Advances in Piezoelectric Atomizers

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Abstract: Piezoelectric atomizers exhibit the advantages of structural simplicity, portability, low energy consumption, low production costs, and good atomization. They have been extensively used in various fields, including inhalation therapy, inkjet printing, and spray cooling. Here, the research of piezoelectric atomizers is first summarized from the perspectives of theoretical investigation and applications. Subsequently, the existing investigation and applications on piezoelectric atomizers are classified in terms of their functionalities. The functions of inkjet printing, spray cooling, and inhalation therapy are described in detail. Finally, the future trends in this field are analyzed. It is indicated that the vibrating-mesh atomizer has a promising prospect in the market, signaling strong demand especially in upgaraded consumption and medical scenarios.

Key words: piezoelectric; piezoelectric ceramic (PZT); atomization device; nebulization

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0 Introduction

Piezoelectric atomization is a process that uses the piezoelectric drive technology to disperse a liquid into tiny droplets and is extensively used in various fields, including aerospace, medicine and health, environmental protection, safety, and energy saving. In the reciprocating piston internal combustion engine of the aviation turbine, injection and atomization devices are being used for fuel injection to save fuel by ensuring that the fuel is entirely burned[1]. In medicine and health, injection and atomization devices are used for atomization inhalation treatment, skin protection, and convenient medicine and have considerably improved the patient comfort. Because of these advantages, such devices have attracted the attention of medical staff and patients[2]. In inkjet printing, the jetting and atomization devices improve the resolution and print quality[3]. In three-dimensional (3D) printing, the spray and atomization devices achieve high-precision spraying of high-viscosity and high-temperature fluids with low energy consumption[4]. In medicine, in particular, nebulization exhibits special significance; for example, there is much interest in inhalation therapy and the evaporation of volatile anesthetics because of convenient administration and minimal patient discomfort. The main directions of current research are how to improve the administration efficiency and the effectiveness of diagnosis and treatment.

Many types of devices can perform atomization; however, piezoelectric atomizers have attracted considerable attention because of their advantages, including low energy consumption, structural simplicity, and high reliability. Herein, we review the research, progress, and development history of piezoelectric atomizers, classify them according to their structure and working principle, introduce their applications, and infer their future development.

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1 Classification of Piezoelectric Atomizers

Piezoelectric atomizers can be divided into two types based on the meniscus and ultrasonic wavelength. The size of the atomized droplets is determined by the wavelength of the surface tension wave when the meniscus is longer than half the length of the surface tension wave[5]. A piezoelectric spraying and atomizing device that uses surface tension waves for atomizing a medium is known as a surface acoustic wave (SAW) atomizer. When the meniscus is shorter than half the wavelength of the capillary wave, the nozzle size can be used to determine the size of the atomized droplets; this type of piezoelectric atomizer is called a mesh atomizer. Mesh atomizers can be divided into static and vibrating types based on the fact whether the micro aperture size changes during the working process.

1.1 Surface acoustic wave atomizer

The SAW-generating device is the basis of SAW atomizing devices. In 1965, White et al.[6] proposed an SAW-generating device, as shown in Fig.1, whose working principle is given as follows. An alternating current (AC) signal drives SAW on the surface of the device substrate, causing the surface layer of the substrate to mechanically vibrate and offering the advantage of energy concentration.

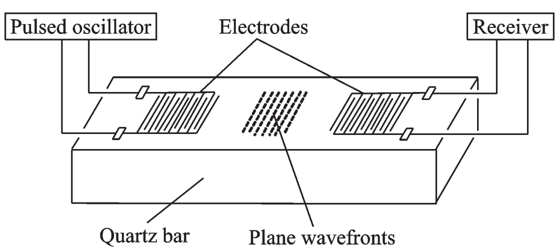

Fig.1 Schematic of the surface-acoustic-wave-generating device

SAWs have been extensively used since their generating devices were proposed. When an SAW propagates in the fluid, it radiates energy to the fluid in the form of leakage sound with a radiation angle θ_r that can be given as

$$\theta_r = \sin^{-1}(v_w/v_r) \tag{1}$$

where v_w and v_r are the SAW propagation speeds in the liquid and the substrate, respectively.

When driven by a low-power signal, the fluid flows or vibrates under the influence of the SAW radiation energy, and this effect can be used to develop a micromixer[7]. With a gradual increase in the power of the driving signal, the radiant energy received by the liquid increases; when the energy reaches a certain level, the liquid becomes atomized.

In 1991, Kuttruff et al.[8] explained the operating principle of the SAW atomizer, as shown schematically in Fig.2. When the power of the driving signal is increased to a certain level, the energy radiated by the SAW forms a capillary wave on the liquid surface. This capillary wave excitation overcomes the surface tension and atomizes the liquid surface.

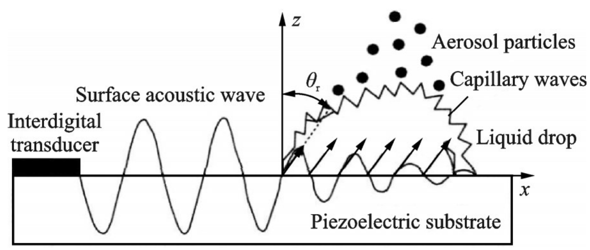

Fig.2 Schematic of the surface acoustic wave atomizer

In 2008, Qi et al.[9-10] proposed a nebulization device, as shown in Fig.3, based on the SAW principle. This nebulization device is portable and can be used for drug delivery, mass spectrometry analysis, and generating cell suspensions.

In 2009, Zhang et al.[11-12] of the Shanghai Jiao Tong University designed an SAW atomizer by designing an interdigital finger structure in each of the four directions of the base (Fig.4). These four interdigital finger structures direct the generated ultrasonic vibration to the center of the substrate, and the size of the atomized particles can be altered by adjusting the period of the interdigital structure. When the period is 40 μm, the atomized droplet size is 100 nm, allowing the generated atomized droplets to directly permeate through the skin and offering improved control over the biological reaction process. The atomization rate is 1 μL/s and the atom-

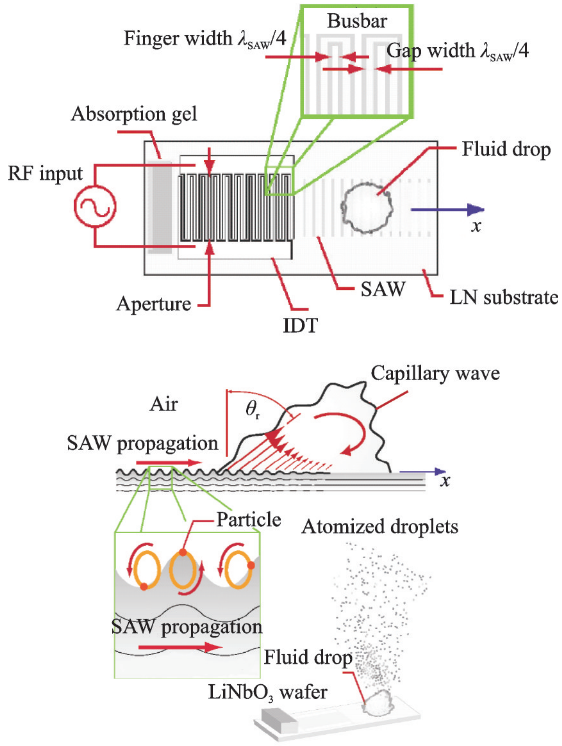

Fig.3 Surface acoustic wave atomizer proposed by Qi et al.[9-10]

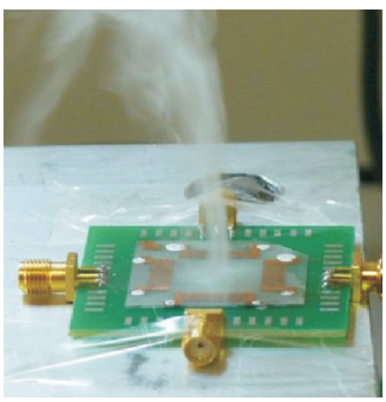

Fig.4 Surface acoustic wave ultrasonic atomizer[11-12]

ized droplet size is 2.61 μm when the driving frequency is 10.1 MHz and the power is 24 W.

In 2010, Heron et al.[13] produced a similar SAW atomizer on the $LiNbO_3$ piezoelectric transducer. This atomizer exhibits good quality during the atomization process and does not require small holes, which can avoid fog. A clogging phenomenon occurs when the atomizer is atomized. These research results have been used in mass spectrometry detection. Subsequently, Ho et al.[14] extended this achievement in 2011 to detect low levels of heavy metals in tap water and the presence of caffeine as well as fluorouracil in human whole blood.

In 2013, Ramisetty et al.[15] designed the SAW ultrasonic atomizer shown in Fig.5. Through experimental research, the driving parameters of the atomizer and the properties of the liquid were observed to be important factors that affect the particle size of atomization. The atomized particle size of the liquid increases with an increase in the driving frequency, the liquid flow rate, and the liquid surface tension and decreases with an increase in the liquid viscosity. Further, the stronger the signal emitted by the ultrasonic wave, the more concentrated will be the particle size distribution of the atomized droplets. Based on multiple experiments and statistics, the particle size of the atomized droplets produced by the SAW atomizer was 60—200 μm.

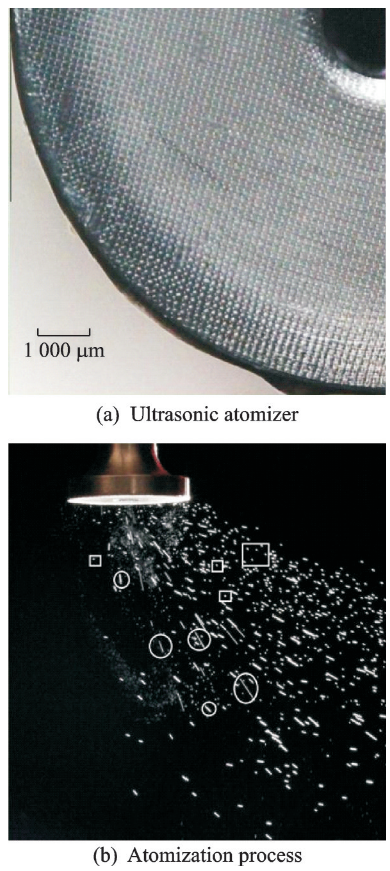

Fig.5 Schematic of the atomizer proposed by Ramisetty et al.[15]

All the aforementioned atomizers are based on the SAW-generating device proposed by White et al.[6]. The working mechanism of this type of atomizer is to apply energy to the entire liquid system, destroy the surface tension of the liquid surface, constrain the liquid droplets, and cause the liquid droplets to fly away from the liquid surface, achieving atomization and spraying. However, in this type of atomizer, the liquid is atomized only at the liquid surface. Further, the energy is applied to the entire system, resulting in a considerably low energy utilization rate of the atomizer. The atomization process is random; the droplet size cannot be controlled, and the particle size distribution of the droplets is not concentrated.

1.2 Mesh atomizer

1.2.1 Static mesh atomizer

The working principle of the static mesh atomizer is to use the vibration of the piezoelectric vibrator to change the pressure inside the liquid cavity. When the pressure in the cavity is sufficiently large, the liquid is ejected from the micro-jetting hole, resulting in atomization.

In 1999, Heij et al.[16-17] proposed a static microporous atomizer, as shown in Fig.6. The atomizer comprises a piezoelectric ceramic (PZT), a liquid inlet, and a metal plate with micro apertures. The holes were obtained by deep reactive ion etching. The properties of the atomizer were studied using a high-speed camera and a Doppler laser vibrometer.

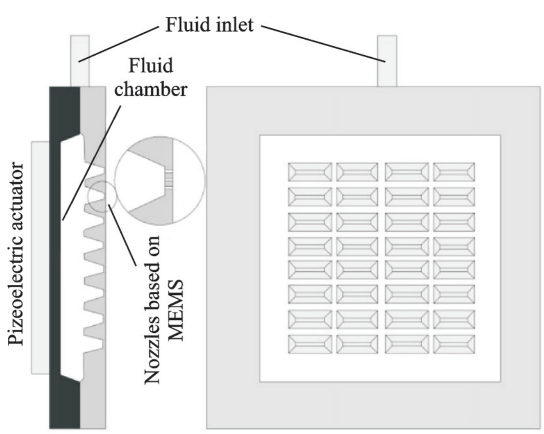

Fig.6 Static mesh atomizer proposed by Heij et al.[16-17]

In 2001, Liu et al.[18] of the Tsinghua University designed an atomizer with a similar structure (such as Fig.6). The atomized droplet size was concentrated around 11 μm, and the spray velocity was concentrated around 0.4 m/s. The atomizer exhibited a stable working performance and good atomization quality. Subsequently, Wang and his team studied the atomizer again and explored the influencing factors of the atomized droplet size from the theoretical and experimental perspectives[19-21]. The experimental results denote the normal distribution of the particle size of the atomized droplets. Simultaneously, the particle diameter of the atomized droplets is observed to be related to the driving frequency, driving voltage, and cone diameter. Subsequently, Wei et al.[22] conducted further research on this type of atomizer. The designed atomizer has a working frequency of 0.4—1 kHz and can achieve controlled spraying of fluids with a viscosity of 0—100 mPa·s. It achieves on-demand ejection, uniform atomization particle size distribution, and stable ejection speed. Further, a mathematical model of the droplet ejection process was established using the Bernoulli equation in an unbalanced state.

In 2006, Pan et al.[23] designed a new type of static microporous atomizer, as shown in Fig.7, and its structure is similar to the atomizer proposed by Wei et al.[22]. The atomizer can achieve high-quality atomization, and the particle size of the generated droplets is finer and more uniform than that of industrial aerosolization. The atomizer has a small volume and a low power consumption of only 1 W. When the driving frequency is 16 kHz, the atomization amount is the largest and becomes 1.8 cm^3/min, and the average particle size of the atom-

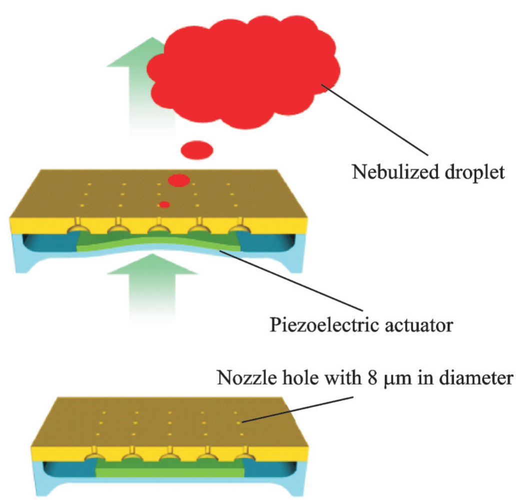

Fig.7 Schematic of the atomizer proposed by Pan et al.[23]

ized droplets is 6.13 μm. The atomizer is used in mass spectrometry analysis.

In 2007, Jeng et al.[24] proposed a dual-piezo-driven high-frequency resonance atomizer, whose working principle is shown in Fig.8. A piezoelectric vibrator is formed by applying an AC voltage to two piezoelectric wafers. The piezoelectric wafers at both the ends contract and expand, which causes the piezoelectric vibrator to deform and ejects the liquid from the micropores. At the same time, Jeng et al. conducted an experimental study on the atomizer. When the driving frequency was 18 kHz, the atomization amount was the largest and became 1.8 cm^3/min. Subsequently, Jeng et al.[24] studied the effect of different types of PZTs and varying the distance between the bottom plate and the nozzle bar on the atomization performance. They compared the amount of atomization produced by the nozzles obtained using different processes. In the mist produced by nozzles obtained using μEDM, the amount of atomization is approximately four times that of laser manufacturing. At a driving frequency of 7 kHz, the amount of atomization generated by the nozzle made by μEDM is 8 mL/min.

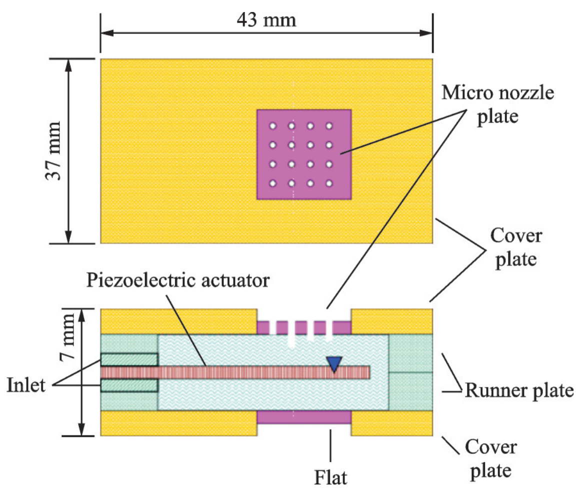

Fig.8 Schematic of the atomizer proposed by Jeng et al.[24]

However, the analysis of previous studies shows that the static mesh atomizer must be designed with an atomizing cavity whose volume can be changed. This complicates the structure of the atomizer and limits its miniaturization, hindering the promotion of such atomizers.

1.2.2 Dynamic mesh atomizer

In 1986, Maehara et al.[25] proposed a new atomizer structure with a piezoelectric vibrator, as shown in Fig.9. One end of the atomizer is in direct contact with liquid, whereas the other end is in contact with air. The variable volume liquid cavity simplifies the structure of the atomizer, and it can control the atomization process. The experimental results indicated that the shape of the pinhole plate and the number of pinholes affected the performance of the atomizer and that the amount of atomization was directly proportional to the number of pinholes. Maehara et al.[26] optimized the structure of the atomizer and observed that its atomization amount at the second-order resonance frequency is larger than that at the first-order resonance frequency. In the second-order vibration mode, the amount of atomization is related to the resonance frequency and the structural parameters of the atomizer; further, the resonance frequency increases with increasing outer and inner diameters of the PZT plate. The atomization amount is the largest when the inner diameter of the PZT sheet is 3.9 mm and the outer diameter is close to the outer diameter of the atomizing sheet. The comparison of theoretical and experimental results generates errors of less than 10%.

In 1994, Toda et al.[27] proposed a piezoelectric atomizer containing microholes, as shown in

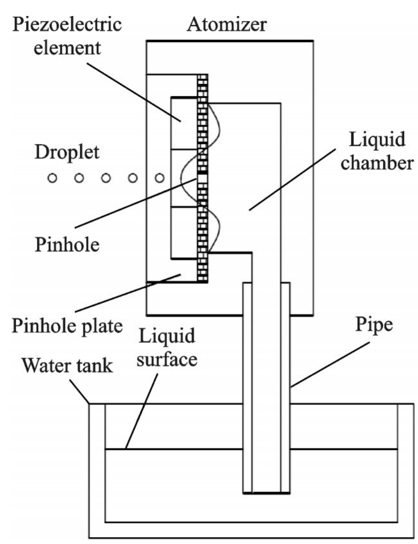

Fig.9 Atomizer with micropores proposed by Maehara et al.[26]

Fig. 10. Each microhole on the atomizing plate is a tapered hole driven by the vibration of a piezoelectric vibrator. Under the action of the vibration plate, the liquid atomizes as it flows through the plate. Subsequently, Toda et al.[28] conducted the related experiments, whose results showed that the atomization rate reached 0.6 mL/min when the driving voltage was 70 V. To simplify the structure of the atomizer, Toda et al.[29] eliminated the water supply of the atomizer and simultaneously obtained the smallest piezoelectric atomizer. They observed that the atomization efficiency was optimal when the coupled resonant frequency of the atomizer is identical to the resonant frequency without the metal plate.

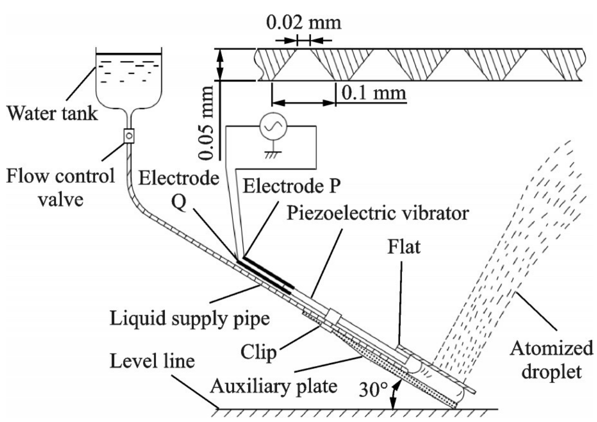

Fig.10 Schematic of the atomizer proposed by Toda et al.[27]

In 1997, Perçin et al.[30-31] proposed a piezoelectric atomizer, as shown in Fig.11. The shaft excited on a circular film by a flexural transducer was stacked into a resonant film to generate atomization. The transducer was obtained by pasting a circular PZT ring on a circular film with microholes. Perçin et al.[32] used the finite element software to optimize the transducer for ensuring that it flexed to the maximum extent at the lowest resonant frequency. Further, on-demand atomization is achieved by controlling the drive voltage of the transducer. Subsequently, Perçin et al.[33] simulated the formation of droplets and verified the atomization performance of the atomizer when the medium was water, ink, powder, and photoresist[34]. Roche[35] established a control model of the atomizer during photolithography, and Lam et al.[36] developed a similar atomizer and applied it to PMN-PT single-crystal spraying.

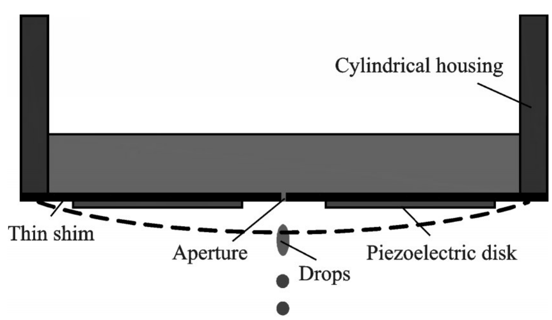

Fig.11 Piezo-driven atomizer proposed by Perçin et al.[31]

In 2008, Shen et al.[37-39] studied an atomizer with a cymbal-type high-power driver, as shown in Fig. 12. The atomizing device mainly comprises a ring-shaped piezoelectric vibrator and a cymbal-shaped nozzle plate. The latter concentrates the energy at the center of the nozzle plate and generates a large driving force to provide a high-power driver of the cymbal shape, atomizing the high-viscosity liquid into fine particles and increasing the atomization rate. The atomizer can generate droplets with a mass median aerodynamic diameter of 4.07 μm, an operating frequency of 127.89 kHz, and an atomization rate of 0.5 mL/min. Simultaneously, the atomizer can atomize liquid with a high viscosity (>3.5 cP) and requires only approximately 1.2 W of power to achieve high-quality atomization. The nebulizer has the advantages of simple operation and small volume and is particularly suitable for achieving portable nebulization inhalation therapy. Lu et al.[40-42] proposed a similar atomizer and applied it to the cooling of electronic products. The atomization mechanism can be explained as follows. The pumping mechanism of the dispenser is dependent on the balance between the inertial and capillary forces. When the micro-nozzle plate moves upward, the liquid is pinched into droplets and passes through the conical nozzles. When the micro-nozzle plate moves downward, the liquid adheres to the hole due to the capillary force. The liquid is repeatedly pinched and adhered, resulting in atomization. Huang et al.[43] improved this type of atomizer and used a sponge to supply water instead of the original water tank. The atomizer was designed to exhibit low energy consumption (8.244 W) and high atomization rate (64.3 mL/min).

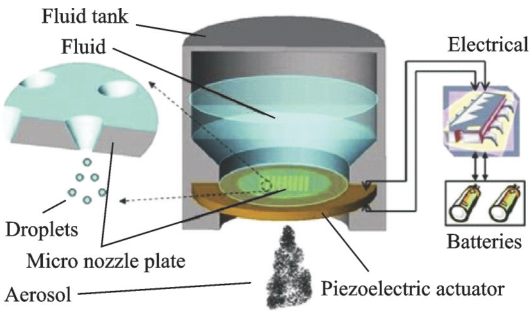

Fig.12 Atomizer developed by Shen et al.[37-39]

Zhang et al.[44] proposed the double-layer atomizer shown in Fig.13, where the atomizer comprises two layers of PZT rings and two layers of metal sheets. The forms are sealed and bonded to form a sealed inner cavity, where only the upper and lower tapered holes are connected to the outside. The taper angles of the lower holes are greater than those of the upper holes. The direction of the tapered holes remains identical. When the lower metal sheet vibrates, the liquid forms atomized droplets into the sealed inner cavity; when the upper metal sheet vibrates, the atomized droplets in the inner cavity are atomized into the external environment for the second time. The particle size of the atomized droplets was effectively controlled after two passes.

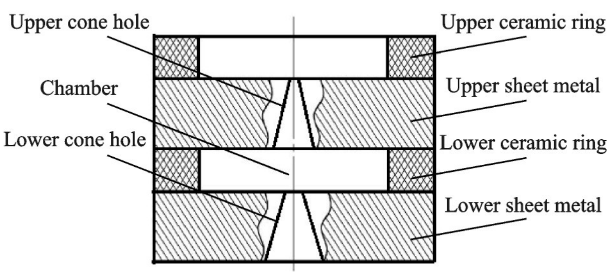

Fig.13 Double-layer atomizer proposed by Zhang et al.[44]

Based on a previous review[40-42], a dynamic mesh atomizer involves micro-cone holes processed in a metal plate of a piezoelectric vibrator, which does not require a variable volume liquid cavity during atomization, simplifying its structure. The energy of the carburetor is concentrated around the micro-cone holes, improving the energy utilization rate and effectively controlling the atomization process. It is beneficial to the popularization of dynamic mesh atomizer. This type of atomizer is bound to become the subject of much future research interest.

2 Progress of Application of Piezoelectric Atomizers

2.1 Inkjet printing

Inkjet printing is a non-contact printing technology[45] that is extensively used for manufacturing solar cells[46], transparent electrodes[47], ceramic components[48-49], etc. Inkjet printing can be classified as on-demand and continuous inkjet printing. On-demand inkjet printing exhibits high production efficiency, high material utilization, and high processing flexibility and is widely used in modern industry. The working mechanism of piezoelectric on-demand inkjet printing is to use piezoelectric technology to change the pressure in the spray chamber so that the ink is deposited on the printing substrate in the form of droplets that are stacked to obtain the required 3D construction.

Recently, because of the heat resistance, corrosion resistance, and wear resistance of ceramics, piezoelectric atomizers has attracted the attention of many scholars. Generally, the ceramic components produced using the traditional methods fail to satisfy the human needs; however, a good solution to this problem has been recently obtained in the form of 3D printing technology based on droplet ejection. In 2002, Zhao et al.[50] printed the ZrO_2 ceramic components using inkjet printing technology and formed a plan of the Hampton Court diagram of the United Kingdom, as shown in Fig.14.

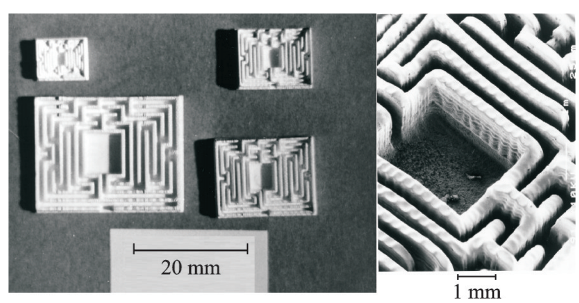

Fig.14 Hampton court diagram of UK

In 2005, Noguera et al.[51] optimized the rheological properties of the ceramic suspensions and improved the driving conditions for inkjet printing, printing a microarray column with a diameter of 90 μm, as shown in Fig. 15. Subsequently, Wang et al.[4] printed the ZrO2 and Al_2O_3 functional gradient films with a thickness of only 9 μm using the inkjet printing technology, which required only 2 min.

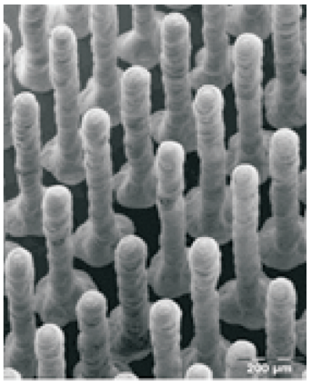

Fig.15 PZT microarray column printed by Noguera et al.[51]

In 2009, Bathurst et al.[52] printed the PZT thin film shown in Fig. 16(a) using the on-demand piezoelectric sheet inkjet technology. Simultaneously, related experimental studies were conducted to verify the electrical properties of the piezoelectric thin film, denoting that the piezoelectric film exhibits good performance. In the same year, Legeune et al.[53] adjusted the parameters and time interval for driving the print head based on the piezoelectric printing technology, and they printed the PZTs shown in Figs.16(b), (c) in short time period.

Piezo-driven atomizers are increasingly being used in inkjet printing, especially in recent years, and the droplet jet 3D printing technology has gradually become a topic of much research interest. However, the existing inkjet printing technology based on piezoelectric atomizers can only print a ceramic member with a simple structure, and the printing accuracy is relatively low.

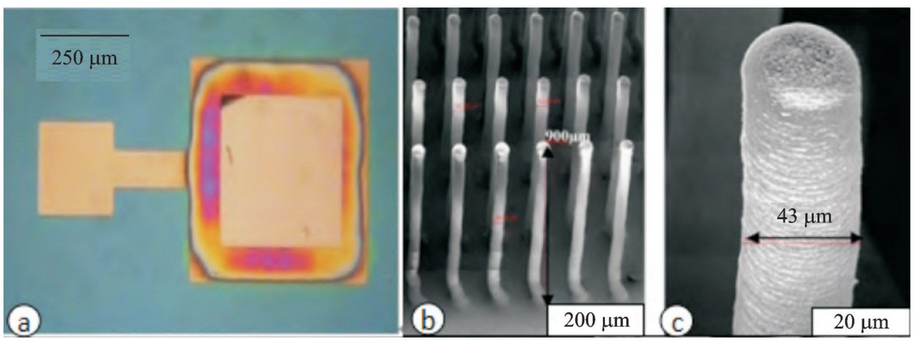

Fig.16 Application examples of inkjet printing by Bathurst et al.[52] and Legeune et al.[53]

2.2 Spray cooling

The spray cooling (SC) technology involves (1) mixing a liquid into a pressurized air stream to form a mist-like gas - liquid two-phase fluid and (2) using a spray to form a jet for spraying atomized droplets onto an object to be cooled. The key to SC is to completely cool the liquid. Compared with the traditional cooling methods, SC exhibits strong heat removal ability, saving of the cooling liquid, and no boiling lag, making it efficient[54-56]. Previous research[57-58] has shown that the higher the spray flow rate, the lower will be (1) the cooling efficiency and (2) the uneven heating of the wall surface. Further, the large-flow SC system is usually of high quality and volume, which cannot be easily transported. Therefore, some scholars have begun to introduce microporous piezoelectric atomizers into SC to achieve small-flow cooling and improve the SC efficiency.

As shown in Fig. 17, Heffington et al.[59-60] applied a microporous piezoelectric atomizer to the cooling system of an integrated circuit in 2003 and obtained a heat dissipation density of 420 W/cm^2. In 2010, Soriano et al.[61-62] proposed a microporous piezoelectric atomizer with a droplet diameter, spacing, and generation rate that could be adjusted according to the demand. Further, they experimentally studied the manner in which the atomization rate, initial atomization temperature, and droplet generation frequency affected the SC heat transfer perfor-

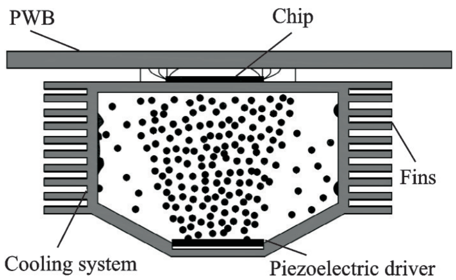

Fig.17 Atomization cooling device proposed by Heffington et al.[59-60]

mance. They used HFE7100 as the refrigerant during the experiment, and the experimental results showed that a heat dissipation density of 25 W/cm^2 was generated when the atomization rate was 4.2 mL/min.

To improve the working efficiency of SC, many scholars have studied the factors that affect the spray cooling efficiency, including the spray rate, nozzle atomization characteristics, and spray tilt angle. In 2002, Karapetian et al.[63] studied the influencing factors of the SC heat transfer density via experiments and observed that the spray flow rate and spray droplet velocity are important, with the effect of the former on the heat transfer density observed to be considerably greater than that of the latter. In 2013, Hou et al.[64-65] studied the SC efficiency and critical heat flux density at different spray rates. They selected R134a as the refrigerant in their experiments; when the spray rate was 3.56 mL/min, the critical heat flux density was 117.2 W/cm^2. They also found that the larger the spray rate, the greater will be the critical heat flux density but the SC efficiency significantly decreased.

In 2016, Cheng et al.[66] proposed the vacuum spray flash cooling system shown in Fig.18. Through research, compared with traditional SC, this cooling device can obtain only one third of the atomization amount. Further, it was found in the experiment that there was an optimal spray amount to maximize the heat dissipation density. The experiment proved that the atomization amount has an extremely important effect on the SC heat transfer characteristics.

In 2016, Chen et al.[67-69] proposed a piezoelec-

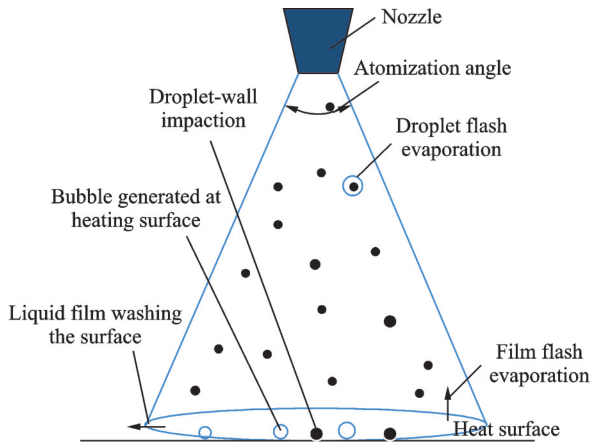

Fig.18 Vacuum spray flash cooling droplet behavior model obtained from Cheng et al.[66]

tric nozzle atomizer that exhibits structural simplicity, low power consumption, and controllable atomization parameters. The use of the piezoelectric nozzle atomizer can make the cooling the temperature distribution of the wall surface is more uniform, and it also can achieved a higher heat transfer density with less atomizing flow. Furthermore, it was found through experiments that with an increase in the nozzle diameter, the amount of atomization gradually increased, the heat transfer density of SC increased, and the SC efficiency significantly decreased, proving that the SC method with low atomization amount can improve the SC efficiency.

In 2018, Cheng et al.[70] used the level-set method to establish a transient two-dimensional axisymmetric model for droplet cooling. Through experimental data verification, the effects of the impact velocity, surface tension, initial droplet radius, equilibrium contact angle, and liquid viscosity on droplet diffusion were studied. The droplet diffusion rate increases with the impact velocity, surface tension, and initial radius with decreasing equilibrium contact angle and liquid viscosity. Under the action of hot capillary force, the cold substrate can promote the diffusion of the liquid droplets, whereas the hot substrate can delay the diffusion of liquid droplets.

In 2019, Cai et al.[71] studied the cooling performance of microporous piezoelectric atomizers. Through experimental research, it was observed that these atomizers have a good cooling effect and that the effect of the atomization rate on the cooling performance exhibits a linear relation, with the driving frequency of the atomizer having no effect on the cooling performance.

Piezoelectric atomizing SC is an SC method with low power consumption, low spray volume, and high working efficiency and exhibits broad application prospects in the cooling of micro-to-small electronic equipment.

2.3 Inhalation therapy

Nebulization treatment involves the usage of a nebulizer to disperse a drug as tiny mist droplets or particles that are suspended in gas and enter the respiratory tract as well as lungs when a patient breathes to achieve local treatment and targeted administration. Recently, because of environmental deterioration, the number of patients with lung diseases has increased every year, and the demand for nebulization treatment has increased. However, not all drug particles can be absorbed by the patients after being atomized. Olseni[2] and Mitchell[72] and other researchers found that when the drug particles are not greater than 5 μm, they can enter the airway and lungs; subsequently, they can be deposited on a lesion by gravity. Make sure that the drug particles can be deposited on the lesion, and to obtain better clinical treatment effect.

In 2006, Vecellio[73] designed two medical atomizers, as shown in Fig.19, where (a) is a static mesh atomizer and (b) is a dynamic mesh atomizer. The electroplating technology was used to process 6 000 3-μm-diameter holes on the mesh plate. Under the excitation of the AC voltage, the piezoelectric transducer generates high-frequency vibrations to cause the atomization of the drug solution to form an aerosol. The respiratory system is directly connected with the lesion, achieving targeted and quantitative administration and reducing the side effects caused by systemic administration.

In 2011, Lin et al.[74] used the laser ablation technology and electroforming technology to prepare a palladium-nickel alloy nozzle plate having a nozzle diameter of 5 μm. The nozzle plate prepared using this method is considerably hard and can be used at a frequency of 100 kHz. Studies have shown that the usage of this nozzle is effective for controlling the particle size of drug droplets when atomizing a drug solution. The particle size of the atomized droplets is approximately 3 μm, which satisfies the requirement that the drug particles must be less than 4 μm when absorbed by the lungs.

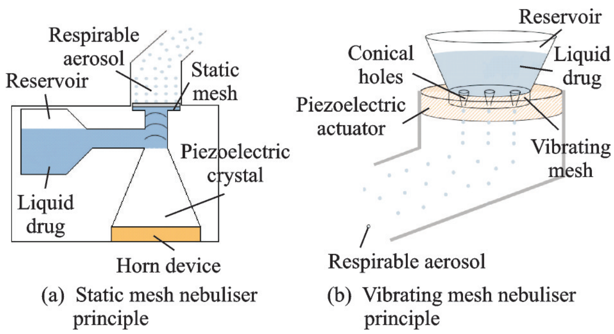

Fig.19 Two medical nebulizers designed by Vecellio[73]

In 2012, Beck-Broichsitter et al.[75] proposed a vibrating-mesh-type nebulizer to atomize the prepared nanoparticle drugs. Experiments have denoted that using nanoparticles to encapsulate sildenafil can maintain its stability and that atomizing the process does not affect the particle size, particle size distribution, or sildenafil content. Dosing through the stable formula of the nebulized prescription drug, it can prolong the release time of the drug. Compared with the traditional free administration method, the frequency of this administration method is significantly reduced, resulting in the convenience of patients. In addition, Rottier[76], Lenney[77], and Montgomery[78], etc. have studied atomization treatment.

The existing nebulizers used for nebulization therapy have a complicated structure, a large volume, and are not readily portable. Therefore, they can only be used in specific medical places, and asthma patients cannot carry them around and perform nebulization treatment at any time.

3 Trends in Development of Piezoelectric Atomizers

According to their structure and working principle, piezoelectric atomizers can be divided into SAW atomizers, static mesh atomizers, and dynamic mesh atomizers. Table 1 shows the working prin-

Table 1 Working principle, characteristics and application of different types of atomizers

Type	Working principle	Advantage/disadvantage	Application
SAW atomizer	This type of atomizer is to apply energy to the entire liquid system, destroy the surface tension of the liquid surface, constrain the liquid droplets, and cause the liquid droplets to fly away from the liquid surface, achieving atomization and spraying.	Energy utilization rate is low./ The atomization process is random. The droplet size cannot be controlled. The particle size distribution of the droplets is not concentrated.	Air humidification
Static mesh atomizer	Use the vibration of the piezoelectric vibrator to change the pressure inside the liquid cavity. When the pressure in the cavity is sufficiently large, the liquid is ejected from the micro-jetting hole, resulting in atomization.	Atomization process is controllable. The droplets are evenly distributed./Complex structure	Spray cooling, inkjet printing, inhalation therapy
Dynamic mesh atomizer	Under the vibration of piezoelectric vibrator, the droplet is broken repeatedly by the balance of inertia force and capillary force to form atomization.	Atomization process is controllable and structure is simple./High energy utilization	Spray cooling

ciple, characteristics and application of different types of atomizers.

The previous review shows that dynamic mesh atomizers exhibit portability, structural simplicity, controllable atomization, and uniform atomization particle size, etc., and constitute the most promising type of atomizers on the market. Since Maehara et al.[25] proposed the first dynamic mesh atomizer in 1986, such atomizers have come to popular attention, bringing convenience to people's lives; for example, see the work of Chen et al.[67] and Cai et al.[71]. This type of atomizer has been used in atomization cooling and has achieved a good cooling effect. Beck-Broichsitter et al.[75] has used it for inhalation treatment. Despite the convenience introduced by dynamic mesh atomizers, various studies are still investigating a methodology to improve their design for obtaining improved performance. However, the atomizer was hindered in the promotion process, caused by the absence of the atomization mechanism. For any new product to be recognized, it must be supported by corresponding theories; unfortunately, the dynamic microporous atomizer lacks a strong theoretical support. Therefore, it is imperative to explore it theoretically, and this will be the research focus for this type of atomizer in the future.

Some studies have investigated the theory of dynamic mesh atomizers. Among them, Lu et al.[40] made a preliminary exploration of the atomization mechanism of dynamic mesh atomizers and explained it as follows. When the micro-nozzle plate moves upward, the liquid is pinched off, and the droplets passed through the conical nozzle; when the micro-nozzle plate moves downward, the liquid adheres to the holes because of capillarity. Under the driving of the high-frequency PZT ring, the liquid is repeatedly pinched and adhered, generating mist. According to Lu's atomization theory, turning the atomizing sheet by 180° should provide the same amount of atomization when compared with that obtained when the atomizing sheet is placed in the forward direction. However, Yan et al.[79] performed related experiments to measure the amount of atomization based on Lu's theory; contrary to expectations, they found that the atomization amount of the atomizing tablets when placed in the forward direction is considerably larger than that when placed in the opposite direction. Consequently, the atomization theory proposed by Lu is not supported.

Therefore, Zhang[80] and Yan[81] proposed the concept of dynamic cone angle and reasoned that the micro-tapered apertures on the stainless steel substrate of the atomizing sheet would follow the vibration of the piezoelectric vibrator to address the deficiency of the research on the theory of dynamic microporous atomization. The dynamic cone angle of expansion and contraction, i.e., the dynamic cone angle, was verified via theory and experiments. Zhang et al. reasoned that the micro-tapered apertures generate a periodic volume change under the excitation of a periodic signal. In addition, the existence of the difference between the forward and reverse flow resistances of the tapered holes causes a pump effect, which causes unidirectional flow of the liquid and fog. The atomization principle proposed by Zhang et al. is similar to the working principle of a valveless piezoelectric pump with a tapered flow tube. They consider the volume change of a micro-tapered aperture to be the volume change of a piezoelectric vibrator of a valveless piezoelectric pump. In the conical flow tube of the valve piezoelectric pump, the expression for the atomization amount of the atomizer is obtained according to the flow formula of the valveless piezoelectric pump, and its variational trend is verified via experiments.

The atomization mechanism proposed by Zhang et al. is effective to explain the atomization process of the dynamic mesh atomizer and shows the direction for future research regarding dynamic mesh atomizers. In future research, we must pay attention to theoretical exploration because dynamic mesh atomizers will have broad market prospects and will be accepted by people only with sufficient theoretical support.

4 Conclusions

(1) Piezoelectric atomizers are categorized as SAW atomizers and mesh atomizers according to the relation between the meniscus length and the capillary wavelength.

(2) In the SAW atomizer, atomization occurs only on the liquid surface; however, energy is applied to the entire system, resulting in extremely low capacity utilization. Furthermore, the atomization process is random and uncontrollable, and the droplet size distribution is not concentrated.

(3) The difference between a static mesh atomizer and a dynamic mesh atomizer is that the former requires a variable volume atomizing cavity, which makes its structure considerably complex and not conducive for miniaturization. In the latter, microholes are processed on a piezoelectric vibrator and energy is directly applied around the microholes. The structure of the dynamic mesh atomizer is simple and exhibits a high energy utilization rate.

(4) Currently, piezoelectric atomizers are extensively used in inkjet printing, SC, inhalation therapy, and other fields.

(5) The research trends of piezoelectric atomizers are explained herein. To popularize such atomizers, the atomization principle must be studied in detail.

References

[1] NEWMAN S P, CLARK S W. The rapeuticaerosols 1-physical and practical considerations[J]. Thorax, 1983, 38(12): 881-886.

[2] OLSENI L, PALMER J, WOLLMER P. Quantitative evaluation of aerosol deposition pattern in the lung in patients with chronic bronchitis[J]. Physiological Measurement, 1994, 1(5): 41-48.

[3] JURGEN B, GRISHIN A M. Piezoelectric shear mode drop-on-demand inkjet actuator[J]. Sensor and Actuators A, 2002, 101: 371-382.

[4] WANG J W, SHAW L L. Fabrication of functionally graded materials via inkjet color printing[J]. Journal of the American Ceramic Society, 2006, 89(10): 3285-3289.

[5] FRIEND J, YEO L Y. Microscale acoustofluidics: Microfluidics driven via acoustics and ultrasonics[J]. Reviews of Modern Physics, 2011, 83(2): 647-704.

[6] WHITE R M, VOLTMER F W. Direct piezoelectric coupling to surface elastic waves[J]. Applied Physics Letters, 1965, 7(12): 314-316.

[7] LI H, FRIEND J R, YEO L Y. Surface acoustic wave concentration of particle and bioparticle suspensions[J]. Biomedicl Microdevices, 2007, 9 (1): 647-656.

[8] KUTTRUFF H. Ultrasonics: Fundamentals and applications[M]. Netherlands: Elsevier Applied Science, 1991.

[9] QI A, YEO L Y, FRIEND J R. Interfacial destabilization and atomization driven by surface acoustic waves[J]. Physics of Fluids, 2008, 20(7): 074103.

[10] QI A, YEO L, FRIEND J, et al. The extraction of liquid, protein molecules and yeast cells from paper through surface acoustic wave atomization[J]. Lab on a Chip, 2010, 10(4): 470-476.

[11] ZHANG G, LI Y G, ZHANG J F, et al. Technology of micro droplet atomizers based on surface acoustic wave[J]. Micronanoelectronic Technology, 2009, 46 (12): 726-729. (in Chinese)

[12] ZHANG G, LI Y G. Trends of micro actuators based

on surface acoustic waves[J]. Micronanoelectronic Technology, 2009, 46(9): 540-545. (in Chinese)

[13] HERON S R, WILSON R, SHAFFER S A, et al. Surface acoustic wave nebulization of peptides as a microfluidic interface for mass spectrometry[J]. Analytical Chemistry, 2010, 82(10): 3985-3989.

[14] HO J, TAN M K, GO D B, et al. Paper-based microfluidic surface acoustic wave sample delivery and ionization source for rapid and sensitive ambient mass spectrometry[J]. Analytical Chemistry, 2011, 83(9): 3260-3266.

[15] RAMISETTY K A, PANDIT A B, GOGATE P R. Investigations into ultrasound induced atomization[J]. Ultrasonics Sonochemistry, 2013, 20(1): 254-264.

[16] HEIJ B DE, SCHOOT B VAN DER, ROOIJ N F DE, et al. Modelling and optimisation of a vaporiser for inhalation drug therapy[C]// Proceedings of Technical Proceedings of the 1999 International Conference on Modeling and Simulation of Microsystems. Puerto Rico: NSTI, 1999: 542-545.

[17] HEIJ B DE, SCHOOT B VAN DER , BO H, et al. Characterisation of a fL droplet generator for inhalation drug therpy[J]. Sensors and Actuators A: Physical, 2000, 85(1/2/3): 430-434.

[18] LIU C G, ZHOU Z Y, WANG X H, et al. The characteristics of piezoelectrically actuated micro jet[J]. Piezoelectrics & Acoustooptics, 2001, 23(4): 272-274. (in Chinese)

[19] WANG G H, ZHOU Z Y, YUAN S M, et al. Theoretical and experimental analysis of droplet characteristics in piezoelectrically actuated microjet[J]. Chinese Journal of Scientific Instrument, 2002, 23(5): 6-8. (in Chinese)

[20] ZHU J H, ZHOU Z Y, FENG Y Y, et al. Research on micro nebulizer based on MEMS technology[J]. China Mechanical Engineering, 2005, 16(19): 1693-1696. (in Chinese)

[21] YUAN S B, ZHOU Z, WANG G, et al. MEMS based piezoelectric array microjet[J]. Microelectronic Engineering, 2003, 66(1/2/3/4): 767-772.

[22] WEI D Z, ZHANG R J, WU R D, et al. Design of piezoelectric micro-droplet injector[J]. Journal of Tsinghua University (Science and Technology), 2004, 44(8): 1107-1110. (in Chinese)

[23] PAN C T, SHIEA J, SHEN S C. Fabrication of an integrated piezo-electric micro-nebulizer for biochemical sample analysis[J]. Journal of Micromechanics and Microengineering, 2007, 17(3): 659-669.

[24] JENG Y R, SU C C, FENG G H, et al. An investigation into a piezoelectrically actuated nebulizer with μEDM-made micronozzlearray[J]. Experimental Thermal and Fluid Science, 2007, 31: 1147-1156.

[25] MAEHARA N, UEHA S, MORI E. Influence of the vibrating system of a multipinhole-plate ultrasonic nebulizer on its performance[J]. Review of Scientific Instruments, 1986, 57(11): 2870-2876.

[26] MAEHARA N, UEHA S, MORI E. Optimum design procedure for multi-pinhole-plate ultrasonic atomizer[J]. Japanese Journal of Applied Physics, 1987, 26(S1): 215-217.

[27] TODA K. Ultrasonic vibrating device: US Patent 5, 297,734[P]. 1994-3-29.

[28] TODA K, AKIMURA Y. An ultrasonic atomizing device using coupled-mode vibration[J]. Review of Scientific Instruments, 1994, 65(10): 3276-3278.

[29] TODA K, ISHII J. Operation performance of self-oscillation ultrasonic vibrating device for liquid atomization[J]. Japanese Journal of Applied Physics, 1995, 34(9B): 5332-5334.

[30] PERÇIN G, LEVIN L, KHURI-YAKUB B T. Piezoelectrically actuated droplet ejector[J]. Review of Scientific Instruments, 1997, 68(12): 4561-4563.

[31] PERÇIN G, LUNDGREN T S, KHURI-YAKUB B T. Controlled ink-jet printing and deposition of organic polymers and solid particles[J]. Applied Physics Letters, 1998, 73(16): 2375.

[32] PERÇIN G, KHURI-YAKUB B T. Piezoelectrically-actuated flextensional micromachined ultrasound droplet ejectors[J]. IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control, 2002, 49(6): 756-766.

[33] PERÇIN G, KHURI-YAKUB B T. Micromachined droplet ejector arrays for controlled ink-jet printing and deposition[J]. Review of Scientific Instruments, 2002, 73(5): 2193-2196.

[34] PERÇIN G, KHURI-YAKUB B T. Piezoelectric droplet ejector for ink-jet printing of fluids and solid particles[J]. Review of Scientific Instruments, 2003, 74(2): 1120-1127.

[35] ROCHE P E, HANSSON A, KHURI-YAKUB B T. Control of a drop-ejector used as photo-resist dispenser[C]// Proceedings of the 5th Annual International Symposium on Smart Structures and Materials. San Diego: [s.n.], 1998, 3323: 446-454.

[36] LAM K H, CHAN H L W, LUO H S, et al. Piezoelectrically actuated ejector using PMN-PT single crystal[J]. Sensors and Actuators A: Physical, 2005, 121(1): 197-202.

[37] SHEN S C, WANG Y J, CHEN Y Y. Design and fabrication of medical micro-nebulizer[J]. Sensors and Actuators A: Physical, 2008, 144(1): 135-143.

[38] SHEN S C. A new cymbal-shaped high power microactuator for nebulizer application[J]. Microelectronic Engineering, 2010, 87(2): 89-97.

[39] SHEN S C, WANG Y J. A novel handhold high power mems atomizer using micro cymbal shape nozzle plate for inhalation therapy[C]// Proceedings of ASME 2009 International Design Engineering Technical Conferences and Computers and Information in Engineering. San Diego: ASME, 2009: 375-382.

[40] LU C F, FU C C, YANG J C, et al. Traveling wave driven micro-dispenser for CPU cooling application[C]// Proceedings of 2006 IEEE Ultrasonics Symposium. Vancouver, BC: IEEE, 2006: 54-57.

[41] LU C F, CHEN C J, FU C C. No back-pressure effect micro-dispenser suction pump[C]// Proceedings of 2006 International Microsystems, Package Assembly. Taiwan, Taipei: IEEE, 2006: 1-4.

[42] LU C F, CHEN C J, FU C C. Anti-wetting trench of nozzle plate for piezoelectric actuating dispenser[C]// Proceedings of 2009 4th International Microsystems, Package Assembly Circuits Technology. [S. l.] : IEEE, 2009: 674-677.

[43] HUANG Y L, CHANG S H. Micro-droplets atomizer using PZT ring actuator[J]. Journal of Mechanics, 2011, 26(3): 423-429.

[44] ZHANG J H, HU F J, JI J. Piezoelectric ceramic ultrasonic atomizing sheet: China Invention Patent: 201110413234.5[P]. 2011-4-6. (in Chinese)

[45] KORVINK J G, SMITH P J, SHIN D Y, et al. Inkjet printing technology[M]. WANG H. Translate. Beijing: Mechanical Engineering Press, 2015. (in Chinese)

[46] HU J B, ZHU P X. Progress in polymer solar cells fabricated by inkjet printing[J]. Journal of Functional Polymers, 2011, 24(3): 323-327. (in Chinese)

[47] HEFFINGTON S N, GLEZER A. Orientation-independent atomization heat transfer cell for thermal management of microelectronics [C]// Proceedings of International Electronic Packaging Technical Conference and Exhibition, Electronic and Photonic Packaging Division. [S.l.]: [s.n.], 2003: 635-640.

[48] LI L, GAO Y, WANG C H, et al. Research development of 3D printing ceramic parts[J]. Bulletin of the Chinese Ceramic Society, 2016, 35(9): 2892-2897. (in Chinese)

[49] ÖZKOL E, ZHANG W, EBERT J, et al. Potentials of the "inkjet printing" direct method for manufacturing 3Y-TZP based dental restoration[J]. Journal of the European Ceramic Society, 2012, 32(10): 2193-2201.

[50] ZHAO X L, JULIAN R G E, MOHAN J E. Direct ink-jet printing of vertical walls[J]. Journal of American Ceramic Society, 2002, 85(8): 2113-2115.

[51] NOGUERA R, LEGEUNE M, CHARTIER T. 3D fine scale ceramic components formed by ink-jet prototyping process[J]. Journal of the European Ceramic Society, 2005, 25(7): 2055-2059.

[52] BATHURST S P, KIM S G. Designing direct printing process for improved piezoelectric micro-devices[J]. CIRP Annals-Manufacturing Technology, 2009, 58(1): 193-196.

[53] LEGEUNE M, CHARTIER T, NOGUERA R, et al. Ink-jet printing of ceramic micro-pillar arrays[J]. Journal of the European Ceramic Society, 2009, 29 (24): 905-911.

[54] KIM J. Spray cooling heat transfer: The state of the art[J]. International Journal Heat and Fluid Flow, 2007, 28(4): 53-67.

[55] KANDLIKAR S G, BAPAT A V. Evaluation of jet impingement, spray and micro-channel chip cooling options for high heat flux removal[J]. Heat Transfer Engineering, 2007, 28(11): 911-923.

[56] SILK E A, GOLLIHER E L, PANEER S R. Spray cooling heat transfer: Technology overview and assessment of future challenges for micro-gravity application[J]. Energy Conversion and Management, 2008, 49: 453-468.

[57] CHENG W L, LIU Q N, ZHAO R, et al. Experimental study of temperature non-uniformity on spray cooling surface[J]. Journal of Thermal Science and Technology, 2008, 7(4): 301-307. (in Chinese)

[58] CHENG W L, HAN F Y, LIU Q N, et al. Experimental and theoretical investigation of surface temperature non-uniformity of spray cooling[J]. Energy, 2011, 36(1): 249-257.

[59] HEFFINGTON S N, GLEZER A. Two-phase thermal management using a small-scale, heat transfer cell based on vibration-induced droplet atomization [C]// Proceedings of Thermal and Thermomechanical Phenomena in Electronic Systems, ITHERM'04. The Ninth Intersociety Conference. [S.l.]: IEEE, 2004.

[60] SORIANO G, ALVARADO J L, LIN Y P. Experimental characterization of single and multiple droplet impingement on surfaces subject to constant heat flux conditions [C]// Proceedings of International Heat

Transfer Conference. [S.l.]: American Society of Mechanical Engineers, 2010.

[61] XU Q, LAN H B, ZHAO W J, et al. Large-area transparent electrodes fabricated by combining the electric-field-driven fusion deposition direct writing and micro-transfer [J]. Journal of Mechanical Engineering, 2019, 55(23): 216-225. (in Chinese)

[62] SORIANO G, ZHANG T, ALVARADO J L. Study of the effects of single and multiple periodic doplet impingements on liquid film heat transfer[J]. International Journal of Heat and Mass Transfer, 2014, 77: 449-463.

[63] KARAPETIAN E, AGUILAR G, KIMEL S, et al. Effects of mass flow rate and droplet velocity on surface heat flux during cryogen spray cooling[J]. Physics in Medicine and Biology, 2002, 48(1): N1-N6.

[64] HOU Y, LIU X F, LIU J H, et al. Experimental study on phase change spray cooling[J]. Experimental Thermal and Fluid Science, 2013, 46: 84-88.

[65] HOU Y, LIU J H, SU X M, et al. Experimental study on the characteristics of a closed loop R134a spray cooling[J]. Experimental Thermal and Fluid Science, 2015, 61: 194-200.

[66] CHENG W L, PENG Y H, CHEN H, et al. Experimental investigation on the heat transfer characteristics of vacuum spray flash evaporation cooling[J]. International Journal of Heat and Mass Transfer, 2016, 102: 233-240.

[67] CHEN H, CHENG W L, PENG Y H, et al. Experimental study on optimal spray parameters of piezoelectric atomizer based spray cooling[J]. International Journal of Heat and Mass Transfer, 2016, 103: 57-65.

[68] CHEN H, CHENG W L, ZHANG W W, et al. Energy saving evaluation of a novel energy system based on spray cooling for supercomputer center[J]. Energy, 2017, 141: 304-315.

[69] CHEN H, CHENG W L, PENG Y H, et al. Dynamic Leidenforst temperature increase of impacting droplets containing high-alcohol surfactant[J]. International Journal of Heat and Mass Transfer, 2018, 118: 1160-1168.

[70] CHENG Y P, WANG F, XU J L, et al. Numerical investigation of droplet spreading and heat transfer on hot substrates[J]. International Journal of Heat and Mass Transfer, 2018, 121: 402-411.

[71] CAI Y F, ZHU C L. Study on the cooling performance of piezoelectric micro-aperture atomizer[J]. Refrigeration and Air Conditioning, 2019, 33(3): 221-227. (in Chinese)

[72] MITCHELL J P, NAGEL M W. Particle size analysis of aerosols from medicinalinhalers[J]. Powder & Particle, 2004: 32-65.

[73] VECELLIO L. The mesh nebuliser: a recent technical innovation for aerosol delivery[J]. Breathe, 2006, 2(3): 252-260.

[74] LIN C Y, MENG H C, FU C. An ultrasonic aersol therapy nebulizer using electroformed palladium-nickel alloy nozzle plates[J]. Sensors and Actuators A: Physical, 2011, 169: 187-193.

[75] BECK-BROICHSITTER M, KLEIMANN P, GESSLER T. Nebulization performance of biodegradable sildenafil-loaded nanoparticles using the Aeroneb® Pro: Formulation aspects and nanoparticle stability to nebulization[J]. International journal of pharmaceutics, 2012, 422(1): 398-408.

[76] ROTTIER B L, VAN ERP C J P, SLUYTER T S. Changes in performance of the ParieFlow® rapid and Pari LC Plus™ during 6 months use by CF patients[J]. Journal of aerosol medicine and pulmonary drug delivery, 2009, 22(3): 263-269.

[77] LENNEY W, EDENBOROUGH F, KHO P. Lung deposition of inhaled tobramycin with eFlow rapid/LC Plus jet nebuliser in healthy and cystic fibrosis subjects[J]. Journal of Cystic Fibrosis, 2011, 10(1): 9-14.

[78] MONTGOMERY A B, VALLANCE S, ABUAN T. A randomized double-blind placebo-controlled dose-escalation Phase 1 study of aerosolized amikacin and fosfomycin delivered via the PARI investigational eFlow inline nebulizer system in mechanically ventilated patients[J]. Journal of aerosol medicine and pulmonary drug delivery, 2014, 27(6): 441-448.

[79] YAN Q F, ZHANG J H, HUANG J, et al. The effect of vibration characteristics on the atomization rate in a micro-tapered aperture atomizer [J]. Sensors, 2018, 18(4): 934.

[80] ZHANG J H, YAN Q F, HUANG J. Experimental verification of the pumping effect caused by the micro-tapered hole in a piezoelectric atomizer[J]. Sensors, 2018, 18(7): 2311.

[81] YAN Q F, WU C Y, ZHANG J H. Effect of the dynamic cone angle on the atomization performance of a piezoceramic vibrating mesh atomizer[J]. Applied Sciences, 2019, 9(9): 1836.

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压电雾化装置的研究进展

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摘要:压电雾化装置具有结构简单、易携带、耗能低、生产成本低及雾化效果好等优点,被广泛应用于吸入治疗、喷墨打印和喷雾冷却等领域。本文首先从理论研究与应用研究两方面对压电雾化装置的研究进展进行综述;然后将现有压电雾化装置的研究与应用进行功能性分类,并分别阐述喷墨打印、喷雾冷却和吸入治疗这三方面的研究结果;最后分析压电雾化装置今后的发展方向,指出振动网孔式雾化器是一种具有市场前景的雾化装置,特别在升级型消费和医疗等应用场景下有广泛需求。

关键词:压电;压电陶瓷;雾化装置;雾化