THE USE OF AIR ATOMIZING NOZZLES TO PRODUCE SPRAYS WITH FINE DROPLETS

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ABSTRACT

In a typical spray nozzle designed for fire suppression, the spray is produced by impinging a cylindrical water jet on a specially designed solid element, called the deflector. The resulting spray pattern is a full cone of droplets with relatively large diameters. In order to reduce the size of the droplets and the amount of water, various type of water mist systems and nozzles have been developed so far, where the water pressure is increased and the orifice diameter is decreased by an order of magnitude.
It would be advantageous to form a spray with fine droplets, although not necessarily as small as those produced by a typical water mist system, without increasing the water pressure or reducing the orifice size significantly. Such a spray could be obtained by using air atomizing nozzles, where air jets are used to break up the cylindrical water jet into fine droplets. In order to produce a spray with an average droplet diameter of less than 1 mm, the required air and water pressure values in the air atomizing nozzle are obtained by using an empirical relation available in the literature. The resulting pressure values are in the order of 1 or 2 bar both at the air and at the water inlet of the air atomizing nozzle. This result yields a promising design alternative, where the amount of water demand for sprinkler system is reduced. Another benefit especially for high-rise buildings is to increase the height of the pressure zones. The motivations of this design are so interesting that the additional requirements for a pressurized air system can be made cost-effective by further investments on its improvement. The pros and cons of this alternative design will be discussed in this study. Specifically, the air-to-liquid ratio value of such an air atomizing nozzle will be calculated to show that the amount of air introduced in to the room of fire is negligibly small.

Key Words: Water mist fire suppression systems, Air atomizing nozzle, Jet break-up, Air-to-liquid ratio, Phase Doppler Interferometer, Diameter distribution.

INTRODUCTION

Watermist fire suppression systems utilize the principles of spray atomization. It has been more than two decades since the fundamentals of sprays and atomization have been thoroughly investigated in literature (Lefebvre 1989 and Bayvel, L. and Orzechowski, 1993). Today, standards are available guiding the design of water mist fire protection systems (NFPA 750, 2010).

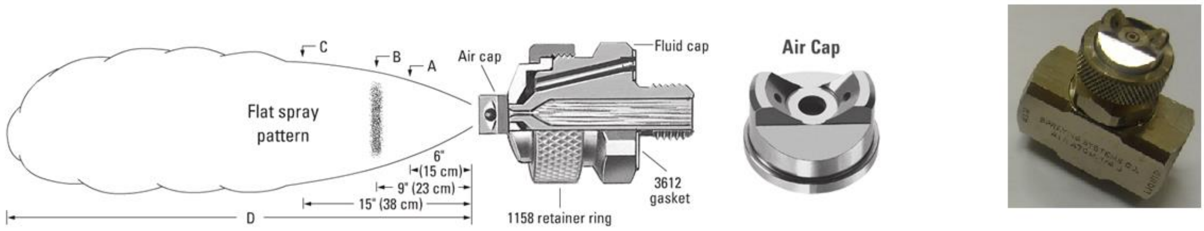
The principle of a water mist fire suppression system is to reduce the droplet size of the water spray to achieve the same heat transfer capability of a conventional spray with a reduced amount of water. This goal is generally achieved by increasing the water pressure and decreasing the orifice diameter of the nozzle in watermist applications. However, both of these approaches have adverse effects on the cost of the system for several reasons. The increased water pressure causes the use of special materials and connection methods that can bear excessive pressure. On the other hand, the reduced orifice diameter means requires a cleaner water source to avoid clogging.

EXPERIMENTAL RESULTS FROM A PREVIOUS STUDY

In this study, it is claimed that an air atomizing nozzle can be used to produce a spray of fine droplets without using excessive pressures and too small orifice diameters, which could achieve the same extinguishing effect of a typical sprinkler system. The key approach in an air atomizing nozzle is using the impinging air jets to break-up the water jet that would form the water spray.

It must be noted that this idea had first arisen to the author, during the experimental studies accomplished in the Von Karman Institute, Belgium (Balık, 2006 and Balık, 2010). In these previous studies, the spray patterns produced by an air atomizing nozzle is observed by taking high speed camera images and obtaining the joint velocity and diameter distributions of the spray by using an advanced measurement system, which is known as the Phase Doppler Interferometer (Bachalo, 1980). Since the experimental results obtained in this previous study have an important impact on the results claimed in this paper, it is found useful to provide a short summary of these experimental observations.

The actual air atomizing nozzle used in the experimental studies and a skecth from the technical catalog of the manufacturing company (Spraying Systems Co.) are given in Figure 1. The stainless steel nozzle is specified as SUE25 combination of 1/4J air atomizing nozzle series, where the product codes of the fluid and air caps given as 60100 and 134255-45^o. This is an external mixing type air atomizing nozzle, where the air and waters jets meet outside the nozzle, i.e. no mixing chamber is available. Two air jets are produced from the 45^o inclined air holes, which are focused at the axis of the nozzle, where the air jets meet the water jet for external mixing. The diameter of the water side orifice is 1.50 mm while each of the air side orifices has a diamater of 1.35 mm. The produced spray is a flat spray with a spray angle of 60^o, i.e. the impinging air jets form a spray that is wide in one direction and thin in the other direction, such as a water curtain.



(a) (b)

Figure 1: Air Atomizing nozzle, a) a sketch from the technical catalog of Spraying Systems Co. b) the actual nozzle used in the experiments (Balık, 2010)

The water source that produce the spray is initially kept still in a water reservoir. Then, pressurized air is used introduced from the top of the reservoir as the propellant agent to push the water out from the bottom of the reservoir and flow into the water inlet of the nozzle. The atomizing air is separately connected to the air inlet of the nozzle from a stable pressurized air source available on the premises. The experiments are performed by using two different experimental setup. The first setup is shown in Figure 2, which is used ot obtain high-speed camera images of the spray pattern at the outlet of the nozzle. The high-speed camera used in these experiments (Vision Research Inc.) is capable of taking upto 160,000 frame per second at the minimum resolution. The second experimental setup is shown in Figure 3, which is used to obtain the simultaneous velocity and size distributions of the droplets at any point of the spray, by using an advanced optical measurement system, i.e. Phase Doppler Interferometer (Artium Technologies Inc.).

The experiments are performed by fixing the water flow rate at approximately $\dot{m}_w = 1.152$ l/min and altering the air flow rate to obtain various air-to-liquid ratio values. The water pressure at the upstream of the nozzle is measured as 0.62 bar during the experiments. The air-to-liquid ratio (w) is defined as the ratio of the mass flow rates of air and water and it is commonly used in literature. However, it has been more practical to use the reciprocal of air-to-liquid ratio (w^{-1}) to express the experimental conditions. The spray break-up patterns are shown in Figure 4 for eight different "w^{-1}" values in an increasing order from left to right ($6 < w^{-1} < 88$). The pressurized air source was 7 bar, but the pressure is reduced to obtain the given "w^{-1}" values. Since the produced flat spray is not symmetrical, the images taken both from the front view and side view are presented. It must be noted that the front and side views of a given image are not taken simultaneously. It can be seen from these images that smaller droplets are obtained by increasing the air flow-rate, i.e. air pressure.

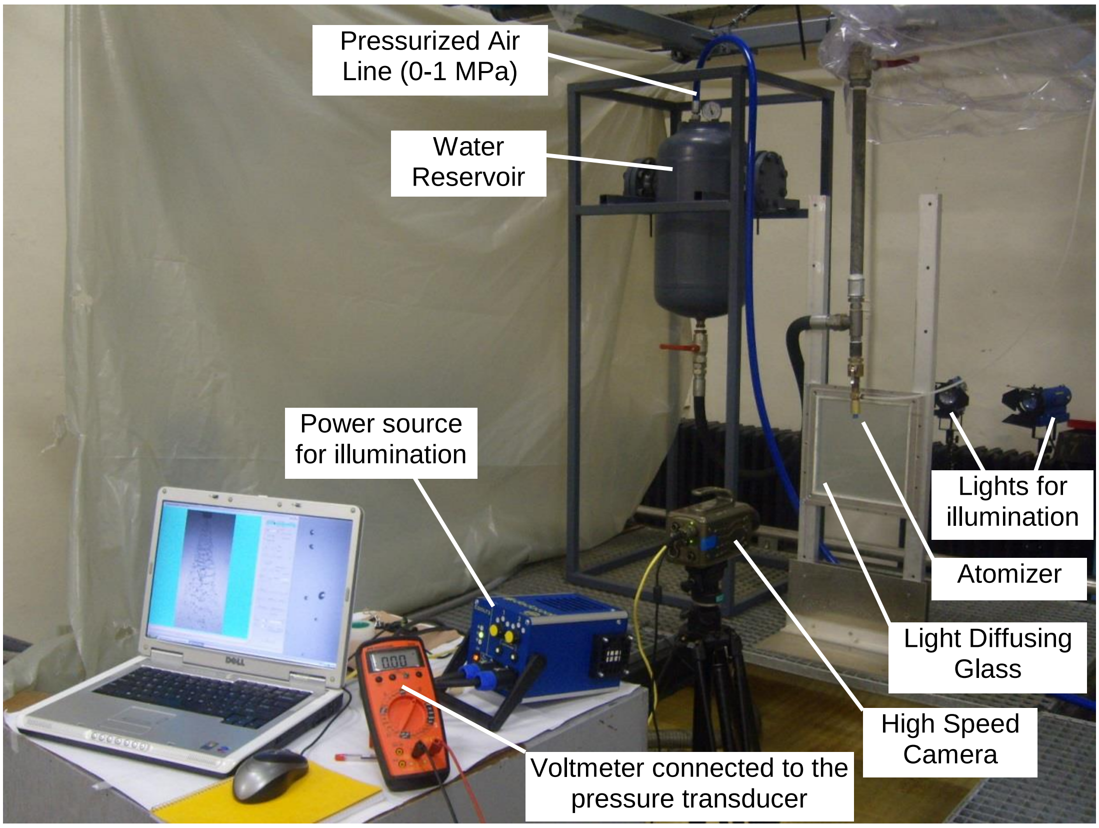


Figure 2: Experimental setup for High Speed Camera Tests (Von Karman Institute)

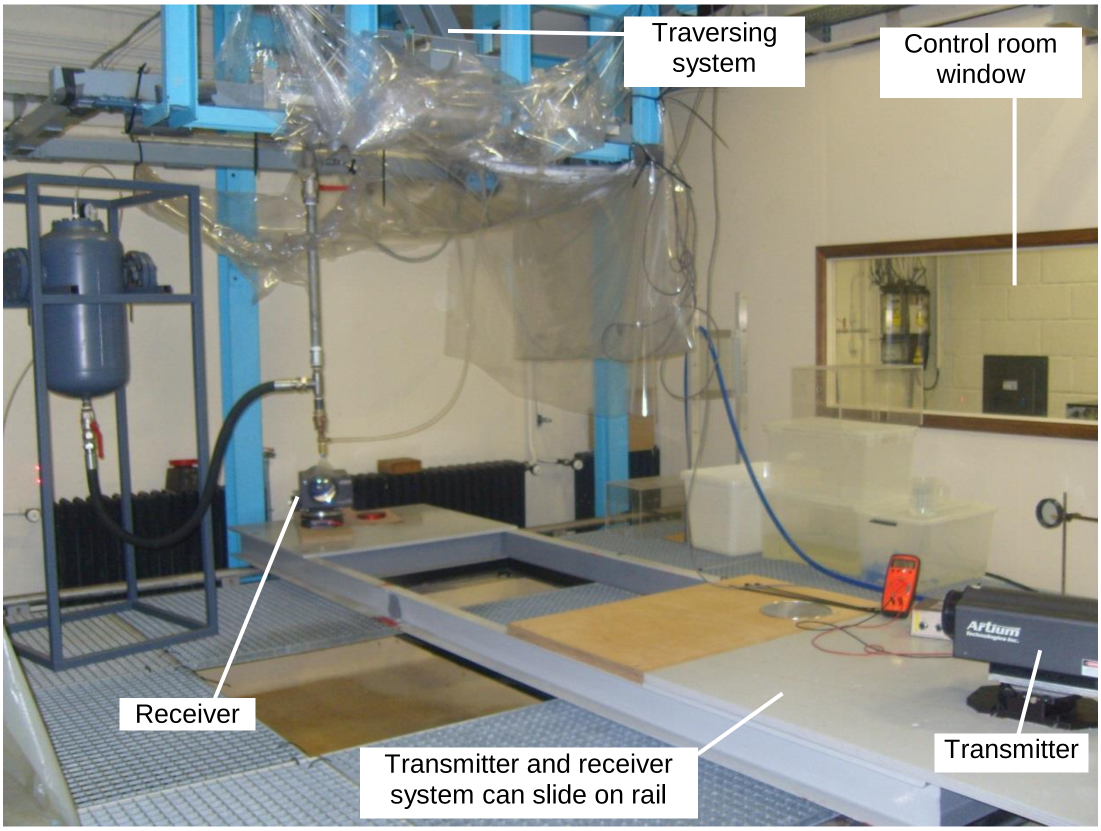


Figure 3: Experimental setup for measuring diameter and velocity of droplets (Von Karman Institute)

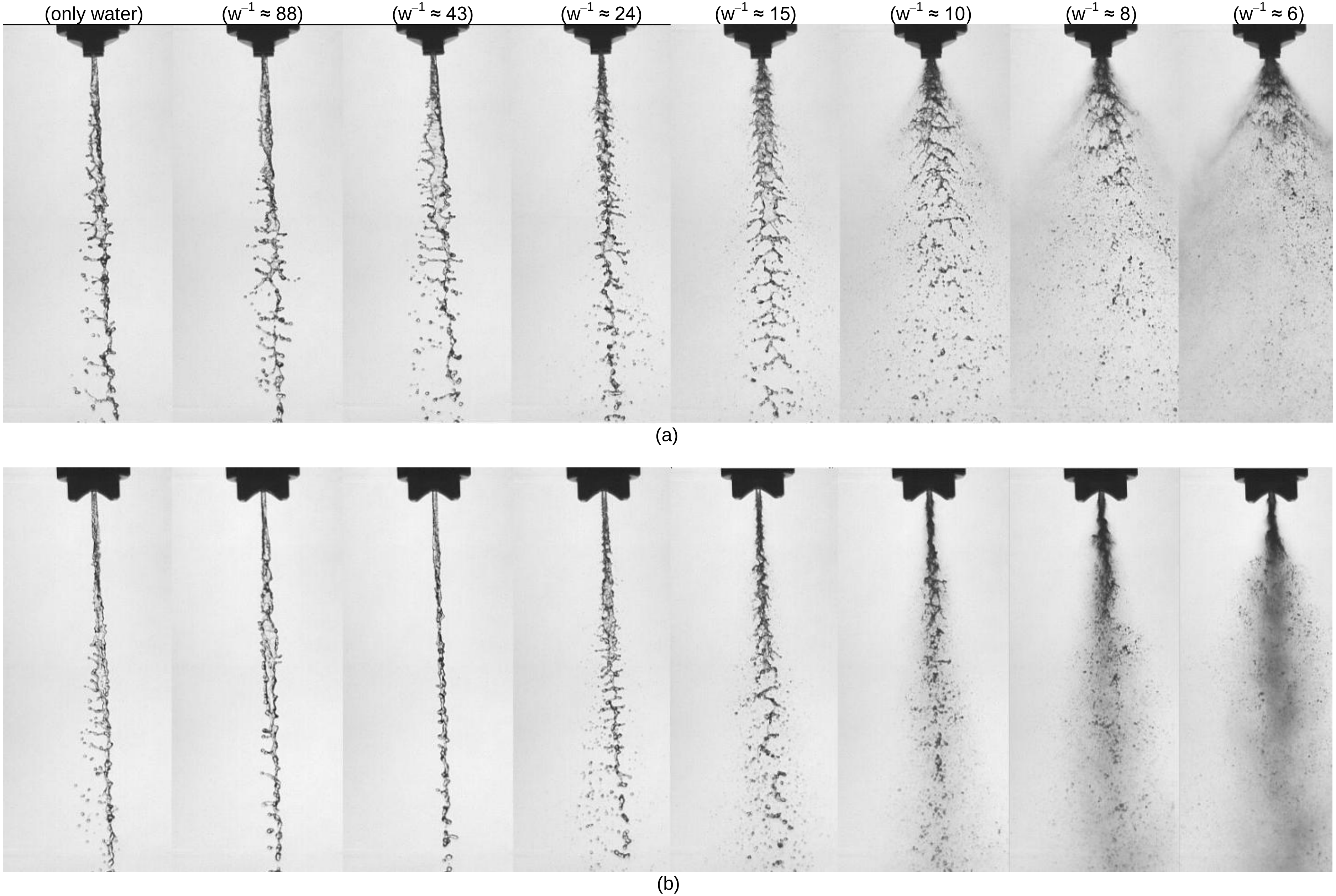


Figure 4: Images from the spray produced by an air atomizing nozzle. Water flow rate is fixed as $\dot{m}_w = 1.15$ l/min and the reciprocal of air-to-liquid ratio ($w^{-1} = \dot{m}_w/\dot{m}_a$) is altered. a) front view, b) side view (the upper and lower images are taken at different moments, Balık, 2010).

The joint velocity and diameter of the droplets are obtained by using the Phase Doppler Anemometer measurement system. The nozzle could be raised or lowered in vertical direction and moved forward or backward in one plane. Also, the measurement system could be traversed over rails to move right or left in the other plane. So that it was possible to measure the velcoity and size distributions at any point of the spray. The results shown in the below figures are taken at the central axis of the spray nozzle at a point $x = 150\ d_0$ downstream of the atomizer. According to the droplet size distribution shown in Figure 5, the majority of the droplets at the measurement point has a diameter of less than 400 μm. Also, Figure 6 reveals that the average velocity of the droplets at the measurement point is around 12 m/s.

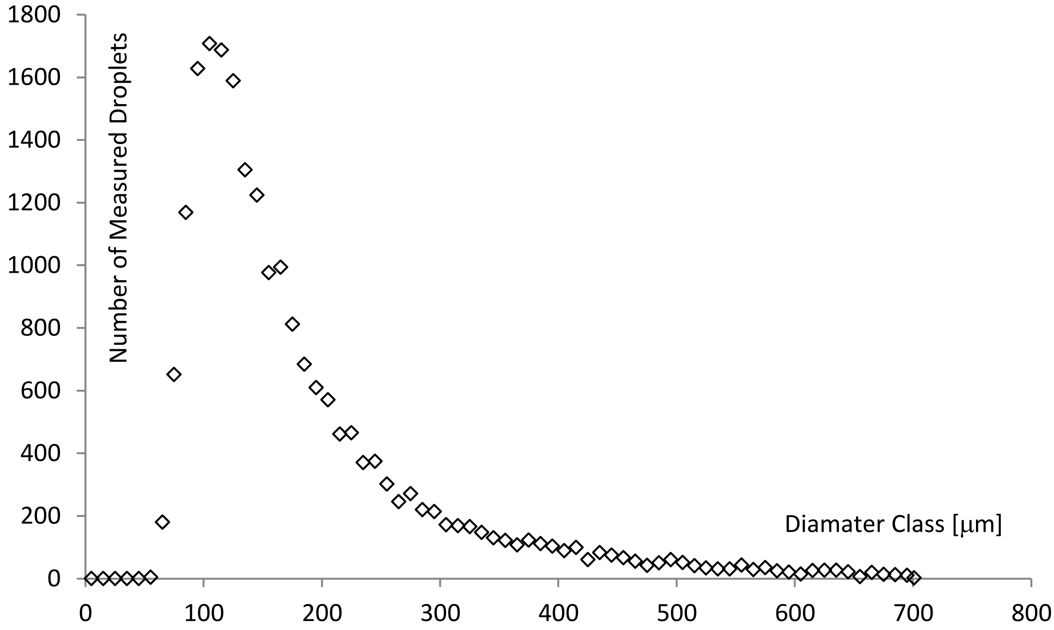


Figure 5: Diameter distribution of droplets passing through the center of the spray at a point $x = 150\ d_0$ downstream of the atomizer (Balık, 2010).

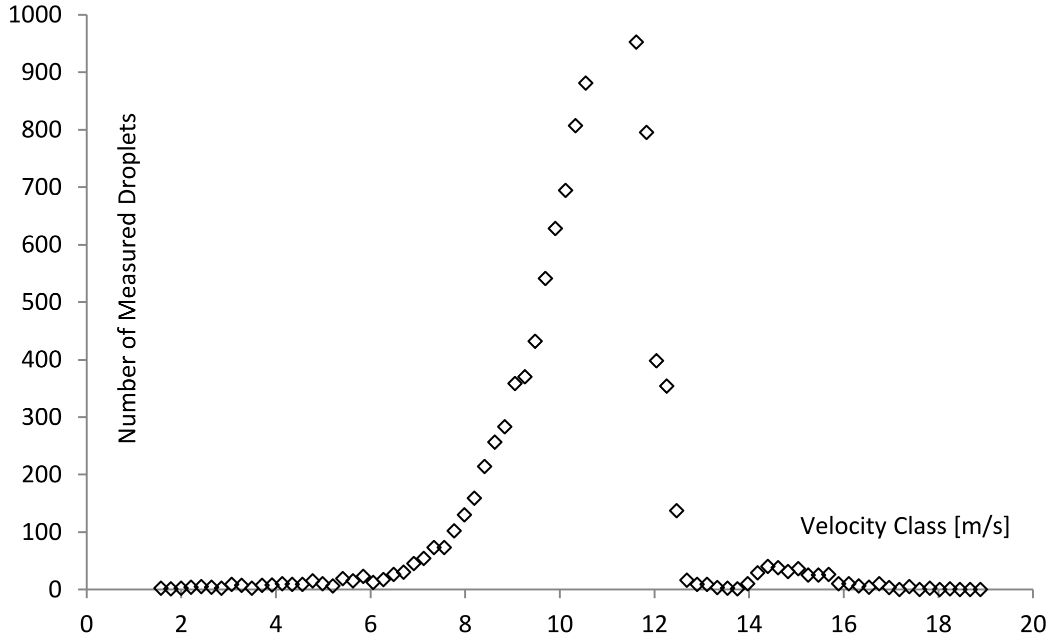


Figure 6: Velocity distribution of droplets passing through the center of the spray at a point $x = 150\ d_0$ downstream of the atomizer (Balık, 2010).

EMPIRICAL RELATION FOR OBTAINING DROPLET DIAMETERS

The aforementioned experimental results obtained with the air atomizing nozzles have inspired the idea of using such nozzles for producing fine droplets in fire suppresion industry. However, further information from literature was required to support this idea and experimental studies are searched from literature. Lefebvre (1989) quoted an experimental study conducted by Elkotb et.al. (1982), where the below empirical relation was introduced for calculating the Sauter Mean Diamater (SMD) of the droplets for an external mixing type air atomizing nozzle.

$$\mathrm{SMD} = 51\, d_0 Re^{-0.39} We^{-0.18} \left(\frac{\dot{m}_L}{\dot{m}_A}\right)^{0.29} \quad \text{(Equation 1)}$$

In this empirical relation, Re and We are the dimensionless Reynolds number and Weber number, which are given in Lefebvre (1989) as in the following equations, where ρ_L (density), μ_L (dynamic viscosity), ν_L (kinematic viscosity) and σ (surface tension) are the thermodynamic properties of water, U_R is the relative velocity of the liquid and air jets and d_0 is the orifice diameter of the water jet.

$$Re = \frac{\rho_L U_R d_0}{\mu_L} = \frac{U_R d_0}{\nu_L} \quad \text{(Equation 2)}$$

$$We = \frac{\rho_L U_R^2 d_0}{\sigma} \quad \text{(Equation 3)}$$

Based on the previous experience and the above empirical relations in lliterature, it is proposed that an air atomizing nozzle can be used to obtain fine spray droplets with significantly low pressures. The schematic design of the proposed nozzle is given in the below figure, where there are four air holes on sides and a single water hole in the center. The air holes are directed to the center of the nozzle at an angle of 45^o. Each of the four air holes has a diamater of 1 mm and the central water hole has a diamater of 3.5 mm.

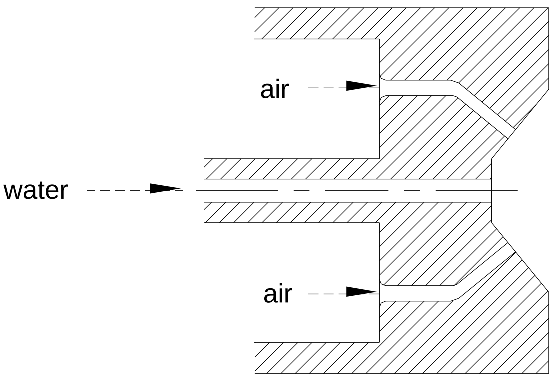


Figure 7: Schematic design of the proposed nozzle

The water hole diamater in the proposed design is approximately 1/3 of a typical sprinkler nozzle but this is still much greater than a typical water mist nozzle. The velocity of the water jet at the outlet of the orifice is taken as 30 m/s and the air jets are assumed to be introduced with a maximum achievable velocity of approximately 330 m/s, which is limited by the speed of sound in air. The relative velocity between the air jet and the water jet is calculated by taking the horizontal component of the air jet as 230 m/s, due to the inclined location of air jets at an angle of 45^o. The flow rate of the water is then calculated as approximately 17 l/min. Assuming the K-factor of the water orifice as $K = 20\ l/(min \cdot \sqrt{bar})$, the calculated water flow-rate can be obtained by a water pressure of not more than 1 bar.

The air flow rate is calculated in a similar manner and the total flow-rate from 4 air holes is obtained as 0.0012 kg/s, which corresponds to a flow rate of approximately 0.1 air change per hour, i.e. negligibly small. The ratio of the mass flow rates of water and air is obtained as $\dot{m}_{water}/\dot{m}_{air} = 231$. And the thermodynamic properties of air and water are used to calculate the Reynolds number (approximately Re = 800,000) and the Weber number (approximately We = 2,600,000). Using the empirical relation described in Equation 1, the Sauter Mean Diameter is obtained approximately 300 μm for this nozzle.

RESULTS

It is important to note that, according to the above calculations obtained from an empirical relation available in literature, a spray with an average droplet diamater of 300 μm can be obtained by using moderate pressure values at both air and water. Water pressure is calculated as 1 bar by assuming the K-factor. Air pressure is not calculated due to lack of information about K-factor values for air, but it is estimated to be in the order of 2 bar, by experience.

The amount of air introduced into the origin of fire is calculated to be negligibly small, i.e. approximately 0.1 air changes per hour, so that there shouldn't be a concern about fire growth due to the air coming from the nozzle.

The water pressure in the proposed system is in the same order with that in sprinkler systems. Since the exposed pressure value is reduced, both the system components and the piping can be made of less expensive materials. It is thought that this will have a great contribution in terms of a cost effective design over the conventional watermist nozzles for producing fine sprays.

On the other hand, the diamater of the water hole in the proposed air atomizing nozzle is smaller than that in a typical sprinkler nozzle but it is still considerably larger than that of a typical water mist nozzle. Therefore, the proposed nozzle design will have an advantage for preventing the clogging problem comparing to typical water mist nozzles. It is open to discussion if conventional sprinkler pipes can be used in the proposed design by simply adding strainers. Further exprimental studies are required to make conclusions on this issue.

The addition of an air compressor and an air pipe to the system is the disadvantage of the system using the nozzle in the proposed design. The idea seems promising but further studies are required to prove its effectiveness in the area of fire suppression industry.

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