Comparative Study of Ultrasonic Waveform to Enhanced The Atomization Rate of Dynamic Mesh Atomizer

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Abstract. The ultrasonic waveform significantly impacts the atomization rate of Dynamic Mesh Atomizers (DMA) by influencing the energy delivery and droplet formation process. The energy transmitted to the liquid can be optimized by adjusting the amplitude, frequency, and shape of the ultrasonic waveform, leading to more efficient atomization. A well-tuned ultrasonic waveform can enhance the atomization rate by ensuring consistent oscillation of the mesh, promoting the rapid ejection of uniform droplets. This precise control over the atomization process allows for higher rates of droplet production and improved consistency in droplet size, which is crucial for applications requiring fine and uniform aerosols. In this study, we will compare several models of ultrasonic waveforms to determine the atomization rate of each waveform. The operation of DMA is significantly influenced by the waveform shape of the energy input applied to the piezoelectric actuator. The waveform determines how energy is delivered to the vibrating mesh, which directly affects the atomization process.

Keywords: Atomization, Frequency, Mesh Atomizer, Ultrasonic, Waveform

1 Introduction

DMA are becoming more popular in various aerosol applications due to their ability to produce droplets of uniform size. The critical role of these atomizers in various fields, emphasizing their importance across a wide range of applications, such as drug delivery (Pritchard et al., 2018), spray coating (Mousavizadeh et al., 2024), thin film deposition, spray drying (Beck-Broichsitter et al., 2015), and mass spectrometry. The performance of an atomizer in these applications largely depends on the size and distribution of the aerosol droplets that it produces. Most applications require small droplets (1–5 µm) with precise size control, which is essential for the specific needs of each application. For instance, in inhaled drug delivery, small droplets are necessary to ensure the medication reaches the respiratory tract, as larger droplets

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may settle in the mouth or throat, while ultrafine particles could enter the bloodstream and cause health risks (Hamedani et al., 2022; Pritchard et al., 2018). Similarly, in agricultural pesticide spraying, droplets must be small enough to cover crops without being carried away by the wind (Ali Lakhiar et al., 2018). In pharmaceutical spray coating, the droplets need to be large enough to coat tablets effectively, but not so large that material is wasted. The generation of dry powders requires a narrow distribution of droplet sizes to ensure uniformity, and advanced manufacturing processes benefit from smaller droplets to improve resolution and thin film uniformity (Gogate & Khaire, 2023; Sosnik & Seremeta, 2015).

The first studies on droplet formation and breakup were conducted in 1954. Since then, researchers have investigated various factors influencing atomization, such as the characteristics and size distribution of droplets in twin flow nozzles, where it was found that spray atomization depends on the gas-to-liquid mass flow rate ratio. Additionally, the distribution of sprays from pneumatic atomizers has been studied using beam steering correction in laser diffraction methods, highlighting the complexity and ongoing research in optimizing atomizer performance (Dombrowski et al., 1997).

In the past decade, new atomization technologies have been introduced, including methods like surface acoustic wave (SAW) atomizers operating in the MHz frequency range (Huang et al., 2021; Kurosawa et al., 1997; Li et al., 2007) and DMA which work at frequencies in the hundreds of kHz. Moreover, the static mesh is also known as one of the atomizers that is based on a piezoelectric actuator. When the ultrasonic waveform drives the DMA, it causes the mesh to oscillate, pushing the liquid through the tiny apertures in the mesh to generate droplets. A carefully tuned waveform can optimize the vibration pattern of the mesh, ensuring consistent oscillations that produce uniform droplets. For instance, a higher frequency waveform may lead to the production of smaller droplets, while the amplitude affects the energy delivered to the liquid, influencing the atomization rate.

This study was focused on the ultrasonic waveform which is driving the piezoelectric in a DMA. The effect of the ultrasonic waveform driving a DMA is critical in determining the atomizer's performance, particularly in terms of droplet size, distribution, and atomization rate. The waveform characteristics, such as its frequency, amplitude, and shape directly influence how the membrane of the DMA vibrates. Different waveforms, such as sine waves, square waves, or more complex shapes, can result in different droplet formation dynamics. A waveform with a smooth, continuous shape might produce a steady flow of droplets, whereas a waveform with sharp transitions might lead to more abrupt droplet formation, potentially affecting the size distribution. Therefore, by adjusting the ultrasonic waveform, it is possible to fine-tune the DMA performance, improving efficiency, controlling droplet sizes more precisely, and potentially reducing power consumption.

1.1 The Structure of DMA

A DMA is a type of atomizer that uses a vibrating mesh or membrane to convert liquid into aerosol droplets. In 1986, Maehara et al. first proposed the structure of a mesh atomizer and subsequently refined it. In this design, the mesh was created using etching techniques to form holes in a plate, resulting in a finer mesh structure (Maehara et al., 1986). Later, Shen et al. improved the shape of the holes and utilized stronger materials, enabling the atomizer to operate at a frequency below 127.89 kHz and an atomization rate of 0.5 mL/min. This atomizer was capable of producing droplets with particle sizes of about 4.07 µm. (Shen et al., 2008). Research on the application of piezoelectric mesh atomizers has continued, leading to various experimental models and research objectives.

The structure of a DMA typically includes several key components that work together to achieve efficient and controlled atomization: vibrating mesh or membrane, piezoelectric ring, housing, and supporting structure. The core component of a DMA is the mesh or membrane, which is usually made of a metallic or silicon-based material. This membrane contains numerous small apertures or nozzles, typically in the micrometer range. Figure 1 shows the structure of a piezoelectric mesh atomizer, which has been widely commercialized. The mesh vibrates at high frequencies, often in the range of tens to hundreds of kilohertz, depending on the specific design and application. This vibration is what drives the liquid through the apertures to create droplets. A piezoelectric actuator is used to drive the vibration of the mesh. When an electrical signal is applied to the piezoelectric material, it undergoes rapid mechanical deformation, causing the mesh to vibrate. The frequency and amplitude of the vibration can be controlled by the characteristics of the ultrasonic waveform applied to the piezoelectric actuator.

The ring is made of a piezoelectric material, typically a ceramic, such as lead zirconate titanate (PZT). Piezoelectric materials have the unique property of generating mechanical strain (vibration) when an electric field is applied across them. The piezoelectric ring is usually positioned around or attached to the mesh or membrane of the atomizer. It is often sandwiched between the mesh and a support structure, ensuring that its vibrations are efficiently transferred to the mesh. When an alternating current (AC) voltage is applied to the piezoelectric ring, it expands and contracts at the same frequency as the applied voltage. This rapid expansion and contraction cause the ring to vibrate at a specific frequency, typically in the range of tens to hundreds of kilohertz. Figure 1 shows the structure of dynamic mesh atomizer (DMA).

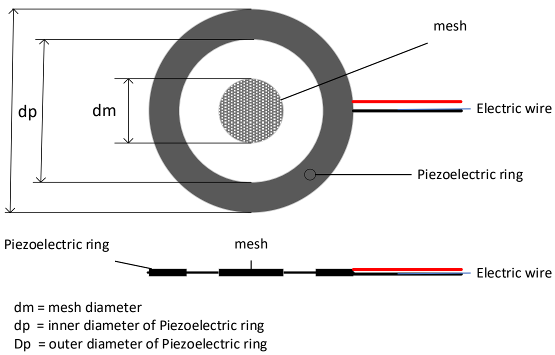

Figure 1. The Structure of dynamic mesh atomizer (DMA)

The working principle of a DMA involves the mesh vibrating in specific modes, which creates pressure waves in the liquid. During the positive cycle of vibration, the liquid is pushed through the apertures, forming droplets. The reverse cycle helps to pinch off the droplets, completing the atomization process. The design of the mesh, including the size and shape of the apertures, along with the properties of the vibrating material, are the factors that determine the droplet size distribution and overall performance of the DMA. It also requires a power source to operate the piezoelectric actuator. The control electronics regulate the frequency and amplitude of the vibration, allowing for precise control over the atomization process. The liquid to be atomized is stored in a reservoir that is positioned so that the liquid comes into contact with the vibrating mesh. In some designs, the liquid is fed to the mesh by capillary action, gravity, or through a controlled pump. In Figure 2, meshing in the metallic surface of the Atomizer can be shown by SEM imaging and Figure 3 is a section of one microhole. Meshing in a DMA refers to the design and function of the mesh or membrane that is central to the atomization process. The mesh is a critical component of the DMA, as it is the part through which the liquid is forced to create fine droplets or aerosols. The mesh in a DMA is typically made from materials like stainless steel, nickel alloys, or silicon. These materials are chosen for their durability, flexibility, and ability to withstand the mechanical stresses induced by high-frequency vibrations.(Kuo et al., 2019; Najlah et al., 2014; Yan et al., 2021).

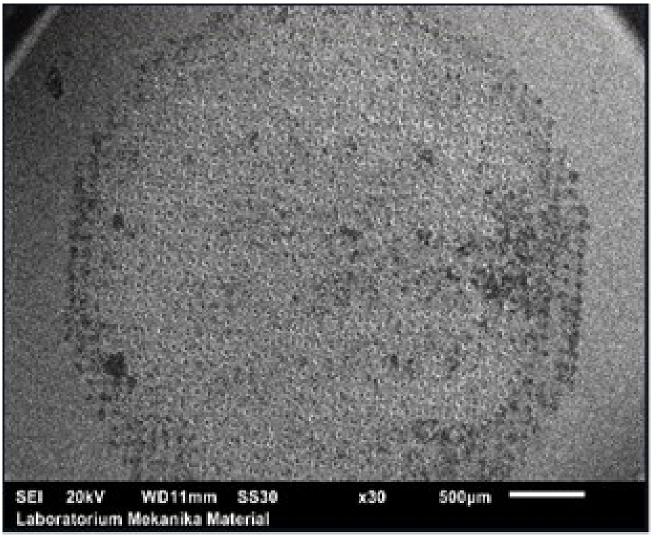

Figure 2. Meshing in the metallic surface of the atomizer (DMA)

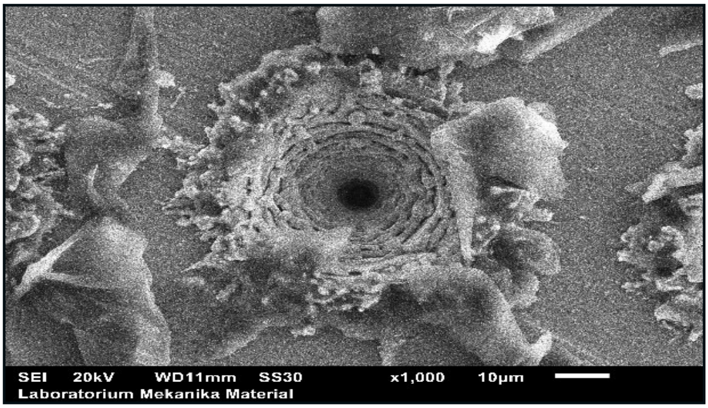

Figure 3. Microhole of the meshing DMA

1.2 A review of The DMA performance experimentally

Research on the mechanisms of droplet formation in various applications has been conducted by numerous research groups. The phenomenon of droplet formation due to ultrasonic vibrations was first introduced as ultrasonic atomization by Wood and Loomis in 1928 (R. W. Wood and A. L. Loomis., 1928). In recent years, two main theories has been proposed for understanding this phenomenom, i.e: the capillary wave theory and the cavitation theory. These theoris served as the foundation for understanding this process. The capillary wave theory explains droplet formation as a result of ultrasonic vibration, where droplets form at the crests of capillary waves on the liquid surface. This theory is based on Lang's hypothesis, which utilizes Kelvin's equation and Rayleigh's instability to describe the surface tension limit at which wavelength occur. Lang (1962) further developed a correlation that relates the median diameter of droplets to the capillary wavelength, supported by experimental data. The average diameter of water droplets (dav) formed can be expressed as follows:

$$d_{av} = a\lambda = 0{,}34\left(\frac{8\pi\sigma}{\rho f^2}\right)^{1/3} \tag{1}$$

d_{av} represents the average diameter of water droplets, where a is the wavelength constant of the ultrasonic wave applied to the liquid, 0.34 is the constant value in the equation proposed by Lang, σ denotes the surface tension of the liquid, ρ represents the density of the liquid, and f is the frequency of the ultrasonic wave (Deepu et al., 2018; Kooij et al., 2019; Kudo et al., 2017).

The cavitation theory proposed by Sollner, supported by his research, offers an alternative explanation for the mechanism of liquid atomization, particularly in the context of high-frequency ultrasonic applications (Eknadiosyants, 1969). Eknadiosyants observed sonoluminescence (a phenomenon where light is emitted by collapsing gas bubbles) during the dispersion of droplets. This observation suggests that droplets form as a result of shock waves, which frequently occur due to the collapse of cavitation bubbles near the liquid surface.

2 Methodology

2.1 Material and Device Measurement

This study aims to investigate the effect of ultrasonic waveform shape on the atomization rate of a Dynamic Mesh Atomizer (DMA) unit. The DMA will be selected from components typically used in ultrasonic humidifiers. This DMA utilizes a piezo-electric ring with a diameter of 20 mm and an inner mesh diameter of 6.2 mm. A specimen from an ultrasonic module commonly used as an ultrasonic humidifier or diffuser will be chosen as the ultrasonic wave source. DMAs in ultrasonic humidifiers are energy-efficient, quiet, and capable of producing a fine mist without generating heat, making them safe for continuous use. The waveform of this module will be analyzed using an oscilloscope. The type of oscilloscope used is an Eduscope 3000. An oscilloscope is a tool in the analysis and characterization of DMA, particularly for determining parameters that influence the device's performance. The oscilloscope allows for the inspection of the waveform shape, detecting any irregularities or noise in the signal. This helps in diagnosing issues with the ultrasonic module or the DMA itself, enabling fine-tuning of the system for optimal performance.

Function generator also used to generate several ultrasonic waveform as comparative study in these terms. The function generator is used to create electrical signals at specific ultrasonic frequencies that are applied to the piezoelectric actuator of the DMA. These frequencies are typically in the range of tens to hundreds of kilohertz. Depending on the design of the DMA, it is set-up for the frequencies between 105-113 kHz (Guerra-Bravo et al., 2021; Lee et al., 2021; Yan et al., 2020). The function generator can also produce various waveform shapes, such as sine, square, and triangle waves. The shape of the waveform can significantly affect the performance of the DMA. For this term, atomization rate is the objektif to the performance of DMA.

Weighing measurements were carried out to determine the atomization rate using a digital weight measurement. Measure and record the initial weight of the liquid container before starting the atomization process. The initial weight represents the total mass of the liquid before any atomization occurs. After the atomization period ends, then measure immediately and record the final weight of the liquid in the cotton. This final weight represents the mass of the liquid remaining in the container.

2.2 Testing Procedure

Two models of generators of the ultrasonic wave has been tested in this study, i.e: the ultra-sonic generator is a module that is suitable for assembly room humidifier and function generator. An ultrasonic generator module is typically operates within a narrow frequency range specifically designed for an ultrasonic wave frequency 109 kHz. The function generator is set up for a frequency range 105-113 kHz. The function generator can be used to modulate the frequency or sweep it across a range to identify the resonant frequency of the DMA. Resonance is where the DMA operates most efficiently, producing maximum atomization for a given input energy. The ultrasonic vibrations generated by the piezoelectric actuator in the DMA is central to the atomization process.

Testing of the atomization rate was carried out by using 3-gram cotton as material that keeps 3 ml of water on the surface of the meshing of DMA. Then, The DMA is connected to an ultrasonic module or a function generator which connected with amplifier, and the output signal is fed into the oscilloscope. The waveform displayed on the oscilloscope screen provides real-time data on the signal's frequency, amplitude, and shape, which are critical for efficient atomization. An oscilloscope is used to visualize and measure the waveform, ensuring it operates at the desired frequency and amplitude.

3 Result and Discussion

3.1 Result

Testing of the atomization rate were carried out experimentally and the result has been shown in Table 1.

Table 1. Ultrasonic waveform testing on DTA

	Frequency	Amplitude	Atomization rate	Power input
Ultrasonic Module Waveform	109 kHz	3 Vp-p	4.3 g/min	3 watts
Sinewave (function generator)	105 kHz	80 Vp-p	1.5 g/min	6 watts
	107 kHz	80 Vp-p	1.7 g/min	7.3 watts
	108 kHz	80 Vp-p	1.72 g/min	7.8 watts
	109 kHz	80 Vp-p	2.1 g/min	8 watts
	110 kHz	80 Vp-p	2.8 g/min	9 watts
	111 kHz	80 Vp-p	3.4 g/min	10 watts
	112 kHz	80 Vp-p	3.3 g/min	11 watts
	113 kHz	80 Vp-p	3.1 g/min	13 watts

The data presented in Table 1 illustrates the relationship between frequencies, amplitude, and power input in the operation of the DMA. As the frequency increases, the amplitude is constant, reflecting the inverse relationship between these two parameters. This reduction in amplitude with increasing frequency is a typical characteristic of piezoelectric actuators, where higher frequencies require more precise control over the mesh vibration. Additionally, the power input required to maintain effective atomization tends to increase with both higher frequencies and greater amplitude. This is because higher frequencies demand more energy to achieve the necessary oscillation of the mesh, while larger amplitudes require additional power to generate the increased mechanical displacement. The table highlights how varying these parameters can affect the overall efficiency and performance of the atomization process, with specific combinations of frequency, amplitude, and power input leading to optimal atomization rates and droplet size distribution.

3.2 Discussion

The change in aperture volume is highly dependent on the surface oscilatory of the DMA, which is determined by the waveform applied to the piezoelectric actuator. Vibrations induced by continuous symmetrical and pulse waveforms deposit energy into the liquid at different rates. Using a continuous symmetrical sine waveform as a reference, the deformation of the micro aperture in the DMA. These operations is a reciprocating of the meshing's movement. Before any input energy is applied to the DMA, the microhole is in a neutral position, and the liquid partially wets the microhole due to surface tension (wetting phase). When the microhole is diverging, the microhole section expands, facilitating the flow of liquid to fill the micro holes (suction phase). When the microhole is returns to the neutral position, the diverging section contracts. This position will trapp the liquid inside. As a result of the microhole's contraction, pressure begins to build up within the hole (pressurization phase).

The ultrasonic waveform applied to the DMA significantly influences both the power input and the atomization rate. Different waveforms, such as continuous sine waves (function generator) or pulsed waves (ultrasonic module), deposit energy into the liquid at varying rates, which in turn affects the efficiency of the atomization process. A continuous sinusoidal waveform typically provides a consistent energy input, leading to a stable atomization rate, while pulsed waveforms can result in intermittent energy deposition, potentially enhancing the atomization rate by creating rapid pressure fluctuations. These fluctuations can increase the atomization efficiency by optimizing the liquid's interaction with the vibrating mesh, leading to more effective droplet formation. The power input required for effective atomization also varies depending on the waveform, with some waveforms requiring higher power to achieve the same atomization rate. Thus, understanding the relationship between the ultrasonic waveform, power input, and atomization rate is crucial for optimizing DMA performance in various applications.

4 Conclusion

The operation of a Dynamic Mesh Atomizer (DMA) is highly influenced by the waveform shape of the energy input applied to the piezoelectric actuator. The waveform determines how energy is delivered to the vibrating mesh, which directly affects the atomization process. When a sinusoidal waveform is applied, the energy input creates a smooth and continuous vibration of the mesh. This results in a steady and consistent atomization process, where the liquid is uniformly pulled through the micro-apertures of the mesh, forming droplets at a stable rate. The continuous energy delivery allows for a predictable and controlled droplet size distribution. In contrast, when a pulsed waveform is used, the energy input is delivered in bursts. These energy pulses cause the mesh to vibrate more sporadically, creating rapid pressure changes within the liquid. This can enhance the atomization process by generating higher shear forces at the mesh surface, leading to the formation of smaller droplets and potentially increasing the atomization rate. However, the pulsed nature of the energy input may also lead to variations in droplet size distribution, depending on the frequency and amplitude of the pulses.

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