the propagation direction and a subsequent pressure drop (Guha et al., 2011).

## 2.2 System used and the influence of nozzle diameter

Regarding the system used to perform the washing nozzle tests, the motor pump provided by the water supply system has the positive displacement type, meaning it operates with a constant flow rate for each cycle. The operating limits of the component are 128 l/min for flow rate and 120 bar for pressure. In order to optimize the pump utilization, it is necessary to respect the boundary conditions for estimating the theoretical velocity and flow rates for each nozzle diameter condition.

Considering water consumption, there is an interest in understanding the relation between water flow rate and nozzle diameter. This is due to the fact that certain diameter ranges imply minimum flow rates, limited by the maximum system pressure. On the other hand, other diameter ranges would be limited by the system flow rate, resulting in low pressures and consequently reduced velocities. Figure 3 illustrates the results obtained for nozzle diameters ranging from 0.5 mm to 8.5 mm.

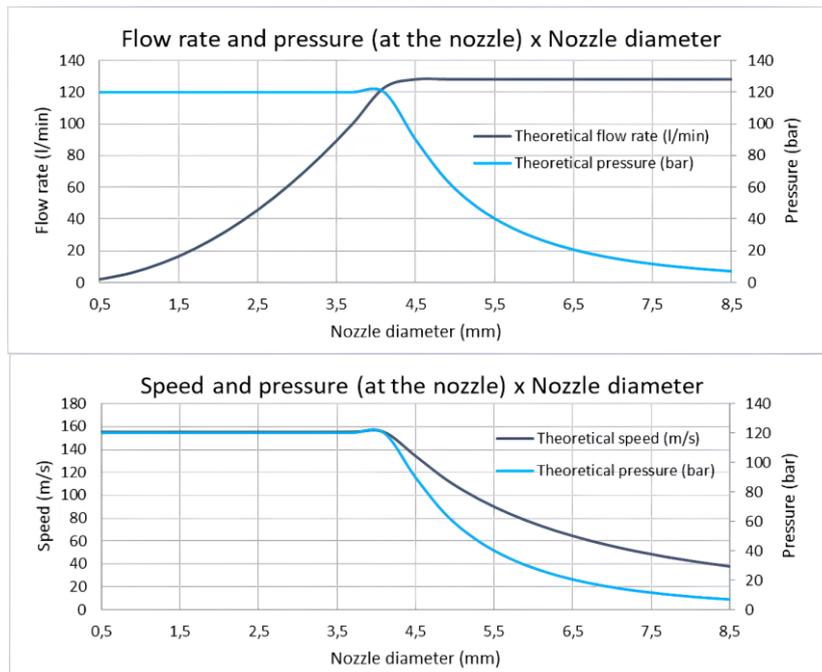


Figure 3. Water jet theoretical pressure, flow rate and speed in function of the nozzle diameter.

Based on this, it can be observed that nozzles with diameters larger than 4.25 mm operate at the flow rate limit, while also experiencing a significant initial reduction in jet velocity. On the other hand, nozzles with diameters smaller than 1.5 mm operate with a significantly reduced flow rate (less than 10% of the motor pump's nominal flow rate) at the maximum flow condition of the pump, resulting in low rotation and high torque of the assembly (undesirable working condition). Therefore, disregarding the pressure loss in the system's pipes, valves, and connections, it can be said that a good range for the nozzle hole diameter is between 2.5 mm and 6 mm, from the perspective of pump operation.

By applying the equations presented in the works of Rajaratnam et al. (1994) and Guha et al. (2011), it is possible to estimate the properties of the water jet based on the distance from the nozzle and its diameter. Figure 4 shows that the jet velocity (for diameters ranging from 2.5 mm to 6.5 mm) decreases almost linearly in the region between 200D and 2500D, where "D" represents the nozzle diameter (in millimeters). This velocity is calculated for the center of the jet, as in longitudinally distant regions, there is a bigger dispersion of the jet and a decrease in velocity.

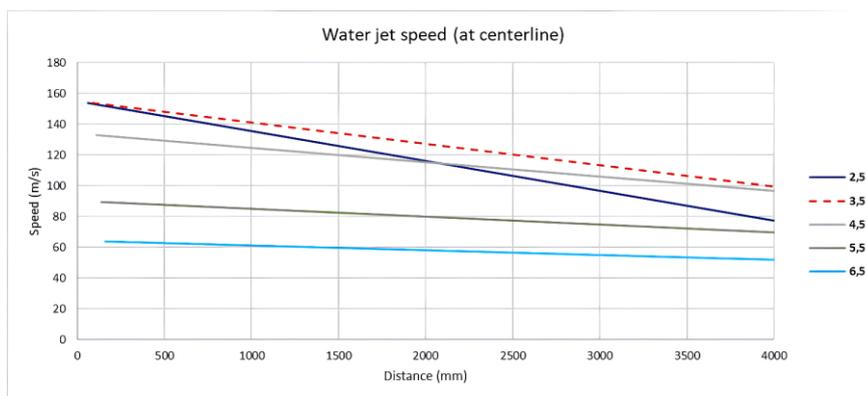


Figure 4. Water jet speed in function of the target distance and nozzle diameter.

Figure 5 demonstrates that the stagnation pressure of the jet, as well as the area in which it occurs, strongly depend on the distance from the nozzle to the target object and the diameter of the nozzle.

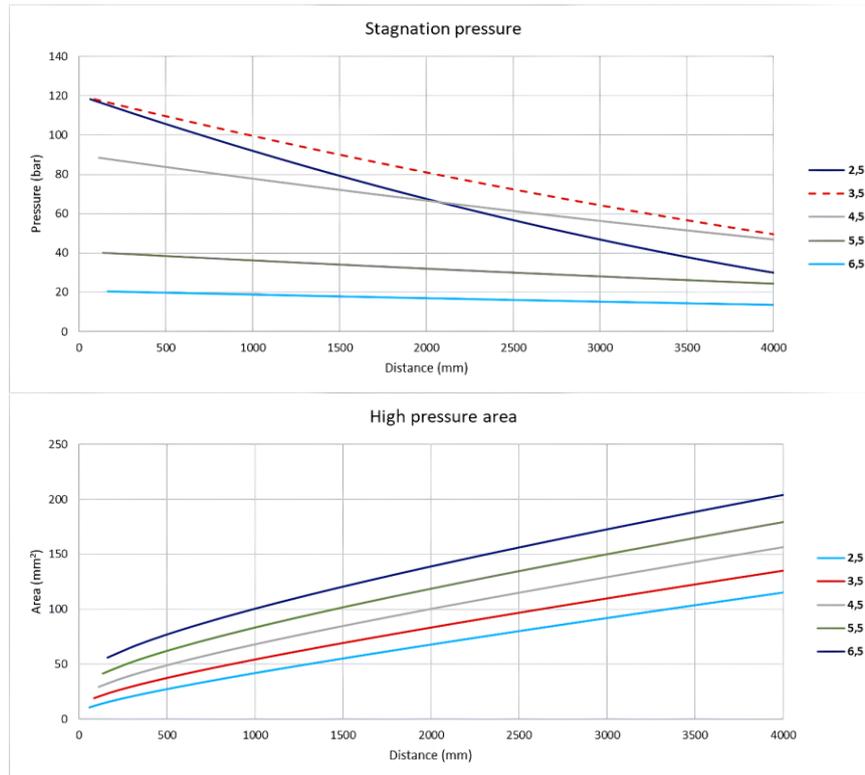


Figure 5. Maximum stagnation pressure in function of the nozzle diameter and standoff distance.

Numerical models allow to assert that nozzles with diameters below 1.5 mm would not function properly with the pump, resulting in low flow rate and no gain in jet velocity, considering the system's pressure limitation. On the other hand, values closer to a diameter of 4.5 mm exhibit interesting values for the parameters of velocity, pressure, and area coverage for the models used.

Considering the pump's operating point at 128 l/min and 120 bar, as well as the distance of application for the washing procedure, it can be concluded that an optimal range for nozzle diameter selection lies between 2 mm and 4.5 mm.

Therefore, it is evident that conducting an initial evaluation is important to define the range of diameters compatible with the intended application prior to the parts manufacturing.

### 3. NOZZLES

The number of nozzles chosen for manufacturing was determined in order to ensure a more refined differentiation among them. It is evident that, the greater the quantity of prototypes manufactured within a pre-established range, the higher the likelihood of achieving a more accurate outcome in accordance with project requirements.

The methodology and models used provide important parameters for defining the geometry of the nozzles. Based on this, nine washing nozzles were proposed and manufactured with the following diameters: 2.5 mm (nozzle 1), 3.0 mm (nozzle 2), 3.5 mm (nozzle 3), 4.0 mm (nozzle 4), 4.5 mm (nozzle 5), 4.76 mm (nozzle 6 - recommended by IEEE 975 and used as a reference for the other models), 5.0 mm (nozzle 7), 3.5 mm with a 15° outlet angle (nozzle 8), and 3.5 mm with a 30° outlet angle (nozzle 9). It is important to note that nozzles 1 to 7 have a 0° outlet angle, while nozzles 8 and 9 have outlet angles of 15° and 30°, respectively. Figure 6 illustrates the designed models for manufacturing, and Figure 7 shows the machined nozzles.

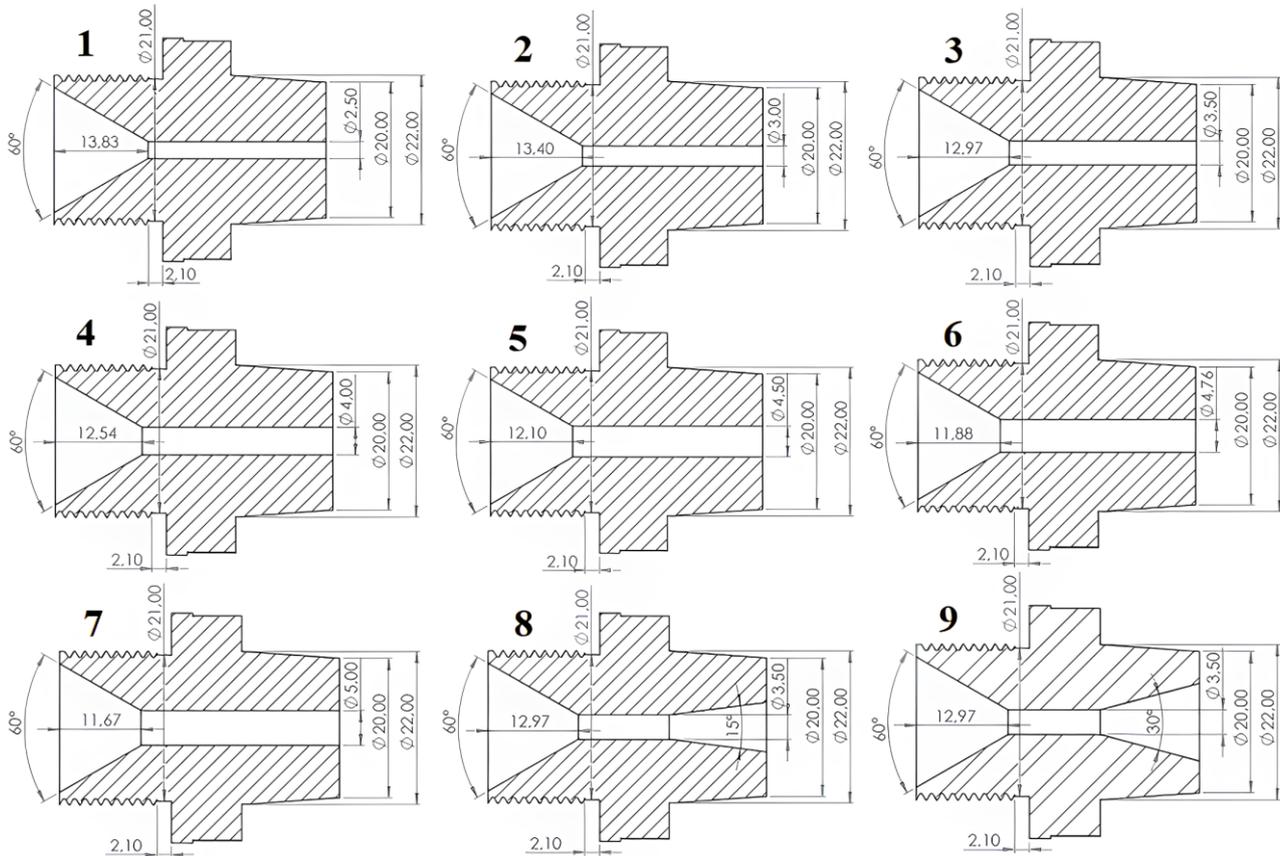


Figure 6. Designed nozzles.



Figure 7. Manufactured nozzles and their respective hole diameters.

## 4. RESULTS AND DISCUSSION

### 4.1 Flow rate and pressure

During the test bench, the working pressure at the nozzle outlets was monitored using a pressure transducer and correlated with the obtained flow rate measurements. Figure 8 allows to verify the relation between flow rate and pressure parameters for each of the developed nozzles.

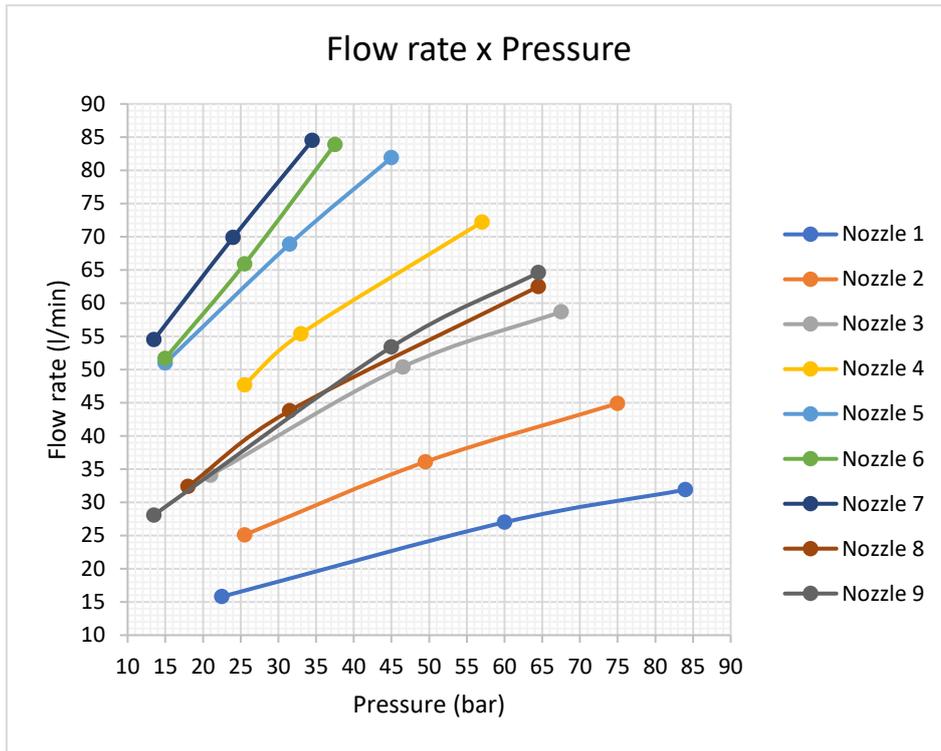


Figure 8. Flow rate and pressure relations according to each nozzle.

Upon observing this figure, it is evident that nozzles with smaller passage diameters provide a good water jet pressure while maintaining a lower flow rate, resulting in lower consumption. When comparing nozzle 1 (2.5 mm) to nozzle 7 (5.0 mm), this difference becomes apparent. Nozzle 7 delivers an elevated water flow rate but at a low outlet pressure, whereas nozzle 1 exhibits a good jet outlet pressure with a lower flow rate.

As for nozzles 3, 8, and 9, which have the same orifice diameter of 3.5 mm but different outlet angles, the difference is found to be quite subtle. The larger the outlet angle of the nozzle, the greater the water flow rate (consumption), while the jet pressure at the nozzle outlet decreases.

#### 4.2 Spray opening

The evaluation of the spray opening for each nozzle was conducted through image analysis. The cones produced by the different nozzles were observed at a distance of 3 meters from their origin. By using guides positioned at this point, it was possible to estimate the opening and make comparisons among the different nozzles in order to obtain an order of magnitude for the water jet spread.

Figure 9 sketches visual comparisons between the developed nozzles, with images presented in the same scale.

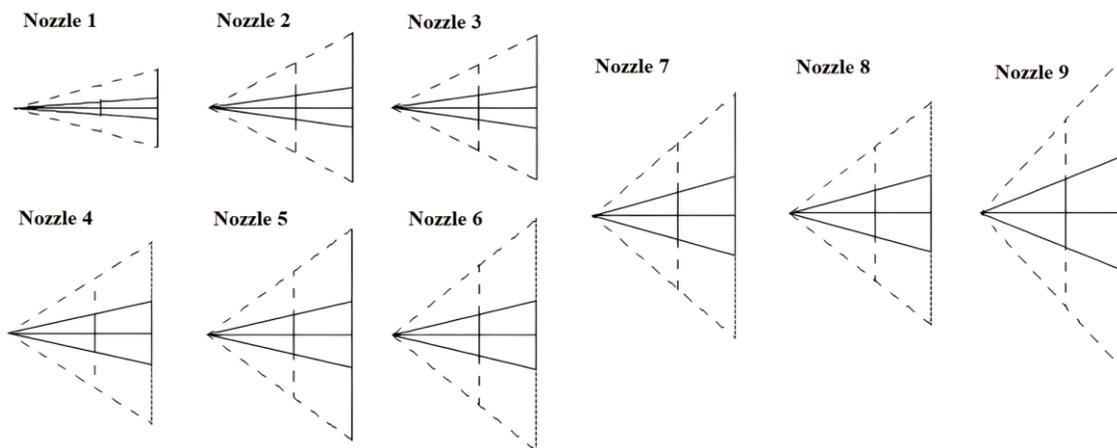


Figure 9. Visual comparison for the spray opening between the nozzles.

Figure 10 illustrates a washing procedure with nozzle 1 (2.5 mm). From it, it can be inferred that the spray cone for this nozzle appears to be sufficient for the dimensions of the electrical insulators, avoiding significant water waste.



Figure 10. Insulator washing using nozzle number one.

Thus, it can be observed that, due to the dimensional limitations of electrical insulators, as well as the range of distances for the washing process, nozzles with larger diameter do not offer efficient washing performance, as a significant amount of water is wasted for this application.

### 4.3 Impact force

To measure the impact force of the water jet, it was determined a distance of 1.8 meters from the wash nozzle to the target, as it is a relevant distance for the application of insulator washing. The acquisition system consisted of a metal plate with a known area, acting as the target, two load cells positioned behind the target, and a Data Acquisition Device (DAQ) connected to them for collecting force data in each situation. The configuration and usage of the system are illustrated in Figure 11.

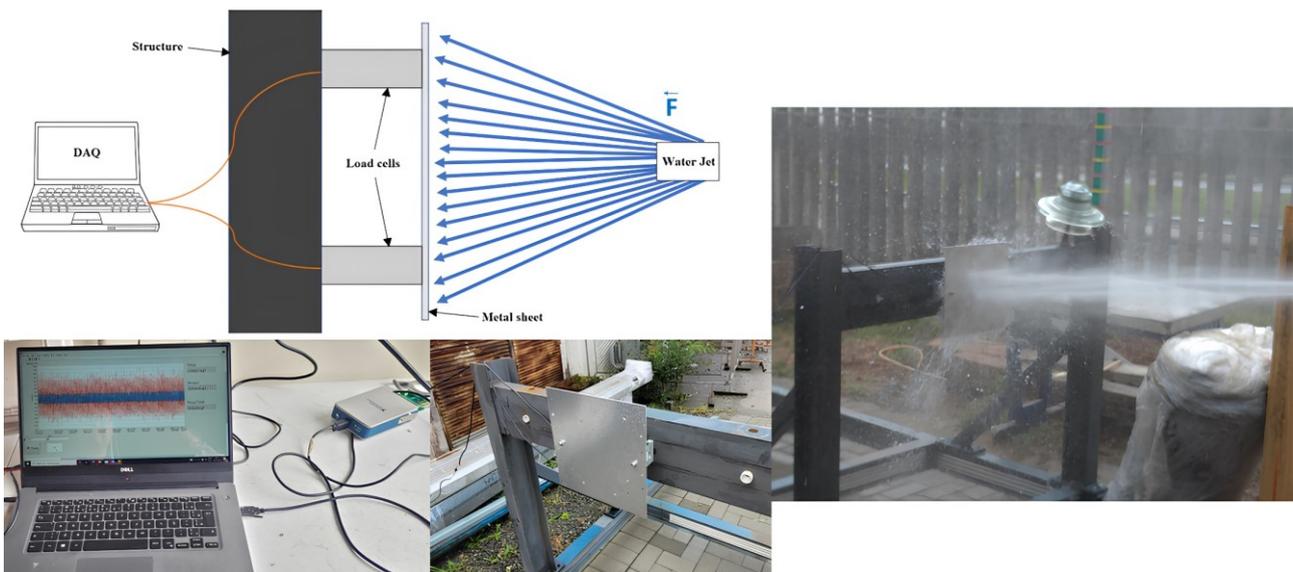


Figure 11. Impact force measurement setup.

As a result, Figure 12 shows the relation between the flow rate and impact force of the water jet in the target.

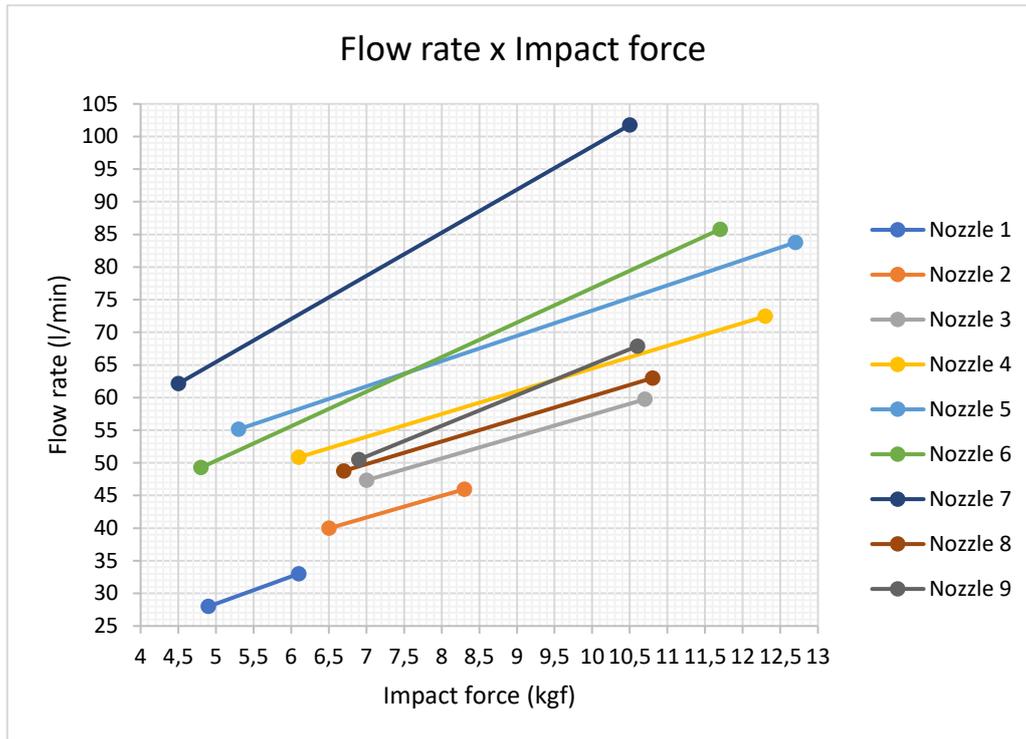


Figure 12. Flow rate and impact force relation for the nozzles.

Despite there being a significant difference in the impact force results for the different nozzles, the conducted tests showed that even the lower indicated impact forces already provide satisfactory cleaning of the insulators, across all different levels of pollution. As the goal, once again, is to achieve successful washing with minimal consumption, it becomes evident that nozzles with smaller diameters provide reduced flow, particularly nozzle 1, which exhibits the lowest consumption among the manufactured models.

Similarly, a subtle difference can be observed regarding nozzles 3, 8, and 9, where nozzles with larger outlet openings also exhibit higher flow rates.

#### 4.4 Results summary

In order to facilitate visualization, Table 1 was prepared containing all the results obtained in the test bench for the developed nozzles.

Table 1. Results summary of the nine nozzles for the spray opening, system pressure, impact force and flow rate measured experimentally.

Nozzle	Diameter (mm)	Spray opening range (at 3 meters) (cm)	Pressure range (bar)	Impact force range (kgf)	Flow rate range (l/min)
1	2,5 / 0°	4,4-16,4	67,5 to 85,5	4,9 to 6,1	15,8 to 31,9
2	3,0 / 0°	8,4-31,3	61,5 to 76,5	6,5 to 8,3	25,1 to 44,9
3	3,5 / 0°	8,7-30,3	44,2 to 67,5	7,0 to 10,7	34,1 to 58,7
4	4,0 / 0°	13,2-37,8	28,5 to 57,0	6,1 to 12,3	47,7 to 72,2
5	4,5 / 0°	13,2-43,9	18,7 to 46,5	5,3 to 12,7	51,0 to 81,9
6	4,75 / 0°	14,3-48,4	13,5 to 39,0	4,8 to 11,7	51,7 to 83,9
7	5,0 / 0°	17,0-52,3	18,7 to 45,5	4,5 to 10,5	54,5 to 84,5
8	3,5 / 15°	16,5-47,7	42,0 to 64,5	6,7 to 10,8	32,4 to 64,5
9	3,5 / 30°	24,4-66,7	43,5 to 67,5	6,9 to 10,6	28,1 to 64,6

Based on the analyses and results presented, among the proposed models, the selected nozzle was nozzle 1, with a 2.5 mm orifice diameter. It can be said that the nozzle demonstrated satisfactory performance in the washing procedure on the test bench, in addition to being suitable for the operating range of the pumping system and providing lower water consumption during operation.

## 5. CONCLUSION

The article presented the development, evaluation, and selection of washing nozzles for cleaning electrical insulators. During the literature review and operational range requirements, it was possible to preselect a range of opening diameters using a numerical model as a starting point for development. By manufacturing nine different nozzles, the models could be experimentally evaluated through bench tests. The primary objective in evaluating the parameters was to achieve the lowest possible flow rate (minimum water consumption) while effectively performing the procedure. Hydro jetting pressure tests at the nozzle outlet allowed establishing the relationship between pressure and water flow rate for different nozzle diameters, revealing that larger orifices consume more water and provide higher outlet pressures. The assessment of the jet impact force at a given distance showed that nozzles with smaller diameters, despite having lower impact forces, effectively carried out the procedure for different levels of insulator pollution, with significantly reduced water flow rates compared to other nozzles. The evaluation of the spray cone allowed observing the effectiveness of each opening relative to the target, revealing that larger orifice openings led to higher water consumption and waste specifically for this procedure.

Therefore, nozzle number 1 (2.5 mm) was selected to proceed with the activities as it demonstrated satisfactory washing results, met the operational range requirements, and had a lower water flow rate.

## 6. ACKNOWLEDGEMENTS

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