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Time–frequency analysis of acoustic and unsteadiness evaluation in effervescent sprays

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HIGHLIGHTS

- An unconventional description of effervescent spray features was obtained.
- Detailed two-phase phenomenon is captured by adaptive optimal kernel spectrogram.
- The acoustic energy was calculated through the Hilbert Huang transfer method.
- A new evaluation of effervescent spray unsteadiness was established.

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ABSTRACT

The acoustic signals from effervescent sprays were experimentally investigated across a range of injection pressures, flow rates, and gas to liquid ratios by mass (GLR). An unconventional description of spray features under various operational conditions was obtained through the time–frequency–amplitude distributions of spray acoustic by adaptive optimal kernel (AOK). The acoustic energy was calculated through the Hilbert Huang transfer (HHT) method and was confirmed to be affected by both the GLR and air flow rate. A new evaluation of spray unsteadiness was established based on this finding. The results show that the gas flowing out of the orifice leads to an increase in the amplitude of the high frequency component. Discrete phenomenon in effervescent sprays was exactly observed by AOK spectrogram as the amplitude distribution was discontinuous with time and the amplitude fluctuations showed variation in different conditions. The factors influencing the acoustic energy include both air and liquid flow rate. The unsteadiness levels under different conditions were calculated after the new spray unsteadiness was evaluated through a simple atomizer. The unsteadiness levels had a low value when the GLR was higher than 5% and varied across a wide range when the GLR was below 4%. The flow regime had a significant effect on the spray unsteadiness as the bubbly and churn flow regimes produce a relatively stable spray, whereas the slug flow regime induces unsteadiness.

1. Introduction

Developed in the late 1980s by Lefebvre et al. (1988), Roesler and Lefebvre (1988) and Lefebvre (1989), effervescent atomization is a promising technique with a two-phase mixture mechanism. This technique has a satisfactory performance only by consuming little atomizing gas under low injection pressure (Roesler and Lefebvre, 1989). It has been widely used in recent years in various industrial applications, such as gas turbine combustors, internal combustion engines, industrial painting, and agricultural sprays (Sovani et al., 2001, 2005; Panchagnula and Sojka, 1999).

The literature (Sovani et al., 2001) characterizes that this technique as having a low sonic velocity for a two-phase mixture and a pressure jump at the atomizer exit, unlike other twin-fluid atomization techniques. The atomizing gas consequently undergoes sudden pressure relaxation and rapid expansion at the atomizer exit, thereby shattering the liquid into ligaments and drops (Ramamurthi et al., 2009). The gas–liquid two-phase interaction reportedly has an important function in aiding liquid atomization.

Many studies using both experimental and theoretical methods have been conducted to deepen our understanding of effervescent sprays. For example, Panchagnula and Sojka (1999) employed a phase/doppler particle analyzer (P/DPA) to measure the velocity and diameter of droplets at a GLR of 2–10% and mass flow rate of 30–120 g/s. They also developed a variable-density single-phase jet model to predict the far-field spatial development of the spray velocity profile. Edwards and Marx (1995) developed an unsteadiness

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evaluation method based on interparticle time distribution using the P/DPA. This method is considered as the classic in the field and has been employed by various researchers in studying effervescent spray unsteadiness (Luong and Sojka, 1999; Heinlein and Fritsching, 2004; Jedelsky and Jicha, 2008). Sovani et al. (2005) investigated the effects of the atomizer structure, including the exit orifice diameter, needle lift, and aerator pore size on the performance of the injector. Camera and Malvern laser particle size analyzer were used in measuring the spray cone half-angle, mean drop size, and drop size distribution. Their results suggested ways of improving spray performance of effervescent atomizers applied in diesel engines. Gomez (2009) and Shepard (2011) investigated the effects of bubble size on the properties of effervescent spray. They applied the shadowgraphy image visualization technique in characterizing the shape, velocity, size, and size distribution of droplets. The results of both their studies demonstrated that bubble and droplet size have a non-linear relationship. Shepard (2011) also indicated that an optimal bubble size that produces the finest spray exists. Jedelsky and Jicha (2008) developed a new method of evaluating spray unsteadiness by measuring the pressure fluctuations in the mixing chamber of the atomizer. The results revealed the relationship between atomizer internal two-phase flow patterns and spray unsteadiness.

Mathematical models and numerical simulations of effervescent atomization have been developed through the decades since the advent of the effervescent atomizer. Sovani et al. (2001) proposed an ideal comprehensive model composed of internal and external flow models. However, knowledge on the relationship between internal and external flow is lacking. Most of the previous studies focus on the external flow model, given its direct relation to spray characteristics. Lund et al. (1993) developed a fundamental model that predicts drop size by considering atomizing gas and liquid mass flow rates, liquid physical properties, and atomizer exit geometry. This model has gained extensive attention and led to much research on a comprehensive model. The accuracy of the predictions of the model developed by Panchagnula and Sojka (1999) is within approximately 15% of the experimental data. Xiong et al. (2009), Qian et al. (2011) and Lin et al. (2009) proposed a three-dimensional model that predicts spray characteristics by describing both primary and secondary atomization. Their results led to an increasingly detailed level of information on spray structure and droplet diameter spatial distribution. Esfarjani (2007) numerically investigated the two-phase flow inside the effervescent atomizer and found that the liquid film thickness is independent of liquid physical properties, such as density and viscosity.

Considerable research has been conducted to improve our understanding of effervescent spray properties. Scant attention has been devoted however to the process of bubbles (gas) flowing out of exit orifice and shattering the liquid into ligaments and droplets. The process is characterized by complex physics and highly nonlinear phenomena, such that theoretical analysis is difficult. Experimental methods, such as high-speed images, constitute a feasible, reliable, and valid approach to studying this issue. Catlin and Swithenbank (2001) used a high-speed video to investigate both the internal two-phase flow and external atomization process. Their experiments demonstrated the process of gas flowing out of the exit orifice and bursting along the liquid jet. Lorcher et al. (2005) combined an electrical measurement technique and high-speed camera to discuss how internal flow parameters (pressure and volumetric flow rates of liquid and gas) and flow regime affect the mean diameter of the spray droplet. The results of their experiment showed that the internal flow parameters vary under a certain condition and cause the mean diameter of the spray droplet to be time dependent. Their experimental images revealed that bubbles undergo a process of deformation when they approach and flow out of the nozzle exit. Maldonado et al. (2008) characterized the spray stability based on the analysis of the wall pressure fluctuations (below 40 Hz) in the amplitude, time, and frequency domains. Their results showed the flow pattern entering the nozzle, directly affecting the spray stability. These investigations have provided useful insights on the evolution of bubbles (gas) both inside and outside the atomizer. However, the information acquired from the abovementioned techniques, such as the high-speed camera, remains limited. A new method or technique is necessary for the in-depth analysis and detailed description of the effervescent atomization especially the process of bubbles (gas) flowing out of exit orifice.

Acoustic signal is a common phenomenon in engineering technology and the natural world. Acoustic analysis has been widely applied in various fields because acoustic wave contains abundant information on the characteristics of the object of study itself (Crighton and Ffowcs Williams, 1969; Husin and Mba, 2010; Szmechta et al., 2011; Karabasov et al., 2013; Xiang et al., 1998). Acoustic wave is also generated during the effervescent spray process; only few studies however have attempted a detailed interpretation of the acoustic characteristics of effervescent spray.

2. Experimental facility

2.1. Atomizer

A simplified transparent outside-in type effervescent atomizer was developed for the experiments. It was made of Plexiglas to allow the visualization of the flow of the air–liquid mixture (see Fig. 1). The point of entry of the liquid was the top of the body of the atomizer. The air entered the mixing chamber through a porous sheet, and thirty drilled air injection holes with a diameter of 0.2 mm each allowed the air to bubble out. The downstream length from the center of the porous sheet to the orifice was 65 mm. The internal mixing chamber had a rectangular cross section (12 mm × 10 mm). The final discharge orifice had a diameter of 2 mm and a length of 1.2 mm. The conical junction between the mixing chamber and orifice was filleted at 4 mm. The geometry of the atomizer was simple, and the geometry size is shown in Fig. 1.

2.2. Experimental setup

The experimental setup is schematically shown in Fig. 2. Water and air were used as the test liquid and atomizing gas. The test liquid was pumped into the atomizer from a 50-l collection reservoir through a pressure regulator, rotameter, and check valve. The air flow (40 l) was pumped into the atomizer from an air compressor through a pressure regulator, rotameter, and check valve. The two fluid pressures were controlled by a pump, compressor, and pressure regulators. The flow rates changed by changing the pressures and were measured by the rotameters. The check valves were used to prevent the fluid from flowing into the reverse direction.

The liquid was admitted in the atomizer at a pressure between 0.1 and 0.5 MPa, and its flow rate ranged from 0.02 L/m to 2.8 L/m.

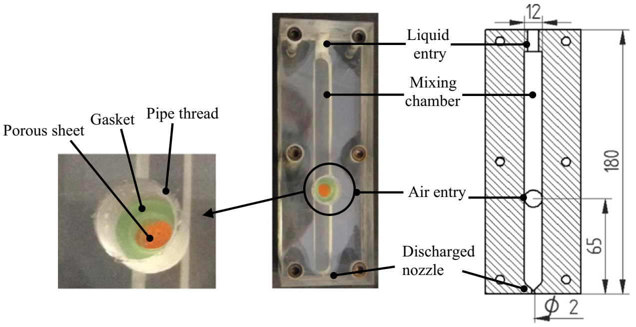

Fig. 1. Plexiglas atomizer used in the experiment.