DROPLET SIZE DISTRIBUTION OF HIGH-PRESSURE WATER MIST NOZZLES

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Abstract

Determining the particle size distribution of water mist is necessary for a wide range of industrial applications or experimental measurements. Particle size defines the ability of water mist to absorb heat, absorb or scatter heat radiation, inertize the environment, reduce environmental dust, regulate odor, etc. The paper presents the principle of measuring droplet size distribution using laser diffraction and the measurement procedure for four hollow cone water mist nozzles with orifice 400 µm, 500 µm, 600 µm and 1000 µm. The measurements were performed at distances of 25 mm, 50 mm, 75 mm, 100 mm, 125 mm, 150 mm, 175 mm, 200 mm and 225 mm from the orifice of the individual nozzles in the middle of the water mist cone. Further measurements were made 25 mm, 50 mm and 75 mm from the nozzle orifices on the edge of the fog cones. All measurements were performed at a working pressure of 70 bar in a water mist system.

Keywords

Water mist, Droplet size measurement, Laser diffraction, High-pressure nozzle, Sauter mean diameter

1. INTRODUCTION

The study of water mist particles covers a very wide area, not only in terms of experimental methods used, but also with regard to the method of production of these particles according to the type of nozzles, liquid inlet pressures and the shape of the spray cone. This is, for example, a spray created using flat-fan misting nozzles, hollow-cone nozzles, solid-cone simplex mist nozzles. [Tanaka 2020, Mehaddi 2020, Zhang 2013] The study of sprays from these nozzles and sprinklers always corresponds to their use in practice, such as cooling, radiation shielding, fuel injection, high quality steam generation in steam generators for in situ thermal recovery of heavy oil and many others, while the non-uniform droplet distribution in the flow can significantly reduce efficiency and utilization possibilities [Sapit 2019, Kashdan 2002, Choi 2002].

Three different mechanisms can be defined according to the principle of particle formation in the mist stream – creating a rotation in the spray, colliding water jets, direct droplet creation from a turbulent water jet on leaving the nozzle, the most common being the third principle mentioned. [Shrigondekar 2018, Husted 2004] The formation of a mist stream and the subsequent formation of droplets depends on the flow rate, the size of the nozzle orifice and the inlet pressure. The droplets form in the mist stream in one of four ways – Rayleigh break-up regime, First wind-induced break-up, Second wind-induced break-up, Atomization. Droplets are also formed by atomization in our experiments, which means that droplet formation takes place at the nozzle orifice and the size of the droplets is much smaller than the diameter of the nozzle orifice. Most publications focus on the use of one or two methods in the analysis of water mist particles, but the widest comparison of experimental techniques can be found in a study [Dodge 1987a] comparing 17 instruments (6 different types) for measuring water droplet size at different workplaces, wherein the repeatability of the water spray characteristics was relatively good with deviations of max. 10 to 15 %. In addition to the most frequently dealt with hollow-cone nozzles, swirl-generated hollow cone nozzles [Kashdan 2006] are also analyzed very frequently in scientific publications. Most of these publications are devoted to the determination of basic parameters such as cone width, spray pressure, velocity and particle size, and especially the Sauter mean diameter (SMD). The effectiveness of swirl nozzle has been experimentally demonstrated, for example, in suppressing coal dust in mines [Gao 2018]. To characterize the dimensions of the mist droplets, a number of experimental methods are used (spray diagnostics), which are based on various principles, such as Phase Doppler Particle Analyzer, respectively Phase Doppler Anemometry, Particle Image Velocimetry, Laser Doppler Velocimetry etc. It is also worth mentioning the very rarely applied analytical technique based on pulsed digital off-axis holography, which is suitable for the study of transient sprays [Wu 2021, Dodge 1987b]. This method allows the visualization of individual particles of the mist stream, to characterize the non-sphericity of these drops and also to determine the SMD – Sauter diameter. The results of these methods show that with increasing pressure, the distribution of Sauter droplet diameters is more even. Holographic reconstruction enables 3D observation of small particles and their ligaments surrounded by an opaque mist with high optical density. Other visualization methods that can be mentioned, for example, are the high-speed videography method [Green 2019], or a number of theoretical studies based on mathematical and computational flow models [Mahmud 2016, Beji 2017].

Droplet size is one of the most important parameters influencing the effectiveness of water mist in fire protection. Droplet size affects the efficiency of endothermic cooling or radiant heat shielding. [Cui 2021] Water mist capabilities are related to the lifetime of a droplet as a function of ambient temperature and the size of a given droplet. The study [Grimwood 2005] shows that droplet sizes of 1,000 µm have the longest lifetime. On the other hand, droplets with a size of 100 µm have the shortest lifetime. The opposite view is offered by the [Andersson [1996] study, which describes the droplet range as a function of droplet size and ambient temperature. For droplet sizes up to 100 µm, the range is not even 1 mm at temperatures in the hundreds of degrees Celsius. Droplet sizes of 1 000 µm have the longest range. Practical results are offered by the study [Xiaohong 2022], where the most effective droplet size for extinguishing a fire was found to be 300 µm in the case of an oil fire. A droplet size of 600 µm was not as effective as the 300 µm size. For the 100 and 200 µm sizes, the time required to extinguish was much higher than for the 300 and 600 µm sizes. The results cannot be applied generally to all fire types. There are a number of studies [Liao 2006, Liu 2003a, Liu 2003b] that look at the effects of different droplet sizes on different types of fire. All of the studies presented in this section offer insight into the importance of determining the particle size distribution because of the significant effect of droplet size on the time required to suppress and extinguish a fire.

Our chosen method for the study of water mist droplets produced by a set of nozzles with a diameter of 400 – 1 000 µm, is mainly based on a search of publications, which are primarily focused on comparing the particle size distribution determined by traditional PDA and LDV methods [Dodge 1987a, Zaremba 2016]. Studies [Husted 2004, Gopesh 2022] present a comparison of the evaluation of the Sauter mean diameter of SMD of droplets by both convolution and deconvolution techniques and a comparison of the agreement between the data thus obtained. It is clear from these studies that the degree of agreement is highly dependent on the position of the measuring points in the spray and on the boundary conditions of the experiments. SprayTec is a non-destructive optical method based on laser diffraction. It provides an accurate analysis of the atomization dynamics of water mist flow. SprayTec has been used in a wide range of studies [Lelong 2014, Dayal 2004, Dumouchel 2009] to determine droplet size distribution. The study [Santangelo 2010] deals with an extensive characterization of the mist flow, primarily using Spraytec. Using optical techniques, it states drop-size and flux distribution, initial velocity and cone angle, which have been investigated to provide a quantitative description of atomization and dispersion [Santangelo 2010]. The next paper [Dumouchel 2009] describes experimental investigation on the practical use of a laser-diffraction instrument, the Spraytec 2007 to characterize sprays produced by a high-pressure GDI injector.

2. EXPERIMENTAL SETUP AND METHODS

2.1 Experimental system

Measuring apparatus

The apparatus includes a high-pressure water pump with filter, piping system, fitting with nozzle and pressure sensor, power source and datalogger, ring with nozzles to ensure defined pump flowrate, Spraytec laser diffraction system (see on Fig. 2) and laptop with software – see diagram on Fig. 1:

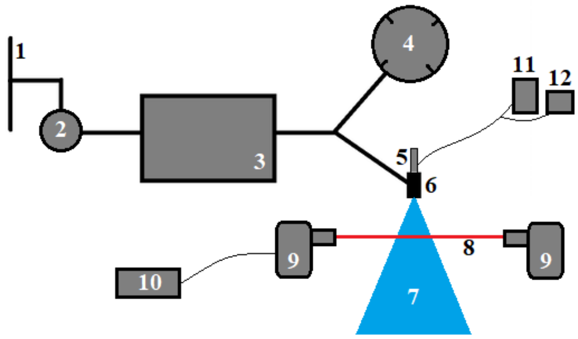


***Figure 1** – Diagram of measuring apparatus*

1 – Water supply, 2 – Filter, 3 – High- pressure pump, 4 - Stainless steel ring with nozzles, 5 – Pressure sensor, 6 – Measuring nozzle, 7 – Water mist cone, 8 – Laser beam, 9 – Laser diffraction system, 10 – Laptop, 11 – Datalogger, 12 – Voltage source

***Figure 2** – Aparature during measurement*

Misting system

The system for creating water mist uses a high-pressure pump with variable flowrate of 1 – 5 l.min^{-1} at a working pressure of 70 bar. To protect against the introduction of mechanical impurities into the pump pistons and high-pressure nozzles, a water filter is included at the inlet to the pump, which can catch mechanical impurities larger than 5 µm. The piping system consists of a durable black nylon hose with a thickness of 3/8" (outer diameter 10 mm, inner diameter 5 mm, wall thickness 2.5 mm). The piping system consists of two branches. The first branch leads to a stainless-steel ring with a diameter 400 mm with four orifices for the misting nozzles. Nozzles are placed on the ring, which together with the measured nozzle ensure a defined pump flow of 1 – 5 l.min^{-1}. The second branch leads to the fitting to which the pressure sensor and the tested nozzle are attached. The pressure sensor is connected via a connector and provides monitoring of the pressure on the measured nozzle. Specifically, they are hydraulic misting nozzles of the hollow cone type, in orifice diameter 400 µm, 500 µm, 600 µm and 1000 µm. The nozzles have an integrated filter that prevents them from clogging. The nozzles are capable of even distribution of water droplets. The pressure on the nozzle is measured by means of a pressure sensor which is powered by a voltage source. A record of the measured pressure is provided by datalogger. For easier handling of the nozzle at the given height, a scissor screw jack is part of the apparatus.

2.2 Experimental Methodology

The aim of the measurement was to determine the particle size distribution for four high-pressure. Misting nozzles produce a hollow cone-shaped mist stream. The nozzles have orifices in diameter 400 µm; 500 µm; 600 µm and 1000 µm. The working pressure was set at 70 bar, whereas the actual measured pressure value was determined as: 69.3 ± 0.6 bar. The flow rates of the individual nozzles were measured five times, and the resulting values are given in the following Tab. 1:

Nozzle Orifice [µm]	400	500	600	1000
Flow rate q [ml.min^{-1}]	107.47 ± 0.12	140.65 ± 0.19	155.97 ± 0.25	248.84 ± 0.34

***Table 1**: Water flow rate through individual nozzles*

The measurements were performed at distances of 25 mm, 50 mm, 75 mm, 100 mm, 125 mm, 150 mm, 175 mm, 200 mm and 225 mm from the orifices of the individual nozzles in the middle of the water mist cone. At distances greater than 225 mm from the nozzle orifice, the spray cone began to deform significantly. In the case of the 400 µm and 600 µm nozzles, deformation of the mist stream already occurs at 225 mm, although the conditions for all measurements were the same. We therefore stopped the measurements at this distance. Measurements at these distances were performed in two axes – X, Y. Thirty measurements were performed for each axis. The resulting value of the Sauter mean diameter, D_{32}, was evaluated as the geometric mean of the values from both axes at a defined distance from the nozzle (geometric mean derived from 60 measurements). Further measurements were made at 25 mm, 50 mm and 75 mm from the nozzle orifices (again 30 measurements for each point) at the edge of the mist cones.

The measured widths of the cones for the individual nozzles are listed on Fig. 3 below:

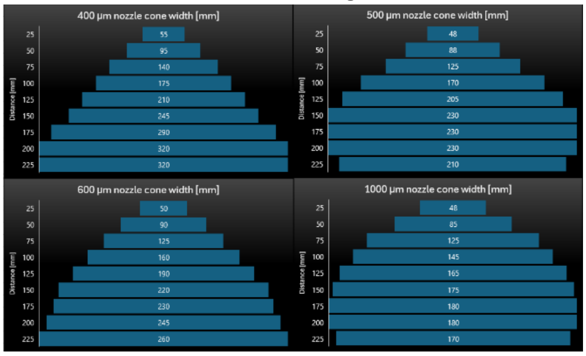


***Figure 3** - Widths of spray cones for individual nozzles*

3. RESULTS AND DISCUSSION

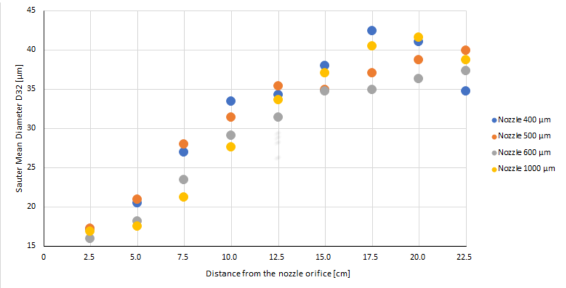
Tab. 2 and Graph 1 below shows the mean values of the Sauter mean diameter droplet size ± standard deviation for each nozzle. These values were created using the geometric mean of the values measured on the X, Y axes at a defined distance from the nozzle.

In addition, Graph 1 clearly shows an increase in D_{32} values along the cone axis with increasing distance from the nozzle orifice. This trend indicates a change in droplet size distribution with distance, which may be due to the redistribution of droplets in the cone due to aerodynamic forces, inertia of larger droplets and stabilisation of their shape. This change can be further considered in the practical design of water mist devices.

	Sauter mean diameter D_{32} ± standard deviation [µm]			
Distance from the nozzle [mm]	Nozzle 400 µm	Nozzle 500 µm	Nozzle 600 µm	Nozzle 1000 µm
25	17.1 ± 0.5	17.2 ± 0.1	15.9 ± 0.5	16.6 ± 0.2
50	20.4 ± 0.9	20.9 ± 0.4	18.1 ± 0.5	17.5 ± 0.3
75	26.9 ± 2.3	27.9 ± 0.6	23.4 ± 1.0	21.2 ± 0.3
100	33.4 ± 2.0	31.4 ± 0.8	29.0 ± 2.8	27.6 ± 1.0
125	34.2 ± 4.4	35.3 ± 0.9	31.4 ± 2.3	33.6 ± 0.8
150	37.9 ± 3.8	34.9 ± 1.0	34.7 ± 2.9	37.0 ± 2.9
175	42.4 ± 2.5	37.0 ± 2.7	34.9 ± 3.5	40.4 ± 3.4
200	41.0 ± 1.9	38.7 ± 2.1	36.3 ± 2.3	41.5 ± 3.1
225	34.7 ± 2.9	39.9 ± 1.5	37.3 ± 3.2	38.7 ± 2.3

***Table 2:** Resulting D_{32} values for individual nozzles in the center of the cone*

A closer look at Graph 1 shows that the geometric mean Sauter diameter is not constant but increases with distance from the nozzle mouth. This increase is likely to be the result of a combination of factors, including the redistribution of droplets in the fog cone and the gradual calming of the turbulent flow. Droplet non-sphericality near the nozzle mouth may also play a role in influencing the spray patterns measured by Spraytec, which we have not considered in this measurement.



***Graph 1** – Geometric mean of Sauter's mean diameters D_{32} for measured nozzles*

Under the given conditions was also measured the values on the surface (edge) of the water mist cone. From Tab. 3, the trend of the measured values is the same as in the middle of the hollow cone of water mist.

Distance from nozzle orifice [mm]	Size of D_{32} on the edge of the misting nozzle ± standard deviation [µm]			
	Nozzle 400 [µm]	Nozzle 500 [µm]	Nozzle 600 [µm]	Nozzle 1000 [µm]
25	30.5 ± 0.1	27.9 ± 0.2	26.8 ± 0.1	25.7 ± 1.7
50	36.1 ± 0.2	33.5 ± 0.3	31.9 ± 0.4	32.4 ± 0.2
75	45.0 ± 0.3	42.8 ± 0.5	40.0 ± 0.5	41.0 ± 0.5

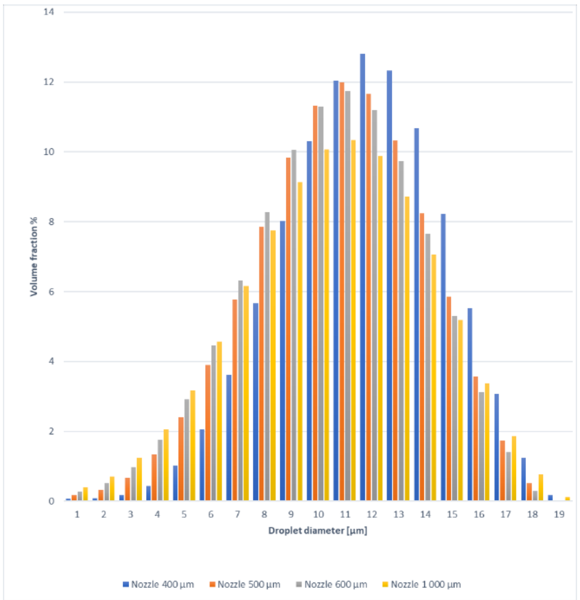
***Table 3:** Resulting D_{32} values for individual nozzles on the surface of the cone*

Water droplet size measurement intervals [µm], in which at least minimal volume percentages were measured, are defined as follows for the Spraytec device (Tab. 4):

	Interval [µm]	Nozzle 400 µm	Nozzle 500 µm	Nozzle 600 µm	Nozzle 1 000 µm
	1.0 – 1.2	0.00	0.00	0.02	0.02
	1.2 – 1.4	0.02	0.04	0.11	0.13
	1.4 – 1.6	0.04	0.12	0.22	0.24
	1.6 – 1.9	0.08	0.19	0.31	0.31
	1.9 – 2.2	0.11	0.25	0.37	0.35
	2.2 – 2.5	0.13	0.30	0.38	0.35
	2.5 – 2.9	0.14	0.43	0.36	0.32
	2.9 – 3.4	0.15	0.48	0.31	0.27
	3.4 – 4.0	1.45	0.24	0.25	0.22
	4.0 – 4.6	0.25	0.16	0.20	0.20
	4.6 – 5.4	0.08	0.14	0.19	0.25
1	5.4 – 6.3	0.07	0.18	0.27	0.40
2	6.3 – 7.4	0.09	0.33	0.51	0.71
3	7.4 – 8.6	0.18	0.68	0.97	1.25
4	8.6 – 10.0	0.44	1.34	1.76	2.06
5	10.0 – 11.7	1.02	2.41	2.92	3.18
6	11.7 – 13.6	2.05	3.90	4.46	4.57
7	13.6 – 15.8	3.61	5.78	6.31	6.15
8	15.8 – 18.5	5.67	7.86	8.27	7.75
9	18.5 – 21.5	8.02	9.83	10.05	9.14
10	21.5 – 25.1	10.31	11.32	11.30	10.07
11	25.1 – 29.3	12.05	12.00	11.73	10.35
12	29.3 – 34.1	12.80	11.65	11.19	9.88
13	34.1 – 39.8	12.33	10.32	9.74	8.72
14	39.8 – 46.4	10.68	8.25	7.65	7.07
15	46.4 – 54.1	8.23	5.86	5.31	5.19
16	54.1 – 63.1	5.52	3.58	3.13	3.38
17	63.1 – 73.6	3.07	1.74	1.41	1.86
18	73.6 – 85.8	1.25	0.51	0.30	0.76
19	85.8 – 100.0	0.18	0.00	0.00	0.11

***Table 4:** Water droplet size measurement intervals*

To create a volume distribution of droplet size, the point in the middle of a mist cone at the distance of 50 mm from the orifice of a particular nozzle was chosen. The size of the water droplets shown in Graph 2 on the X-axis is the geometric mean of the above-mentioned size intervals.



Graph 2 – Droplet size distribution for the 400 µm and 500 µm nozzles, 50 mm from the orifice, cone center, 30 measurements arithmetic mean

Considering the principle of measurement, and practical findings, 50 mm from the nozzle orifice was chosen as a representative value.

The width of the water mist cone in the distance of 50 mm from the orifice is 85 mm for the 400 µm nozzle, 90 mm for the 500 µm nozzle, 88 mm for the 600 µm nozzle and 95 mm for the 1000 µm nozzle.

The results of Sauter mean diameter in the same distance were determined as follows. For the nozzle with an orifice diameter of 400 µm, the value of Sauter mean diameter is D_{32} [20.4 ± 0.9 µm]. Nozzle with an orifice of 500 µm produces drops of D_{32} [20.9 ± 0.4 µm]. For a 600 µm orifice nozzle, D_{32} is [18.1 ± 0.5 µm]. For the nozzle with the largest orifice 1000 µm, the value of D_{32} is determined as [17.5 ± 0.3 µm].

The volume fraction of the size of water droplets related to their diameter is in the order of tens of micrometers, for individual nozzles. The maximum volume fraction of water droplet size for 500 µm, 600 µm and 1000 µm nozzles is in the range [25.1 – 29.3 µm], while the percentage for the 500 µm nozzle is [12.8 ± 0.2%], for the 600 µm nozzle it is [11.8 ± 0.1%] and for a nozzle of 1000 µm it corresponds to [10.5 ± 0.1%]. For the 400 µm nozzle, the droplet sizes in the interval [29.3 - 34.1 µm] are most often represented, in a percentage of [11.9 ± 0.4 %].

4. CONCLUSION

This paper deals with the measurement of the characteristics of water mist, created by hydraulic misting nozzles with a hollow cone type with orifice diameter of 400 µm, 500 µm, 600 µm and 1000 µm. For measurement, a laser diffraction system was chosen, which operates on the principle of laser diffraction. The characteristics were measured at a working pressure of 70 bar in a water mist system.

Considering the principle of the chosen method, and accounting for the Lambert-Beer law, it can be seen that the measurement results are affected by the measuring distance from the nozzle orifice (width of the water mist cone through which the laser beam passes) as well as homogeneity of the mist stream (spray). "To increase the accuracy of the measurement results, it is necessary to take into account the measuring distance from the nozzle, the length of the penetrating laser beam path, the expected droplet shape, the homogeneity of the mist cone and the flow turbulence, in relation to the principle of the given SprayTec device method."

As the distance from the nozzle orifice increases, the droplet size, defined by Sauter mean diameter D_{32}, increases. This result can be observed both in the middle of the water cone in the nozzle axis and at the edge of the mist cone, for each measured nozzle. The volume fraction of the size of water droplets related to their diameter is in the order of tens of micrometers, for individual nozzles.

The data clearly show that the mean Sauter diameter (D_{32}) increases with increasing distance from the nozzle, both in the centre of the cone and at its edge. This trend is likely to be due to droplet redistribution in the cone (larger droplets migrate towards the periphery of the cone due to their inertia, while smaller droplets remain closer to the axis) and droplet stabilisation (droplets adopt a spherical shape due to surface tension and turbulent flow settling at greater distances).

At the edges of the cone, D_{32} values are systematically higher than at the centre, confirming the typical inhomogeneous distribution of droplets in a spray cone.

Smaller jets (e.g. 400µm) produce smaller droplets close to the nozzle orifice and there is a steeper increase in D_{32} with increasing distance. They are also more sensitive to turbulent flow, which can lead to a wider range of values. Larger nozzles (e.g. 1000 µm) show a more uniform increase in D_{32} and less scatter of values, corresponding to a more stable flow.

The data shows that the droplet size distribution is not constant along the cone and has important practical implications, e.g. for the design of extinguishing systems (water mist) - based on changes in D_{32} the optimum distance of the nozzle from the target area can be designed to ensure effective droplet coverage of the cone. The size of the droplet affects its lifetime and range during a fire. It affects the ability of endothermic cooling or shielding of radiant heat. Droplet size has a significant effect on the suppression and extinguishing of fires. However, it is not possible to apply the results generally. For each type of fire, the most effective size value may vary, which emphasizes the need to work with different droplet sizes in experimental practice.

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References

[Andersson 1996] Andersson, P., et al. Small scale experiments and theoretical aspects of flame extinguishment with water mist. Lund University [online], 1996. [cit. 01-25-24]. Available from: https://lucris.lub.lu.se/ws/files/6369816/4450577.pdf

[Beji 2017] Beji, T., et al. Influence of the particle injection rate, droplet size distribution and volume flux angular distribution on the results and computational time of water spray CFD simulations. Fire Safety Journal. July 2017, Vol.91, pp 586-595. ISSN 03797112

[Choi, 2002] Choi, S.H., et al. Steady-flow characteristics and its influence on spray for direct injection diesel engine. KSME International Journal. July 2002, Vol.16, No.7, pp 986-998. ISSN 1226-4865

[Cui 2021] Cui, Y., et al. Research progress of water mist fire extinguishing technology and its application in battery fires. Process safety and enviromental protection. May 2021, Vol. 149, pp 559-574. doi:10.1016/j.psep.2021.03.003

[Dayal 2004] Dayal, P., et al. Evaluation of different parameters that affect droplet-size distribution from nasal sprays using the Malvern Spraytec®. Journal of Pharmaceutical Sciences. April 2004, Vol.93, No.7, pp 1725-1742. doi:10.1089/jamp.2012.1030

[Dodge 1987a] Dodge, L.G., Comparison of performance of drop-sizing instruments. Applied Optics. 1987, Vol.26, No.7, pp 1328,1341. ISSN 0003-6935

[Dodge 1987b] Dodge, L.G., et al. Drop-size measurement techniques for sprays: comparison of Malvern laser-diffraction and Aerometrics phase/Doppler. Applied Optics. 1987, Vol.26, No.11. ISSN 0003-6935

[Dumouchel 2008] Dumouchel, C., et al. Light multiple scattering correction of laser-diffraction spray drop-size distribution measurements. International journal of Multiphase Flow. March 2009, Vol.35, No.3, pp 277-287. doi:10.1016/j.ijmultiphaseflow.2008.11.001

[Dumouchel 2009] Dumouchel, C., et al. Light multiple scattering correction of laser-diffraction spray drop-size distribution measurements. International Journal of Multiphase Flow. March 2009, Vol.35, No.3, pp 277-287. ISSN 03019322

[Gao 2018] Gao, G., et al. Experimental Studies on the Spraying Pattern of a Swirl Nozzle for Coal Dust Control. Applied Sciences. September 2018, Vol.8, No.10. ISSN 2076-3417

[Gopesh 2022] Gopesh, T., et al. Vacuum exhausted isolation locker (VEIL) to reduce inpatient droplet/aerosol transmission during COVID-19 pandemic. Infection Control & Hospital Epidemiology. January 2022, Vol.43, No.1, pp 105-107. ISSN 0899-823X

[Green 2019] Green, A., et al. Experimental Characterization of wildfire sprinkler sprays using high-speed videography. Atomization and Sprays. 2019, Vol.29, No.5, pp 381-402. ISSN 1044-5110

[Grimwood 2005] Grimwood, P. Fire-fighting Flow-rate. Highrisefire.co.uk, 2005, Northwood [online]. [cit. 01-25-24]. Available from: https://www.highrisefire.co.uk/docs/FLOW-RATE%20202004.pdf

[Husted 2004] Husted, B.P., The physics behind water mist systems. IWMA conference. Rome, Italy, 2004

[Kashdan 2002] Kashdan, J.T., et al. Dynamics structure of direct-injection gasoline engine sprays: air flow and density effects. Atomization and Sprays. December 2002, Vol.12, No.4, pp 539-557. ISSN 1044-5110

[Kashdan 2006] Kashdan, J.T., et al. Characteristics of transient, swirl-generated, hollow cone sprays. Atomization and Sprays. 2006, Vol.16, No.5, pp 493-510. ISSN 1045-5110

[Lelong 2014] Lelong, N., et al. 1 of 1 Comparison of Laser Diffraction Measurements by Mastersizer X and Spraytec to Characterize Droplet Size Distribution of Medical Liquid Aerosols. Journal of Aerosol Medicine and Pulmonary Drug Delivery [online]. May 2014, Vol.27, No.2, pp 94-102. doi:10.1089/jamp.2012.1030

[Liao 2006] Liao, G., et al. Progress in water mist fire suppression technology. Journal of University of Science and Technology of China. 2006, Vol.36, No.1, pp 9-19.

[Liu 2003a] Liu, J., et al. Progress in research and application of water mist fire suppression technology. Chinese Science Bulletin. April 2003, Vol.48, pp 718–725. Avaliable from: https://doi.org/10.1007/BF03187040

[Liu 2003b] Liu, J., et al. Experimental study on the interaction of fine water mist with solid pool fires. Science in China Series E: Technological Science. April 2003, Vol.46, 218–224. Avaliable from: https://doi.org/10.1360/03ye9024

[Mahmud 2014] Mahmud, H.M., et al. Study of water-mist behaviour in hot air induced by a room fire: Model development, validation and verification. Fire and Materials. 2014, Vol.40, No.2, pp 190-205. ISSN 03080501

[Mehaddi 2020] Mehaddi, R., et al. Use of a water mist for smoke confinement and radiation shielding in case of fire during tunnel construction. International Journal of Thermal Sciences. February 2020, Vol. 148. ISSN 12900729.

[Santangelo 2010] Santangelo, P.E. Characterization of high-pressure water-mist sprays: Experimental analysis of droplet size and dispersion. Experimental Thermal and Fluid Science. November 2010, Vol.34, No.8, pp 1353-1366. ISSN 08941777

[Sapit 2019] Sapit, A., et al. Spray Characteristics for Cooling Application. International journal of integrated engineering. September 2019, Vol.11, No.3., pp 299-303. ISSN 2229-838X

[Shrigondekar 2018] Shrigondekar, H. et al. Characterization of a simplex water mist nozzle and its performance in extinguishing liquid pool fire. Experimental Thermal and Fluid Science. 2018, Vol. 93, pp 441-455. ISSN 08941777

[Tanaka 2020] Tanaka, F., et al. Fire cooling performance by water sprays using medium and small-scale model experiments with scaling relaxation. Fire Safety Journal. March 2020, Vol. 112. ISSN 03797112.

[Wang 2020] Wang, J., et al. Spray Structure and Characteristics of a Pressure-Swirl Dust Suppression Nozzle Using a Phase Doppler Particle Analyze. Processes. September 2020, Vol.8, No.9. ISSN 2227-9717

[Wu 2021] Wu, Y., et al. Picosecond pulsed digital off-axis holography for near-nozzle droplet size and 3D distribution measurement of a swirl kerosene spray. Fuel. 2021, Vol.283. ISSN 00162361

[Xiaohong 2022] Xiaohong, G., et al. Influence of Water Mist Nozzle Characteristic Parameters on Oil Pool Fire Extinguishing in Confined Space. Arabian Journal for Science and Engineering. March 2022, Vol.48, pp 3441–3454. doi:10.1007/s13369-022-07162-0

[Zaremba 2016] Zaremba, M., et al. Comparison of different configurations of Phase Doppler Analyser. EPJ Web of Conferences. March 2016, Vol. 114. ISSN 2100-014X

[Zhang 2013] Zhang, H., et al. Droplet dispersion characteristics of the hollow cone sprays in crossflow. Experimental Thermal and Fluid Science. February 2013, Volume 45, pp 25-33. ISSN 08941777.

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