FLUID-SOLID COUPLING AND EXPERIMENTAL REALIZATION OF A PIEZOELECTRIC ATOMIZER UNDER STANDING-WAVE RESONANCE

S. Wen, J. Zhang, Y. Lan, Z. Ning, S. Li, D. Jiang, H. Xing

ABSTRACT. This article introduces the design and analysis of a piezoelectric atomizer based on the principles of standing-wave resonance and a pressure-swirl nozzle. Experiments are conducted to demonstrate that the developed piezoelectric atomizer can produce uniformly sized liquid droplets. The atomizer uses piezoelectric composite plates to acquire a large displacement from the vibration of Pb(Zr, Ti)O₃ (PZT) ceramic and to exert excess pressure on the liquid using standing-wave resonance. The three-dimensional dynamic characteristics of the piezoelectric composite plates, considering the effect of the fluid-solid interface, are determined. An analysis of the fluid-solid coupling between the fluid in the resonance chamber and the vibration of the piezoelectric composite plates is conducted. The Sauter mean diameter (SMD) values of the ejected droplets and the flow rate of the piezoelectric atomizer are measured experimentally as different driving voltages. The experimental results demonstrate that the atomizer is capable of generating droplets with an SMD of 93.5 μm at a flow rate of 18.4 g/s. Relatively uniform droplets are formed below the ligaments, where the cone swirl sheet is fully developed. The piezoelectric atomizer has the potential for use in industrial and agricultural applications.

Keywords. Fluid-solid coupling, Piezoelectric atomizer, Pressure-swirl nozzle, Spray characteristics, Standing-wave resonance.

Spray atomization is a common liquid delivery method used in industrial and agricultural production. The primary objective of liquid atomization is to transform a bulk liquid into drops in a gaseous atmosphere such that the maximum surface-to-volume ratio is achieved. A higher surface-to-volume contact ratio can increase the contact area between the droplets and the ambient air and thereby achieve better atomization. There are many types of atomizers in engineering and agricultural applications, such as pressure atomizers (Basak et al., 2013) and air blast atomizers (Herrero et al., 2007). In recent years, the PZT (Pb(Zr, Ti)O₃)-driven atomizer has received increasing attention because it can provide a mist-like spray with a particularly narrow droplet size distribution and very low spray velocity (Topp et al., 1972; Jeng et al., 2007; Ho et al., 2008). The PZT-driven atomizer can be more energy efficient than conventional atomization because of its lack of moving parts, as it requires only that electrical energy be transmitted to a piezoelectric vibrator. The process of PZT-driven atomization is the ejection of tiny droplets from a liquid film formed on an ultrasonically vibrating surface. There are two major hypotheses that explain the ejection of droplets from a vibrating surface: the capillary wave hypothesis and the cavitation hypothesis (Rajan et al., 2001; Avvaru et al., 2006). The capillary wave hypothesis is the formation of capillary waves composed of crests and troughs on the vibrating surface, with the droplets ejected from the crests when the amplitude of the ultrasound is greater than the threshold value. The cavitation hypothesis is generally applied to liquid disintegration in high-frequency and high-intensity ultrasonic systems. When a liquid film is sonicated, cavitation bubbles are formed. The collapse of these bubbles, especially near the surface, results in the direct ejection of the droplets. Donnelly et al. (2004) used PZT-driven atomization to produce a high-density and relatively monodisperse aerosol of water droplets (with an average droplet diameter of approximately 2 μm). These droplets

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The authors are Sheng Wen, University Associate Professor, College of Engineering, South China Agricultural University, Guangzhou 510642, China, and International Lab of Agricultural Aviation Pesticide Spraying Technology, Guangzhou 510642, China; Jiantao Zhang, University Associate Professor College of Mathematics and Informatics, South China Agricultural University, Guangzhou 510642, China; Yubin Lan, ASABE Member, University Professor College of Engineering, South China Agricultural University, Guangzhou 510642, China; Zhihua Ning, University Associate Professor, College of Science and Engineering, Jinan University, Guangzhou 510632, China; Shenghua Li, Graduate Student, College of Engineering, South China Agricultural University, Guangzhou 510642, China; Dingxin Jiang, University Associate Professor, College of Resources and Environment, South China Agricultural University, Guangzhou 510642, China; Hang Xing, University Associate Professor, College of Engineering, South China Agricultural University, Guangzhou 510642, China. Corresponding author: Jiantao Zhang, College of Mathematics and Informatics, South China Agricultural University, Guangzhou 510642, China; phone: 86-130-7675-9646; e-mail: zhangjt@scau.edu.cn.
are generated by driving the fluid harmonically in the MHz frequency range. Jeng et al. (2009) developed a PZT-driven atomizer based on a flexible membrane and a micro-machined trumpet-shaped nozzle array. The atomizer is capable of generating droplets with a Sauter mean diameter (SMD) of 4.6 μm at a flow rate of 2.5 g/min. Although high-frequency PZT-driven atomizers can achieve a small particle size, the use of an air pump to expel the atomized particles increases the power consumption of the device. Especially when used for crops, the smaller droplet diameter makes it prone to spray drift, causing serious environmental problems.

On the fluids side, in addition to the damping effects, the surrounding liquid exerts a reaction force characterized as the added mass, which plays an important role in the dynamic analysis of the piezoelectric structure (Kramer et al., 2013). A number of papers have been published in recent years that investigated the added mass effects of the interacting fluids in macro and micro structures (Jeong et al., 2003; Esmailzadeh et al., 2008; Askari et al., 2010). Although several methods for considering the fluid inertial effect have been developed, the solid structure is mainly considered an isotropic material, such as a metal or metallic alloy. For anisotropic piezoelectric structures, which generally have a lower effective density than metallic structures, the added mass effect of water should be analyzed also. Furthermore, because of the piezoelectric effect, the fluid-solid coupling analysis of the piezoelectric composite structure is more intricate. Therefore, the fluid-solid coupling of the piezoelectric structure, especially the need to consider the piezoelectric effect, should be researched further.

The objectives of this study were:

1. To design a piezoelectric atomizer based on the principles of standing wave and a pressure-swirl nozzle. In this design scheme, the piezoelectric atomizer can produce uniformly-sized liquid droplets without an additional air pump, which will also be verified by experiments;
2. To develop a numerical model to investigate the fluid-solid-electric coupling of the piezoelectric atomizer; and
3. To test the atomization characteristics of the Sauter mean diameter and flow rate by experiments.

In this article, the principle of a piezoelectric atomizer understanding-wave resonance is demonstrated in Section II. The flow-field analysis of the piezoelectric composite plates based on the finite element method, considering the piezoelectric effect, is performed in Section III. The fluid-solid coupling of the standing-wave resonance chamber is developed in Section IV. The analysis of the two-phase flow in the pressure-swirl nozzle is described in Section V. Finally, the continuous spraying experiment using the piezoelectric atomizer is demonstrated.

**DESIGN AND FABRICATION OF ATOMIZER**

**DESIGN CONCEPTS OF CURRENT ATOMIZER**

To generating appropriate droplets with a simplified structure, a novel piezoelectric atomizer is designed based on vibrating piezoelectric composite plates and the principle of standing-wave resonance. Figure 1 presents a schematic illustration of the piezoelectric atomizer. It shows that the device comprises six major components, namely, the piezoelectric composite plates, a standing-wave resonance chamber, a one-way valve as the inlet, a one-way valve as the outlet, and a swirl spool in the swirl chamber.

**PRINCIPLE OF OPERATION**

The piezoelectric atomizer shown in figure 1 operates on the direct rectification of a standing pressure wave inside a resonance chamber filled with fluid. The vibration amplitude of the piezoelectric composite plates produces an oscillating flow that may cause the chamber volume to change slightly. As the vibration direction of the piezoelectric composite plates moves outward to increase the chamber volume as shown in figure 2a, the pressure inside the chamber decreases. The inflow enters the chamber based on the pressure difference between the resonance chamber and the outside atmosphere, while the one-way inlet open and the one-way outlet closed. As the vibration direction of the piezoelectric composite plates moves inward, decreasing the chamber volume, as shown in figure 2b, the pressure inside the chamber increases. Partial fluid flows from the outlet close the inlet and open the one-way outlet. With the piezoelectric composite plates at higher frequency, the fluid in the chamber also produces oscillation. Eventually, the motion of the piezoelectric structure causes the fluid to form a standing-wave oscillation into the chamber. According to wave propagation theory (Lighthill, 2001), when the wavelength is a proper divisor of $2L$ ($L$ is the length of the chamber), the fluid oscillation in the chamber will be in the situation of standing-wave resonance. In fluid resonance, the standing pressure wave increases significantly, and pressure fluctuations are obtained as follows (Lighthill, 2001):

![Figure 1. Schematic illustration of piezoelectric atomizer.](image)
\[ \delta P = \rho_f c_H \] (1)

The pressure fluid flows from the outlet and generates a spiral movement through the swirl slots of the pressure-swirl nozzle. Eventually, the pressure fluid forms a rotating flow inside the swirl chamber. The swirling liquid pushes against the walls of the swirl chamber and develops a hollow air core. As this rotating flow exits the axial orifice, an unstable conical swirling sheet is formed that breaks up into ligaments and droplets. The transition from the internal injector flow to a fully developed spray can be divided into three steps: film formation, sheet breakup, and atomization.

**FLUID-SOLID COUPLING OF THE PIEZOELECTRIC COMPOSITE PLATES**

**GOVERNING EQUATIONS**

A piezoelectric structure submerged in a dense fluid changes its natural frequencies in comparison with those in a vacuum due to fluid-structure interaction (FSI). This change is significant when the fluid density is on the order of the structure density. FSI has been the subject of intense research, and various theories have been developed to study the wide array of problems that are of interest. Among these methods, a commonly accepted formulation is outlined in Zienkiewicz (1978). The basic idea is to use a coupled equation that uses the pressure in the fluid domain and the structural displacement as the working variables.

According to the theory, when an alternating electric field is exerted on the piezoelectric composite plates, the governing equation of the transverse deflection can be expressed as:

\[ \nabla^2 \psi^2 w_c + \frac{\rho_c h}{D_c} \frac{\partial^2 w_c}{\partial t^2} = \frac{f_c - P_l}{D_c} \] (2)

where

\[ D_c = E h^3 \left[ \frac{1}{12} (1 - \nu^2) \right] \] (3)

In our study, assuming incompressibility and inviscidity, the fluid movement can be described by the Navier-Stokes equations 4 and the mass continuity equation 5:

\[ \rho_l \frac{d\mathbf{v}}{dt} = \rho_l g + \mu \nabla^2 \mathbf{v} - \nabla P_l \] (4)

\[ \frac{\partial P_l}{\partial t} + (\nabla \cdot \mathbf{v}) \rho_l = 0 \] (5)

The edge of the piezoelectric composite plates is bonded with the resonance chamber; it can be considered as a clamped boundary condition. Thus the boundary conditions are:

\[ w_c \mid \theta = \phi_1 = 0, \quad \frac{\partial w_c}{\partial r} \mid \theta = \phi_1 = 0 \] (6)

The movements of the piezoelectric composite plates and the fluid pressure of the working fluid are coupled, which are represented by the dynamic pressure \( P_l \).

The actuating force \( f_c \) can be deduced from the coupled electro-mechanical constitutive equation as:

\[ T_h = c_{bh} A_j - h_{jh} D_j \] (7)

\( h, k = 1, 2, \cdots, 6 \) and \( j = 1, 2, 3 \)

**NUMERICAL SIMULATION**

It is notably difficult to solve these governing equations analytically. Hence, numerical simulations are commonly used to predict the natural frequencies and mode shapes of a piezoelectric structure (Kozie\'ń et al., 2011; Galchev et al., 2012; Pérez et al., 2014). To solve the governing equations numerically, the finite element method (FEM) is applied to predict the performance of the piezoelectric composite plates. In this work, the ANSYS® parametric design language (APDL) is used to determine the dynamic characteristics of the piezoelectric composite plates, e.g., the natural frequencies and the mode shapes in air and in water. The selection of the piezoelectric composite plates is shown in figure 3. A circular PZT-4 piezoelectric element

![Figure 3. Geometry of the piezoelectric composite plates.](image-url)
is glued on a 0.2 mm thick brass sheet that is attached to the end of the standing-wave resonance chamber (see fig. 1). These piezoelectric elements are light, inexpensive, and convenient to use in experiments.

To evaluate the dynamic characteristics of the piezoelectric composite plates, a symmetrical three-dimensional finite element model, including the piezoelectric composite plates, the standing-wave resonance chamber, and the working fluid, is used for coupled-field analysis. As the one-way outlet is closed in the phase of the inflow, the fluid in the pressure-swirl nozzle has little effect on the inner flow field of the resonance chamber. The pressure-swirl nozzle will be ignored in the subsequent analysis of fluid-solid coupling. In this section, two fluid media are analyzed, air and water, defined as dry and wet configurations. In the dry case, the air is assumed to have a negligible effect that is ignored. Figure 4 illustrates the FE mesh and the geometry, with sizes of φ₁ = 27 mm, φ₂ = 19 mm, φ₃ = 23 mm, t₁ = 0.35 mm, t₂ = 0.2 mm, t₃ = 2 mm, and L = 75 mm. The FE mesh consists of two major parts: the solid domain and the fluid domain. The solid domain consists of the piezoelectric composite plates and the resonance chamber, which is made of Plexiglas. The material properties are listed in table 1. In the dry analysis, the fluid domain is not included in the FE mesh.

A flowchart of the fluid-solid coupling between the piezoelectric structure and the working fluid is given in figure 5. The working fluid used in the study is water, and the properties used for the numerical computation are shown in table 2. The commercial finite element (FE) software ANSYS® (ANSYS Inc., Canonsburg, Pa.) is used to validate the fluid-solid coupling model in this work. In the process of numerical simulation, the FSI is modeled by coupling an acoustic fluid domain to the fluid-solid coupling surface of the piezoelectric composite plates. 41,108 three-dimensional fluid elements and 16,655 solid elements are used in the ANSYS® FE simulations. The sound pressure (eq. 8) is adopted for the fluid-solid coupling problem, in which the working liquid is treated as an ideal fluid (incompressible and non-viscous):

\[
\frac{\partial^2 p_f}{\partial t^2} = c_f^2 \nabla^2 p_f
\]  

(8)

The first four in-water (wet) natural frequencies and mode shapes of the piezoelectric composite plates, which are attached to the chamber of the coupled fluid, are shown in figure 6. The natural frequencies of the symmetrical

| Table 1. Material properties for finite element analysis (Daniels et al., 2013). |
|-----------------|-----------------|-----------------|
|                 | PZT             | Brass           | Plexiglas       |
| Density (kg/m³) | 7500            | 8300            | 1200            |
| Young’s modulus (GPa) | -- | 110            | 20              |
| Poisson’s ratio | --              | 0.34            | 0.25            |
| Elastic constant (GPa) | c₁₁=119.0 | c₂₂=57.9       | c₃₃=56.0        |
|                  | c₁₂=110.0       | c₁₃=110.0       | c₂₃=30.5        |
|                  | c₃₃=30.4        | --              | --              |
| Piezoelectric constant (C/m²) | e₁₁=5.6 | e₁₂=11.3       | e₁₃=7.6         |
| Dielectric constant | e₁₁=100       | --              | --              |

| Table 2. Properties of the working fluid (water). |
|-----------------|-----------------|
| Properties      | Value           |
| Density (ρ)     | 1000 (kg/m³)   |
| Bulk modulus (Bₚ) | 2.2 (GPa)     |
| Viscosity (μ)   | 1×10⁻³ (Pa · s) |
| Sound speed in fluid (cₚ) | 1380 (m/s) |
vibration modes corresponding to the $B_{11}$ and $B_{12}$ modes are found at 4160 and 7496 Hz, while those of asymmetrical vibration modes are at 4070 and 8212 Hz for the $B_{10}$ and $B_{20}$ modes, respectively. In the modal shapes $B_{mn}$, $m$ is equal to the number of the nodal circle, and $n$ is the number of the nodal diameter. Compared with other mode shapes, the $B_{10}$ mode can provide the volume of the resonance chamber with a greater variation and can obtain better energy conversion efficiency; therefore, it is generally used as the working mode of the piezoelectric atomizer.

By comparison, the in-air (dry) natural frequencies and mode shapes of the piezoelectric composite plates are shown in figure 7. The comparison of the coupled system with the non-coupled system is given in table 3. It is noted that the mode shapes of the diaphragm of the coupled system are almost the same as the counterparts in the non-coupled system. The numerical results also indicate that the natural frequencies of the fluid-solid coupling system are lower than those of the non-coupled system, because of the interaction between the piezoelectric structure and the working fluid.

### Flow-Field Analysis of the Resonance Chamber Background

This section is mainly concerned with the unsteady fluid dynamic processes occurring in the resonance chamber and the interactions between the solid and fluid elements. In theory, at standing-wave resonance, the pressure of the fluid inside the chamber can produce a large enhancement. The excess pressure ($\delta P$), for undamped pressure waves, is given in equation 1.

According to wave propagation theory (Koveos et al., 2013), the wave celerity in an inviscid fluid is:

$$c = \sqrt{\frac{B}{\rho_f}}$$

### Table 3. Comparisons of natural frequencies and mode shapes.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Mode Type</th>
<th>Natural Frequency /Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Dry Mode (in air)</td>
</tr>
<tr>
<td>1</td>
<td>$B_{10}$</td>
<td>4904</td>
</tr>
<tr>
<td>2</td>
<td>$B_{11}$</td>
<td>6736</td>
</tr>
<tr>
<td>3</td>
<td>$B_{12}$</td>
<td>11112</td>
</tr>
<tr>
<td>4</td>
<td>$B_{20}$</td>
<td>13123</td>
</tr>
</tbody>
</table>

Figure 6. Mode shapes of the piezoelectric composite plates in water (wet mode).

Figure 7. Mode shapes of the piezoelectric composite plates in air (dry mode).
The corresponding wavelength ($\lambda$) is:

$$\lambda = \frac{c}{f}$$

(10)

To form a standing wave, the condition to hold for a closed chamber of length ($L$) should be

$$L = k \frac{\lambda}{4}$$

(11)

where $k = 1, 2, ...$. From equations 9 to 11, the standing-wave resonance frequency ($f_r$) is:

$$f_r = \frac{c}{4L} = \frac{1}{4L} \sqrt{\frac{B}{\rho_l}}$$

(12)

The fluid oscillation within the chamber is caused by the vibration of the piezoelectric composite plates. Therefore, the vibration frequency of the piezoelectric composite plates should be same as the standing-wave resonance frequency ($f_r$) in equation 12. Using the wet mode numerical method of piezoelectric composite plates in Section III, combined with equation 12, the length ($L$) of the standing-wave resonant chamber can be obtained (fig. 8). The dash-dotted curve represents different standing-wave resonant frequencies corresponding to the different lengths ($L$) of the chamber, based on equation 12. The solid curve with triangles represents different wet mode frequencies of the piezoelectric composite plates corresponding to different lengths ($L$) of the chamber, as obtained by the FE numerical method in Section III. The wet mode frequency of the piezoelectric composite plates decreases gradually with the increase of chamber length ($L$), as shown in figure 8. This is because the mass and viscous damping of the fluid increase as the length of the chamber ($L$) increases, causing the wet mode frequency of the piezoelectric composite plates to decrease (Rodriguez et al., 2012). It can be concluded that the standing-wave resonance frequency of the chamber equal to the wet mode frequency of the piezoelectric composite plates is 1995 Hz, as the resonance chamber has a length of 185 mm. This finding also means that a standing-wave resonance can be produced at the $B_{10}$ mode shape when the length of the resonance chamber ($L$) is 185 mm. At this time, the vibration frequency of the piezoelectric composite plates coupled with the working fluid is 1995 Hz.

**FLUID-SOLID COUPLING OF THE RESONANCE CHAMBER**

In the present work, a numerical model was built using the commercial CFD (computer fluid dynamics) code FLUENT® (ANSYS Inc., Canonsburg, Pa.) to obtain the flow and concentration characteristics. The CFD modeling involves the numerical solution of the unsteady Navier-Stokes conservation equations for mass, momentum, and energy based on a finite volume technique (Payri et al., 2005). As explained before, the piezoelectric composite plates were appended to the bottom of the resonance chamber. The transverse vibration of the piezoelectric composite plates, which is excited by an alternating electric field, changes in volume within the resonance chamber. With the periodic vibration of the piezoelectric structure, the fluid in the chamber also produces oscillation. Finally, the fluid motion is turned to form a standing-wave resonance in the chamber. The transverse vibration of the piezoelectric composite plates, which is excited by an alternating electric field, changes in volume within the resonance chamber. This is because the mass and viscous damping of the fluid increase as the length of the chamber ($L$) increases, causing the wet mode frequency of the piezoelectric composite plates to decrease (Rodriguez et al., 2012). It can be concluded that the standing-wave resonance frequency of the chamber equal to the wet mode frequency of the piezoelectric composite plates is 1995 Hz, as the resonance chamber has a length of 185 mm. This finding also means that a standing-wave resonance can be produced at the $B_{10}$ mode shape when the length of the resonance chamber ($L$) is 185 mm. At this time, the vibration frequency of the piezoelectric composite plates coupled with the working fluid is 1995 Hz.

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resonance chamber. Three monitoring points in the computational domain, approximately 21,082 grids are used for the analysis is presented in Figure 11. In the entire computational domain, the mesh model used in this numerical fluid-solid coupling can be realized.

Finally, the periodic transverse vibration of the piezoelectric composite plates can be simulated, and the effect of the fluid-solid coupling can be realized.

RESULTS OF FLUID-SOLID COUPLING

To research the characteristics of the fluid flow in the resonance chamber, the mesh model used in this numerical analysis is presented in Figure 11. In the entire computational domain, approximately 21,082 grids are used for the resonance chamber. Three monitoring points $P_1$, $P_2$, and $P_3$ are arranged to monitor the fluid dynamics of the flow field. The boundary conditions for the import and export are the pressure inlet and pressure outlet, respectively. The convergence criteria are supposed to be $10^{-5}$ for all predicted parameters. The SIMPLEC pressure-velocity coupling algorithm and the second-order upwind discretization scheme for momentum are utilized.

Figure 12 illustrates the pressure distribution and streamline diagram at the phase of the inflow. As the vibration direction of the piezoelectric composite plates moves outward, the volume of the resonance chamber increases while the pressure inside the chamber decreases. The fluid flows into the resonance chamber through the one-way valve at the inlet. Figure 13 describes the pressure distribution and streamline diagram at the phase of the outflow. When the piezoelectric composite plates move inward, the pressure inside the chamber rises, and then the fluid in the chamber is discharged outside through a one-way valve on the outlet. Hence, continuous fluid output can be achieved by using the periodic vibration of the composite piezoelectric plates.

The pressure curves of the monitoring points ($P_1$, $P_2$, and $P_3$) are presented in Figure 14a. With the change in volume of the resonance chamber, the flow-field pressure varies periodically. At the phase of the outflow, the flow-field pressure in the chamber is positive-pressure, and the maximum value of $P_1$ is 2.5 MPa. Pressures $P_2$ and $P_3$ decrease gradually, and their maximum values are 1.5 and 0.3 MPa, respectively. Figure 14a also illustrates that, at the phase of the inflow, the entire flow-field pressure in the resonance chamber is negative-pressure. The pressure value is gradually reduced from $P_1$ to $P_3$, and the minimum pressure of $P_1$ is -2.8 MPa. The frequency spectrum of the monitoring points, which is verified by performing a fast Fourier transform (FFT), is illustrated in Figure 14b. It is shown that the oscillation frequency of the fluid inside the resonance chamber is 1997 Hz, which accords with the vibration frequency of the piezoelectric composite plates for the $B_{10}$ mode shape.

Figure 15 illustrates the time variations of the static pressure and x-directional velocity at $P_1$. The flow-field static pressure and the X-directional velocity of the $P_1$ variation with time are sinusoidal curves, and the phase difference is $\pi/2$. According to the principle of wave interference (Min et al., 2012), a standing wave is produced across the fluid chamber, and the fluid oscillation is a type of standing-wave resonance.

ANALYSIS OF PRESSURE-SWIRL NOZZLE IN TWO-PHASE FLOW

BACKGROUND

The pressure-swirl nozzle is one of the most commonly used nozzles; it can produce small droplets at low inlet pressures and is used in the industrial and agricultural fields (Laryea et al., 2003). A simplex swirl nozzle always comprises a swirl chamber with several tangential fluid inlets and an axial fluid outlet. The tangential fluid produces a rotating flow inside the swirl chamber. A conical swirling sheet is formed when the rotating flow ejects from the orifice and finally breaks into small droplets. Despite the simple geometry of the pressure-swirl nozzle, its internal flow behavior is complex due to the strong swirling velocity component of the swirl flows. Therefore, the prediction of the fluid dynamics of the pressure-swirl nozzle for design and analysis is critical. In recent years, many experimental and numerical studies have been carried out to determine the internal flow characteristics in a pressure-swirl nozzle. Yang et al. (2012) used a high-speed camera to record detailed information regarding the liquid sheet breakup process and spray development. Experiments were performed with pressure-swirl nozzles of different configurations to test the effect of the nozzle geometry on the spray characteristics. Yule et al. (2000) used laser Doppler anemometry (LDA) to measure a large-scale pressure-swirl nozzle, and information on the air core size and the velocity fields inside the swirl chambers was obtained. However, such studies are difficult to perform on production-scale nozzles. As a complement to the experimental techniques, computational fluid
dynamics can provide additional insight into the dynamics of the pressure-swirl nozzles. Zeoli et al. (2011) examined fluids during atomization from different pressure-swirl nozzle designs via the Reynolds stress model (RSM) and the volume of fluid (VOF) method. Mandal et al. (2008) investigated non-Newtonian fluid behavior in a pressure-swirl atomizer. Using the VOF method, they concluded that the spray cone angle and the variation in the film thickness decrease upon increasing the ratio between the orifice length and diameter.

The motivation of this section is to simulate the internal flow field inside the pressure-swirl nozzle of the piezoelectric atomizer. Using the volume of fluid computational fluid dynamics approach, the pressure swirl

Figure 12. Pressure distribution and streamline diagram at the phase of the inflow.

Figure 13. Pressure distribution and streamline diagram at the phase of the outflow.

Figure 14. Pressure curves and frequency spectra of the monitoring points.

Figure 15. Pressure and velocity curves at $P_1$.

Figure 16. Pressure-swirl nozzle.
process of the nozzle is investigated. The axonometric drawing of the pressure-swirl nozzle used for this study is shown in figure 16, in which fluid is fed into the swirl chamber through four swirl slots grooved on the swirl spool. After undergoing rotational acceleration in the swirl chamber, the fluid is finally released from the orifice of the nozzle. The geometrical characteristics of the swirl spool and the swirl chamber are illustrated in figure 17.

**Numerical Results of the Pressure-Swirl Nozzle**

FLUENT® is used to calculate the governing equations for both the gas and liquid phases. The VOF model is applied in this investigation because it has a conservative formulation and allows for the direct determination of the steady solution of the flow. The second-order centered scheme and the second-order upwind interpolation scheme have been applied to the continuity and momentum equations. The SIMPLE algorithm has been chosen to tackle the pressure-velocity coupling. Because the fluid is injected helically into the swirl chamber, it is not possible to perform two-dimensional simulations on the internal fluid field of the pressure-swirl nozzle. A three-dimensional model is constructed to investigate the flow of water \( \rho_1 = 1000 \text{ kg/m}^3 \) into the air \( \rho_2 = 1.225 \text{ kg/m}^3 \) from the inside of the nozzle to the external air flow field (see fig. 18). The model is comprised of two parts: Part I represents the internal flow field of the pressure-swirl nozzle, and Part II represents the outlet computational domain attached to the atomizer to calculate the flow at the exit. The fluid is initially injected from the pressure inlet. The outlet boundary conditions are atmospheric pressure, a 5% turbulence intensity and a turbulent viscosity ratio of 10. The wall is a solid wall with a no-slip condition. A non-uniform mesh grid composed of 652,934 tetrahedral elements and 116,980 nodes is used. The VOF method together with the Reynolds-averaged Navier-Stokes (RANS) equations is implemented to capture the turbulent solution of the two-phase flow field.

Figure 19 illustrates the velocity contour and streamlined diagram of the nozzle flow field when the fluid pressure at the inlet is 2000 Pa. Passing through the swirl slots, the liquid generates high-speed rotation in the swirl through conical contraction, and a low-pressure area is established at the center of the internal flow field (see fig. 19a). The atmospheric air is sucked into the interior of the nozzle under the action of reverse pressure. An air core is formed around the centerline inside the swirl chamber to balance the static pressure of the working fluid and the ambient pressure, as can be observed in the present simulations (fig. 19b). Consequently, a closed rim sheet is formed near the nozzle orifice. The air core can be developed in the nozzle, resulting in a thin film of liquid exiting the nozzle, as the sheet is fully developed. Belhadef et al. (2012) and Datta et al. (2000) indicate that the liquid sheet exhibits instability linked in particular to the large slip velocity between the liquid sheet and the ambient air that causes the liquid sheet to break up into ligaments and droplets.

The contour of the velocity near the orifice, obtained in the numerical simulations, is shown in figure 20. When the liquid swirls in the chamber, hydrodynamic instabilities develop between the liquid and the gas, and vortices are formed inside the nozzle. These vortices are called Gortler vortices, which accord with the experimental observations of Cooper (1999). Nouri-Borujerdi et al. (2012) considered that these instabilities are produced by Gortler vortices rotating about the air core. An interesting phenomenon is also illustrated in figure 20 in which waves of small amplitude are observed along the interface between the liquid and the gas. The waves originate at the top of the swirl chamber and propagate toward the orifice. One possible explanation is that the wave formation is caused by the recirculating air flow in the swirl chamber.

**Experiment**

**Sweep Frequency Experiment**

Frequency measurements of the piezoelectric composite plates in wet mode are taken using a 2-channel Agilent
35670A (Agilent Technologies Company, Santa Clara, Calif.). The piezoelectric composite plates of the prototype are driven directly by the sweep sine source of the dynamic signal analyzer (fig. 21). This instrument, in the sweep frequency mode, gives rise to a sinusoidal voltage at discrete frequencies over the specified frequency range. The process of sweeping frequencies is that the dynamic signal analyzer supplies a fluctuating periodic chirp. Complying with the oscillograph, an upsurge signal will emerge when the resonant point is experienced. The graph in figure 21b output by the oscillograph demonstrates the resonance frequency of the piezoelectric atomizer coupled with the working fluid. The first two natural frequencies are 1860 Hz and 4510 Hz, which correspond to the $B_{10}$ and $B_{11}$ modes, respectively. The theoretical analysis of fluid-solid coupling in Section III and Section IV shows that the first two wet mode frequencies are 1995 Hz and 4160 Hz when the length of the standing-wave resonance chamber $L$ is 185 mm, and the theoretical and experimental errors are 6.77% and 7.76%, respectively.

**Spray Measurement**

In assessing the piezoelectric atomizer, two spray parameters, namely, the particle diameter distribution and the flow rate, are experimentally measured. The experimental system for the particle size analysis is presented in figure 22a-b. The experimental setup comprises a signal generator (WF1946A, NF Corporation, Yokohama, Japan), a power amplifier (HSA4052, NF Corporation, Yokohama, Japan), and a laser particle size analyzer (Winner318, WP Corporation, Jinan, China). Using the experimental setup, the effective measurement range of the particle size extends from 15 to 711 μm. A sinusoidal signal of 1860 Hz is generated by the signal generator and is amplified by the power amplifier. Consequently, the piezoelectric atomizer produces droplets in the signal excitation. The laser light is generated by the transmitter of the laser particle size analyzer and passes through the collimating mirror such that it emerges as a parallel light beam with a diameter of 10 mm. When the light beam passes through the spray flow field, a diffraction effect takes place. The diffracted light illuminates the photoelectric detector and is collected by a Fourier lens. The detected light signal is transformed into a digital signal by the A/D converter and analyzed by the computer. The working fluid used to perform the flow rate measurement is...
water. The flow rate is surveyed from the weight of the droplets that are ejected from the piezoelectric atomizer. An electronic balance (YP-B 500g/0.01g, SHH Corporation, China) with a resolution of 0.01 g is used in the experiment. A schematic illustration of the experimental setup used to perform the flow rate analysis is shown in figure 22c.

Figure 23 shows the spray patterns of the piezoelectric atomizer for a series of increasing peak-to-peak voltages $V_{\text{pk-pk}}$ from 10 to 150 V. The transition from a swirling jet to the complete atomization of the spray cone can be seen in figure 23. The sheet cone angle increases as the liquid flow rate increases due to the increase of the liquid momentum. When the peak-to-peak operating voltage $V_{\text{pk-pk}}$ reaches 30 V, a jet flow with a circular cross-section is formed near the orifice of the piezoelectric atomizer. A twisted sheet appears below the orifice because of the competition between the swirl strength of the jet flow and the gravity of the fluid (fig. 23a). A low mass flow rate jet is generated by the resonance chamber with a lower driving voltage, and a lower tangential velocity of the swirling sheet results. Consequently, the twisted sheet occurs under gravity, and larger droplets appear in the fog drops.

As the peak-to-peak driving voltage ($V_{\text{pk-pk}}$) increases to 70 V, there still exists a circular jet flow near the orifice (fig. 23b). With the increase of the driving voltage, a rudimentary hollow cone of the swirling sheet near the orifice has been developed because the axial and tangential velocities both increased. The ligaments are formed downstream, and then most of the ligaments break up into droplets. As the peak-to-peak driving voltage ($V_{\text{pk-pk}}$) increases to 120 V, a fully developed hollow cone forms.

Figure 23. Spray characteristics of the piezoelectric atomizer with different driving voltages. (a) $V_{\text{pk-pk}}=30$ V (flow rate is 7.6g/s), (b) $V_{\text{pk-pk}}=70$ V (flow rate is 12.7g/s), (c) $V_{\text{pk-pk}}=120$ V (flow rate is 15.2g/s), (d) $V_{\text{pk-pk}}=150$ V (flow rate is 18.4g/s).
(fig. 23c-d). Figure 23 also shows that for a given nozzle geometry, the effective spray cone angle increases with an increase in the driving voltage or liquid mass flow rate of the working fluid due to the increase of the liquid momentum. This phenomenon is also consistent with the experiment of Inamura et al. (2003).

The mean diameter with the same ratio of volume to surface area as the entire ensemble is known as the Sauter mean diameter (Wei et al., 2014). It corresponds to values of \( p = 3 \) and \( q = 2 \) in equation 16.

\[
D_{pq} = \sqrt[1/(p-q)]{\sum_{i=1}^{\infty} n_i D_i^p \sum_{i=1}^{\infty} n_i D_i^q}
\]

(16)

The Sauter mean diameter is extensively used in the characterization of liquid/liquid and gas/liquid dispersions. Figure 24 illustrates the dimensions of the sprayed particles at peak-to-peak driving voltages of 30, 70, 120, and 150 V. The particle size distribution for different driving voltages corresponds to the sub-figure shown in figure 23. The figure demonstrates that when operated at a lower driving voltage, the piezoelectric atomizer produces droplets with a less uniform diameter than when operated at a higher driving voltage. When the driving voltage is \( V_{pk-pk}=30 \text{ V} \), the minimum droplet size produced by the atomizer is 47.7 \( \mu \text{m} \), and the maximum droplet size is 418.2 \( \mu \text{m} \). By comparison, when the driving voltage is increased to \( V_{pk-pk}=150 \text{ V} \), the minimum droplet size is 60.7 \( \mu \text{m} \) and the maximum droplet size is 151.9 \( \mu \text{m} \). In addition, more than 76% of the total volume of the droplet diameters is concentrated in the interval from 85.1 to 108.4 \( \mu \text{m} \). This is because a higher driving voltage increases the displacement of the piezoelectric composite plates, which in turn increases the kinetic energy of the ejected liquid, thereby reducing the particle size. It is also deduced that a higher velocity between the spray cone and the ambient gas promotes the centrifugal force of the swirling sheet, and long ligaments are established. Eventually, relatively uniform droplets are formed.

**CONCLUSIONS**

A piezoelectric atomizer based on the principles of standing-wave resonance and a pressure-swirl nozzle was developed, analyzed, and tested. This atomizer uses piezoelectric composite plates to acquire a large displacement from the PZT vibration and exert an excess pressure on the liquid with standing-wave resonance. Utilizing the pressure-swirl nozzle, uniformly-sized liquid droplets can be produced without the use of an additional air pump, which satisfies the need for low-cost mass production for engineering and agricultural applications.

In this study, the three-dimensional dynamic characteristics of the piezoelectric composite plates, considering the effect of the fluid-solid interface, are determined. The natural frequencies and mode shapes of the PZT diaphragm have been simulated using the ANSYS parametric design language in which the FSI is modeled by coupling an acoustic fluid domain to the surface of the fluid-solid coupling.

The hydrodynamics inside the standing-wave resonance chamber of the piezoelectric atomizer are determined using the dynamic mesh method and UDF. A subsequent analysis of the fluid-solid coupling between the fluid in the resonance chamber and the vibration of the piezoelectric

![Figure 24. Variation of particle size distribution for different driving voltages.](image)

SMD=175.6 \( \mu \text{m} \); \( V_{pk-pk}=30 \text{ V} \); current of 2.7 mA
D(10)=55.9 \( \mu \text{m} \); D(50)= 208.3 \( \mu \text{m} \); D(90)= 376.6 \( \mu \text{m} \)

(a)

SMD=131.4 \( \mu \text{m} \); \( V_{pk-pk}=70 \text{ V} \); current of 7.8 mA
D(10)= 69.3 \( \mu \text{m} \); D(50)= 144.7 \( \mu \text{m} \); D(90)= 212.9 \( \mu \text{m} \)

(b)

SMD=115.2 \( \mu \text{m} \); \( V_{pk-pk}=120 \text{ V} \); current of 13.9 mA
D(10)= 73.2 \( \mu \text{m} \); D(50)= 121.4 \( \mu \text{m} \); D(90)= 163.7 \( \mu \text{m} \)

(c)

SMD=93.5 \( \mu \text{m} \); \( V_{pk-pk}=150 \text{ V} \); current of 18.2 mA
D(10)= 81.9 \( \mu \text{m} \); D(50)= 94.1 \( \mu \text{m} \); D(90)= 108.2 \( \mu \text{m} \)

(d)
composite plates is conducted. It is found that a standing-wave resonance can be achieved in the chamber for the $B_{10}$ mode shape of the PZT diaphragm when the length of the resonance chamber $L$ is 185 mm.

The inner flow and performance characteristics of the pressure-swirl nozzle using the two-phase flow method are investigated. The SMD and flow rate of the piezoelectric atomizer are measured by experiments. We find that a smaller and more uniform SMD could be achieved by operating at a higher amplitude of the driving voltage. The atomizer also demonstrates that relatively uniform droplets are formed below the ligaments when the cone swirl sheet is fully developed. This reveals that this atomizer has the potential for applications that require fine droplets.

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**NOMENCLATURE**

- B: bulk modulus
- c: wave celerity
- \( c_r \): sound speed in water
- \( c_{hk} \): sixth-rank symmetric tensor under a constant electric field, \( h,k = 1,2,\cdots,6 \)
- \( D_i \): droplet diameter for size class i
- \( D_J \): electric displacement, \( j = 1,2,3 \)
- E: elastic modulus
- f: wave’s frequency
- \( f_c \): periodic actuating force generated by the piezoelectric structure
- \( f_p \): vibration frequency of the piezoelectric composite plate
- \( f_r \): standing-wave resonance frequency
- h: thickness of the piezoelectric composite plate
- \( h_{jh} \): piezoelectric constant tensor, \( h = 1, 2, \ldots, 6 \) and \( j = 1,2,3 \)
- L: length of standing-wave resonance chamber
- n_i: number of the droplets in size class i
- \( p_f \): sound pressure in water
- \( P_l \): dynamic pressure imposed on the piezoelectric composite plates by the fluid
- S_k: mechanical strain tensor, \( k = 1,2,\cdots,6 \)
- t: iteration time
- T_h: stress, \( h = 1,2,\cdots,6 \)
- u: fluid velocity
- \( \vec{v} \): velocity vector
- \( w_c \): displacement of the piezoelectric composite plate
- \( \delta P \): fluid pressure fluctuation
- \( \lambda \): wavelength
- \( \mu \): viscosity of the fluid
- \( \rho_c \): density of the piezoelectric composite plate
- \( \rho_f \): fluid density
- \( \nu \): Poisson ratio
- \( \nabla^2 \): Laplacian operator


