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A Brief Review on Design and Operation Principle for Nozzles Discharging Water Mist

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Abstract

Water mist systems are widely used for fire protection in substituting gas protection Halon system. Very few articles appeared in the literature on the design and operation principles of the nozzles though there must be some restricted reports for commercial products. A brief review on the water mist nozzle reported in the literature will be presented in this paper.

It is observed that three common types of nozzle are widely applied: impinging type, pressure-jet type and twin-fluid air-atomizing type. These products have their own characteristics and application areas. To improve reliability and performance of the system, more efforts should be paid on developing nozzles for discharging less water but extinguishing a fire faster.

Nomenclature:

$\dot{m}_{aw}$:	Mass flow rate of air in presence of water
$\dot{m}_a$:	Mass flow rate of air
X:	Lockhart-Martinelli parameter
c_a:	Discharge coefficient for air
c_w:	Discharge coefficient for water
r:	Pressure ratio($=p_{atm}/p$, where p is p_a or p_m or p_w or p_l)
σ:	Cross-sectional area ratio
χ:	Isentropic exponent of air
$\bar{X}$:	Distribution constant

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N_1:	Size constant
D:	Diameter of droplets
$\overline{D}$:	The overbar in $\overline{D}$ designates an averaging process
(p-q)p>q:	The algebraic power of $\overline{D}_{pq}$
p and q:	The integers 1,2,3 or 4
D_i:	The diameter of the i^{th} drop
W:	Width of the histogram bin
IQAR:	Interquartile range (the 75th percentile minus the 25th percentile)
N_2:	Number of available samples
fv:	velocity distribution function
$\overline{v_v}$:	Average velocity vertical component of entrained air
α:	Velocity angle

1. Introduction

Following the increasing concern on ozone depletion, total flooding gas protection systems based on halon are being substituted since 1987 [1]. New effective and clean fire extinguishing agent are developed for protecting the machinery room, electronic room, computer room and submarine. It is reported that water mist fire suppression system (WMFSS) would use very small amount of water to extinguish a fire. System components include water source, water pump, pipe works, and nozzles. System performance depends on the design of those components.

The nozzle is a key component as the droplets size and velocity distribution at an operating pressure and a flow rate are determined by its design. A better understanding on the physical structure and the working principles would help the improving performance of the system. The main characteristics of the water mist nozzle are shown in the Fig.1.

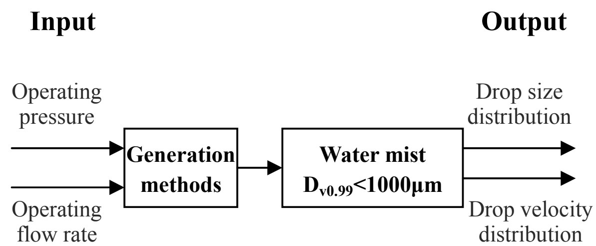


Fig.1: Characteristics of water mist nozzle

One of the main design objectives is to minimize the operating pressure and operating flow rate but still gives sufficient amount of fine droplets with adequate velocities. Input parameters include operating pressure which would give momentum of the water droplets. The higher the pressure, the bigger is the momentum of the water droplet. The operating flow rate would give sufficient water to suppress the fire, say by extracting heat and cooling down the environment. These two parameters, together with good design of nozzle would generate water drops. Droplets size and velocity depend on the generation methods. According to NFPA 750, $D_{v0.99}$ (i.e. 99% of the water droplets are having diameter less than this value) is smaller than 1000μm [2]. The system shall give water droplets of suitable size and velocity distributions, as fire suppression depends on these two distribution functions.

One major extinguishing mechanisms of the water mist is cooling [3]. The temperature of the water droplets would be increased to the vaporization point when the heat is transferred from the fire and environment. With continuous supplying heat, the water may be further heated to the superheat status. As the latent heat of vaporization for the water is very high, large amount of heat could be extracted by evaporation.

The amount of heat extracted depends on the water volume and droplet size. Finer water droplets would extract more heat due to the bigger surface area with the same amount. In order to penetrate through the plume and flaming regions, the droplets must have sufficient momentum to travel from the spray nozzle to the flaming regions or the burning object by overcoming the fire-induced turbulent hot gases flows. These gas currents might carry fine water mist upwards or away from the fire. To fulfill these requirements, enough operation pressure and the flow rate should be considered carefully in system design.

Water mist systems can be classified as low pressure system, intermediate pressure system and high pressure system [2]. The minimum working pressure for low pressure system is 12.1 bar. For the intermediate pressure one, the operating pressure is between 12.1 bar to 34.5 bar and for the high pressure system, the working pressure is more than 34.5 bar.

Fine water droplets can be generated by atomization which is defined as "the breaking down of a liquid into a fine mist can be suspended in air [4]. A high ratio of surface to mass in the liquid phase would be achieved to give high evaporation rates. Apart form some minor atomization methods like supersonic and subsonic vibration, mechanical vibration, high voltage electrical energy and others; there are four major methods to breakup the water by atomization [5]:

- Atomization by means of centrifugal or swirl-type pressure nozzle, such as the GW water mist [6].
- Atomization by pneumatic or gas stream, i.e. a jet of water is disintegrated by a high-velocity gas stream (twin-fluid atomization), such as the Fike protection system [7].
- Atomization by impingement, such as the Grinnel Auqamist System [8].
- Atomization by spinning-disk, i.e. the water droplet is broken up by discharging it at high velocity from the periphery of a rapidly rotating disk.

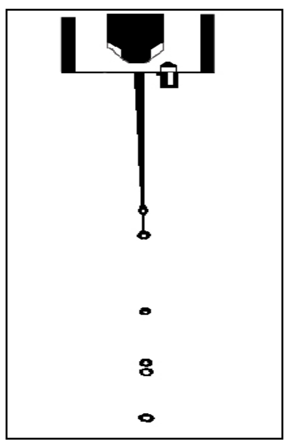
The first three types of atomization methods are commonly used in water mist nozzle design. Each method and the associated atomizing mechanisms are reviewed as following.

2. Centrifugal or swirl-type pressure nozzle

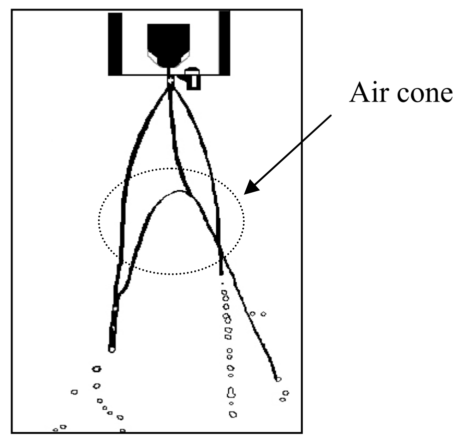
Liquid turbulence and attenuation effect of the tangential velocity component of the liquid in a centrifugal or swirl-type nozzle leads to atomization. The atomization conditions of the centrifugal type nozzle depend on the magnitude of the angular or swirling velocity of the water. After leaving the orifice, water forms an air cone following the axis of the jet when discharging pressure reaching a certain value. For different liquid with varying viscosity, the pressure setting is different. For water having low viscosity, the threshold pressure is relatively low. Prior to the formation of the air cone, water discharging from the orifice is more or less performing like a corkscrew. It is because with that discharging pressure, swirling or spinning velocity provided is not high enough to form the air cone. It is also found that impacts due to tangential velocity component are stronger that that from axial component in breaking up the liquid [5].

The working mechanisms of the nozzle under different pressures are different. At lower pressure, the cone formed by the nozzle is similar to a film or a thin sheet, and with the film extended outward from the nozzle.

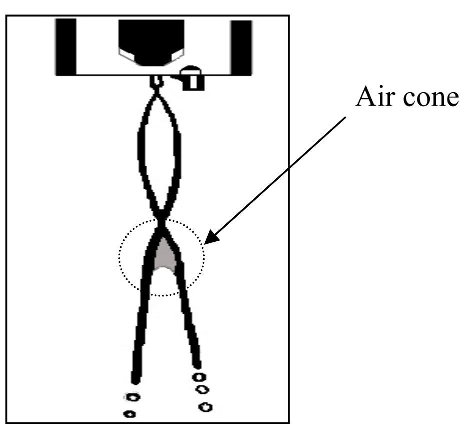
The drops form when the film thickness cannot provide enough force to resist the disruptive forces created by the oscillating wave motions in the film [5]. Up to the present moment, the working mechanism at high pressure is not understood yet. The suggested explanation for breakup is due to the turbulence effects at the annular ring of water which discharging from the nozzle. The water breaks up almost instantaneously at the orifice exit because of the fluctuating velocities randomly at all directions [9,10]. This is clear shown in Fig.2.



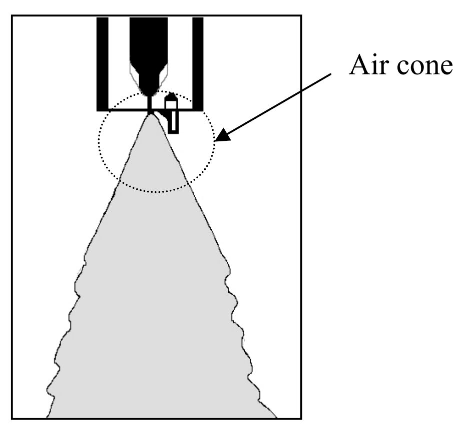
(a) 0.69 bar without air cone



(c) 9.65 bar with air cone



(b) 4.96 bar with small air cone



(d) 43.33 bar with air-cone angle fully developed

Fig.2: Swirl-type nozzle air cone formation procedure at different pressure [5]

3. Pneumatic type nozzle (twin-fluid

type nozzle)

It is easier to form fine water droplets by the pneumatic type nozzle than others, and so more convenient for smaller-scale premises. However, this type of nozzles require large amount of energy to atomize water. There are two steps in the atomization process for the pneumatic type nozzle. The first step is that the fluid consumed (can be water or mixture of compressed air and water) emerges as small ligaments due to the potential energy of the liquid, i.e. the liquid pressure or mixture pressure along with the geometry of the nozzles. The air friction tears the ligaments from the main flow of water. The second step is that ligaments collapse and break up further into very small 'pieces' as fine water droplets. However, ligament can only be lasted for a very short period, say, 1.67 x 10^{-4} s for a ligament of 2.65 μm in diameter [11]. The detail for water droplets breakup in pneumatic nozzle [5] is shown in Fig.3.

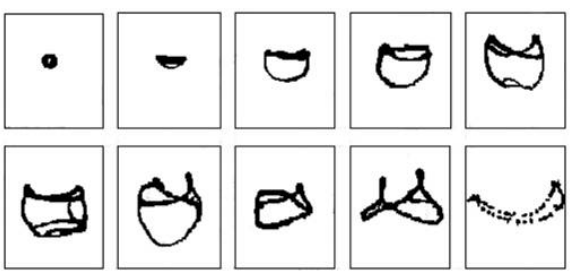


Fig.3: The breakup mechanisms of a drop suddenly impacted by a high-velocity air jet

The jet instability and breakup of the water droplets might be due to rotating symmetrical oscillation as explained by some theories. The critical wavelength of the oscillation λ_{opt} is taken to be equal to the length of ligament separating from the main liquid flow [12]. Two different fluids will be used to generate water mist. Geometry [12] of the pneumatic nozzle together with the mixture of water and compressed gas at the exit orifice is shown in Fig.4.

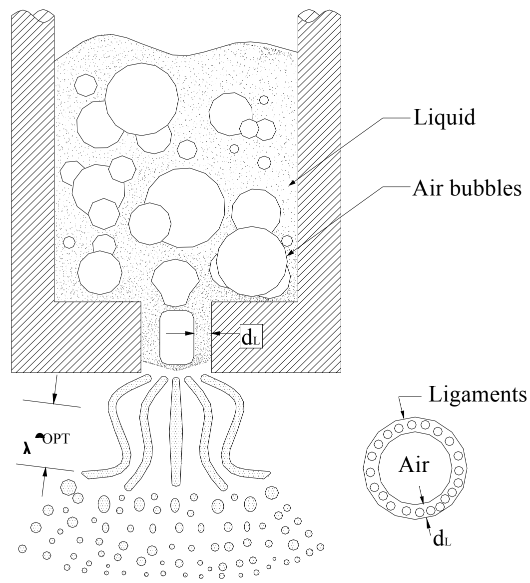


Fig.4: Spray geometry at the nozzle exit [9]

4. Other generation methods

The mist generation mechanism by impingement type of nozzle is relatively simple. High velocity water jet is discharged from the orifice and bump into a solid target. Sudden change of the momentum would give the water energy attenuation and disintegration into fine droplets. Appearance and the structure of the impingement nozzle are quite similar to a conventional sprinkler head. The solid target might be in ball-shape, plate shape or other special spiral-shape. Normally, there is a screen for filtering the impurities to prevent blocking the orifice.

Another generation method not so widely used is by flashing superheated water. This method was developed by Brown and York [13] based on the change of pressure and temperature. Superheated water at 175 ^{o}C in an under-pressure container with 10 bar was released to atmosphere. Part of the superheated water will be flashed into the vapor, and then condensed into fog. Much finer water droplets can be produced using this method than by any mechanical generation methods. The sudden energy release leads to the intense cooling of the spray. Therefore, after traveling for about 30 cm, the temperature of the water mist cannot be higher than 35 ^{o}C, giving low evaporation rates. Studies carried out [14-16] concluded that ultra-fine water droplets may not be more effective than the normal water mist droplets in extinguishing the liquid pool fire.

Other methods of atomization like by mechanical vibration, by supersonic or subsonic vibration and by high-voltage electricity are not commonly used for water mist design. These methods will not be described in details in this paper.

A brief survey on the commercial product of water mist nozzles available in the market was carried out. Some of them are listed under the Factory Mutual Approval lists, which are worldwide accepted.

5. Design of twin fluid water mist nozzle

Special attention should be paid when designing the twin-fluid type nozzle as mist generation mechanism is different from that of single-fluid nozzle. As the water and compressed air are mixed before discharging from the orifice, two parameters should be considered together. In the past, the air-to-liquid pressure ratio (ALR_p) and air-to-liquid mass flow rate ratio (ALR_m) were defined to help in working out the upper and lower limits for the air/water ratio for the nozzle [3].

However, the ALR_m ratios for the mixture is not very easy to be obtained as the mass of air or mass of liquid cannot be measured experimentally. In order to simplify the problem, a series of experiments on air/water ratio was carried out by Koria and Datta [17] to get a relationship between mass flow rate of air in presence of water $\dot{m}_{aw}$ and mass flow rate of air only $\dot{m}_a$ which could be measured physically.

As the situation is quite complex when two fluids appeared at the nozzle both, the simplified concepts embraced are to measure the flow rate of single phase fluid which could create the same pressure drops to that twin-fluid case. By referring to Murdock's theory and Lockhart-Martinelli parameter X, the final expression of $\dot{m}_{aw}/\dot{m}_a$ is a function of Lockhart-Martinelli parameter, discharge coefficient c, pressure ratio r, the cross section area ration σ and the isentropic exponent of air χ.

$$\frac{\dot{m}_{aW}}{\dot{m}_a} = 1 + X\,\frac{c_a}{c_W}\,\frac{\left(1-\sigma_W^2\right)^{1/2}}{\left(1-\sigma_a^2 r^{2/\chi}\right)^{1/2}} \quad \ldots (1)$$

All the parameters in the equation (1) could be measured experimentally. After these mathematical deduces, the term could be used to help engineers on designing and modifying the twin-fluid nozzle easily.

Recently, a twin-fluid nozzle was developed by Yang and Wang et.al [18] by using the emulsifiable substance as the atomizing medium. The operation principles are that when compressed air is passing through the air atomizing orifice, the velocity of the air is further increased to a higher value. Meanwhile, water under pressured passes through the water atomizing orifice would give higher velocity. When the high velocity water flow strike and collide with high velocity air flows from the orifices, the water begins to be emulsified in the mixing chamber. After emulsification, viscosity and surface tension of the water drops are decreased. The characteristic of emulsifiable water is very un-steady and easy to break up into smaller parts under disturbances. The emulsifiable water inside the mixing chamber is still kept at very high pressure. Upon discharged from the discharging orifices, it is broken-up to the water mist with expected water droplet sizes.

The twin-fluid type nozzle makes use of two different fluids to generate water mist. There are challenges to design a new type of water mist nozzle by modifying the atomizing medium or the physical structure to reduce the operation pressure and flow rate.

6. Characteristics of the water spray

Characteristics of the water spray can be described by many factors like drop size distribution, flux density, spray momentum, additives, cone angle, velocity of the discharge jet, mass flow rate and so on [e.g. 3,19]. Among all of these, the droplet size distribution and velocity distribution function are the representative characteristics for the system.

6.1 Droplet size distribution

As pointed out by Sprakel [20]:

"The drop size distribution is the most important instrument that determines the extinguishing properties of a water mist system."

The droplet size distribution means the range of drop sizes contained measured at a specification location in a spray [3]. Measurement of distribution should be carried out at the minimum and maximum rate pressure of the water mist nozzle. The measurement points [2] are located at the series of concentric rings with the radius from 0.203D, 0.353D and 0.456D, with D stands for the nozzle spray patterns diameter. Experimented data will be analyzed and fitted.

- Sampling techniques

There are two major types of sampling techniques widely used. One is called spatial technique and the other one is flux technique. The spatial technique is collecting the drops which occupy a given volume instantaneously. The flux technique is implied when individual drops which pass through the cross-section of a sampling region in a certain time. The flux technique and spatial technique can be transformed from each other through dividing the number of samples in each calls size by the average velocity of the drops in that size class. For the fire research, the spatial sampling technique is more appropriate.

- Mathematical distribution functions

Two drop size distribution functions used in industry are the Rosin-Rammler distribution function and the one proposed by ASTM

Standard E799-92 [21]. The Rosin-Rammler distribution can be expressed as a function of distribution constant $\overline{X}$, size constant N and diameter of the drops D [22]:

$$F(D) = 1 - \exp[-(\frac{D}{\overline{X}})^N] \quad \text{........... (2)}$$

The Rosin-Rammler distribution is widely used for dealing with the particle distribution. The parameters $\overline{X}$ and D can be obtained from measuring by the analyzers. The ASTM E 799-92 distribution is a function of mean drop diameter D_{pq} and the i^{th} drops diameter D_i:

$$(\overline{D}_{pq})^{(p-q)} = \frac{\Sigma_i D_i^p}{\Sigma_i D_i^q} \quad \text{........... (3)}$$

With different p and q value, the D_{pq} represents different physical meanings for the droplet diameter. Mean drop diameters widely used are listed in the literature [21,23].

The ASTM E 799 is a guideline on measuring, analyzing and fitting the droplet sizes. To determine the optimum histogram bin size, the following expression by Freedom and Diaconis might be used [24]:

$$W = 2(IQAR)N^{-1/3} \quad \text{........... (4)}$$

The optimum bin width W is a function of Interquartile range (the 75th percentile minus the 25th percentile) IQAR and number of available samples N. The commercial company provides some figures and analysis on the water droplets size distribution based on these two mathematical distribution functions like examples in Fig.5 and Fig.6 [8]. In addition, the spray cone angle affects the droplet size distribution also. The cone angles are usually [24] 90° or 120°.

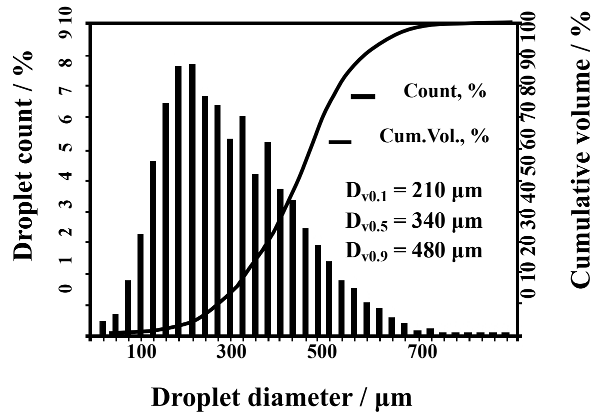


Fig.5: Representative droplet size distribution data at 11.7 bar [8]

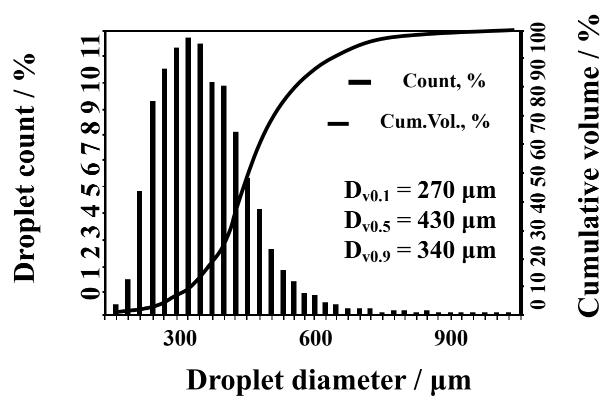


Fig.6: representative droplet size distribution data at 12.1 bar [8]

6.2 Velocity distribution f(v)

The spray momentum affects the successful application of water mist system. As the momentum is the product of mass and velocity, when mass discharge rate is constant, the spray velocity mainly determines the magnitude and direction of the spray momentum.

As a vector quantity, the velocity distribution can be expressed as a function of average vertical component of entrained air $\overline{v_v}$ and the velocity angle α: $f_v = f\left(\overline{v_v}, \alpha\right)$ [3]. The vertical component of the velocity is measured by using the vane-type anemometer which puts at different location with two certain distances below the nozzle. The measurement includes both the velocity of water drops and the entrained air in the surrounding environment. In the case of fire, the directions of water drops are opposite to the entrained air and might eliminate from each other. Therefore, the average velocity of the entrained air is used instead of that of fastest moving drops. The velocity angle indicates the direction component of the spray. The controlling of "directionality" of the spray is even more important than controlling the droplet size distribution or mass flow rate [3]. In some cases, a small modification of the velocity angle range could improve the extinguishing performance of the whole system dramatically.

7. Application of the nozzles

Different nozzles with water mist generated by different methods have their own applications.

The impingement nozzles are widely adopted to control the solid fire where relatively large water droplet sizes are more effective. They have bigger orifice diameter operating at relatively lower operating pressure to generate bigger drops. These types of nozzles show good performance when used on the submarine, ship or in the residential buildings and their uses are quite similar to the sprinkler system [25].

The high pressure jet nozzles are usually used to extinguish the Class B fire in the machinery room or in gas turbine room [3,19,25]. In some cases, they also appear in the computer room or electronic room to protect the high price equipment. As the high pressure used to discharge the water mist, the droplets contain large momentum and can overcome the effect of the fire plume and indoor aerodynamics to reach the flame surface. Therefore, for some special room geometry and local application, they are good choices. However, for this type of nozzle, the equipment initial input and maintenance fee is a big burden for the users. The safety problems should also be paid attention as all the systems are under great pressures.

The twin-fluid nozzles are most commonly used for industrial buildings. For the industrial building, dusts bring lots of problems especially for the fire installation like water mist nozzle. The nozzles are very easy to be blocked by the dusts in the air as the orifices are very small. The orifices for the twin-fluid nozzles are relatively big and therefore, using this type of nozzle can reduce the risk of blockage inside the industrial building [25]. The low pressures used are also safe and cheap. Another outstanding point is its space saving characteristic. It only requires two cylinders and a set of pipe work. For those premises which could not provide large pump room, this system is a good choice. The main disadvantages of this type of nozzle are the running cost. As the system uses compressed air to pump the water and form the water mist. After using once, the compressed air should be refueled. However, the twin-fluid nozzles only make use of low pressure to generate mists; the water droplets do not contain large momentum. Therefore to some extents, the extinguishing capabilities of the system are not so good and the droplets are very easy affected by the ventilation conditions inside the compartment.

8. Conclusion

The nozzle is the most important part of the water mist system. Firstly, the nozzle must be reliable to operate at the design condition expected. Secondly, a particle size and velocity distribution of the water mist discharge depends on the nozzle. Therefore, the system performance depends on the nozzle selected to give a good distribution pattern as well as to optimize the extinguishing capabilities. As there are not much information reported on the water mist nozzles, it is difficult to understand how the water mist nozzle works and how fire extinguishment is affected. For the commercial products, there are no universal standard and design guide to direct the application of the nozzles. Even for the same premises and same fire scenarios, different brand nozzles require different discharging flow rate and pressure. For example, in protecting a 260 m^3 combustion turbine, machinery spaces and special hazard machinery spaces, the Fike protection system requires 21 bar operation pressure and 8l/min flow rate [7] but the Securiplex system needs only 5.5 bars [26]. Therefore, it leads the confusion for the users. For the water mist nozzle design, there are great spaces for the further development, especially for the low-cost, low-pressure and high-reliability nozzles.

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