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# Experimental investigation on the surface wave characteristics of conical liquid film

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ABSTRACT

The disintegration of the liquid sheet is due to the growth of the unstable surface wave. Research on the surface wave characteristics mainly uses the linear stability analysis, and the surface wave characteristics, for example the frequency and wave length of the surface wave, have not been analyzed well experimentally. In the present study, the proper orthogonal decomposition is adopted to analyze the instantaneous spray images and the extracted surface waves on the interface of the gas and liquid. The wavelength and frequency of the surface wave are obtained, and the influence of the injector mass flow rate is investigated. The results show that the spray pattern moves from onion stage to tulip stage and fully developed wavy cone stage with the increase of liquid mass flow rate. In the tulip stage, the wave frequency decreases slightly and then increases with the increase of liquid mass flow rate. On the contrary, the wavelength increases gradually with the increase of liquid mass flow rate and then decreases slightly. This variation trend is caused by the competition effect of the film thickness and the axial film velocity. The decrease of film thickness decreases the wave frequency and increases the wavelength, while the increase of the axial film velocity increases the wave frequency and decreases the wavelength. In the fully developed wavy cone stage, the wave frequency increases gradually with the increase of liquid mass flow rate. And the bandwidth of the surface wave frequency increases gradually, which means that the leading role of the dominant surface wave is weakened and the conical film is dominated by surface waves with multiple frequencies. The wavelength decreases with the increase of liquid mass flow rate because of the significant increased axial film velocity.

## 1. Introduction

Liquid-propellant rocket engines have been used as the primary propulsion systems in most launch vehicles and spacecraft since the late 1920's [1,2], such as the planet landers and low-cost engines [3]. The performance of liquid rocket engine is determined not only by the propellant selection but also by fuel and oxidizer atomization performance [4,5], evaporation and ignition of droplets [6–8]. The atomization performance of propellants is determined by the injector. And there are many types of injector, for example the liquid centered gas-liquid pintle injector [9,10], liquid-liquid pintle injector [11], liquid centered swirl coaxial injector [12,13], etc.

Pressure swirl injectors are extensively used in liquid rocket engines [14], gas turbine engines [15], internal combustion engines [16,17], and many other combustion applications [18]. Commonly, a pressure swirl injector consists of tangential inlet ports, a swirl chamber, a converging spin chamber, and a discharge orifice [19]. The liquid is injected through the tangential ports, forming an air core along the centerline due to high liquid swirl velocity. The liquid flow at the discharge end presumes a hollow conical swirling film. Then the swirling film becomes unstable and breaks up into droplets.

The breakup of conical liquid film occurs when the unstable wave reaches the most unstable state [20]. It means that the surface wave characteristics determine the breakup of the conical liquid film and the atomization performance of a pressure swirl injector. Commonly, the surface wave characteristics include the wavelength, amplitude, wave velocity and frequency of the surface wave. Linear stability analysis has long been used to investigate the surface wave characteristics of conical liquid film. Yue and Yang [21] derived the dispersion equation of a conical liquid sheet, and solved the dispersion equation numerically. In their dispersion equation, spray cone angle, injector diameter, film thickness at the injector exit and film thinning along the injector axis are considered. Wang [22] also derived the dispersion equation of a conical liquid sheet in static atmosphere. However, film thinning along the injector axis is not considered in his equation. Fu et al. [20,23] obtained the same dispersion equation with Yue and Yang [21]. They

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figured out that the maximum disturbances growth rate and the dominant wave number increase as the pressure drop increases, while the breakup length and breakup time decrease with the increase of the pressure drop.

The surface wave characteristics can also be measured from experiments. Chinn et al. [24] directly measured the wavelength from the instantaneous spray image, calculated the wave velocity by multiplying the displacement of a specific wave structure between two neighbored shot images by the frame rate and estimated the wave frequency with the wavelength and wave velocity. Fang et al. [25] and Zhang et al. [26] also measured the wavelength, amplitude and wave velocity with direct measurement method. Kang et al. [27] proposed a characteristic wave structure tracing method based on mutual information to measure the wave velocity, and found that the film velocity equals to the varicose wave velocity and slightly larger than the sinuous wave velocity. Fu et al. [20] measured the film velocity with two neighbored shot images and found that the film velocity increases with the increase of pressure drop.

The aforementioned literature quantitatively measure the surface wave characteristics with direct measurement method. However, the biggest shortcoming of this method is that the measurement accuracy is greatly affected by the limited sampling points. POD (proper orthogonal decomposition) has been a popular tool to extract systematically hidden but deterministic dynamic structures [28]. And these deterministic dynamic structures of the liquid jet or film are strongly related with the surface wave characteristics. Arienti and Soteriou [28] investigated the liquid jet in cross flow with POD. And found that the specific orthogonal modes can track long waves traveling along the liquid column, and the waves are linked to the growing Kelvin-Helmholtz waves. Teshome et al. [29] investigated the shear-coaxial jets exposed to transverse acoustic forcing, and extracted the spatial and temporal characteristics of the dominant flow structures with POD. For the conical liquid film, Eberhart et al. [30,31] calculated the proper orthogonal modes (POMs) and the corresponding temporal amplitude coefficients of a conical liquid film with coaxial outer gas flow. And found that the self-pulsation of swirl coaxial injector is caused by the Kelvin-Helmholtz-like instabilities on the conical liquid film surface. Kang et al. [32] used POD technology to extract the wavelength and frequency of a conical liquid film with and without outer coaxial gas flow. And found that the wave frequency increases gradually with the increase of liquid mass flow rate. Chatterjee [33,34] investigated the breakup of a conical liquid film with inner and outer coaxial gas flow. He obtained the frequency of the spray with POD technology and found that the spray with high liquid flow and relatively low airflows has a single dominant frequency while the spray with low liquid flow and higher airflows has multiple smaller temporal frequencies.

Although several experimental research regarding the surface wave characteristics have been performed, the wavelength and frequency of the surface wave on conical liquid film have not been investigated systematically. The relation between the proper orthogonal modes and the surface wave has not been clarified clearly even though the POD technology has been introduced to analyze the spray structure. In the present study, the instantaneous spray image was obtained with a high speed camera. The wavelength and frequency of the surface wave are calculated with the proper orthogonal decomposition (POD) technology instead of the direct measurement method. The relation between the proper orthogonal modes and the surface wave is analyzed. The effects of injection condition on the surface wave characteristics are also included and analyzed systematically.

## 2. Experimental methods

### 2.1. Experimental facilities

As depicted in Fig. 1, the experimental apparatus is composed of a propellants feed system, a pressure swirl injector, a spray collector and a Photron Fastcam SA-Z camera. Non-reactive spray experiments were conducted at atmospheric pressure, with filtered water supplied through a pressurized feed system. A pressure sensor with an accuracy of 0.5% FS was used to measure the pressure in liquid manifold, and the full scale output for the pressure sensor is 5 MPa. Liquid mass flow rate was measured by a turbine flowmeter with an accuracy of 0.5% FS. The full scale output for the turbine flowmeter is 4 $m^3/h$, namely the accuracy of the turbine flowmeter for water is 5.6 g/s. When the liquid mass flow rate decreased beyond the measurement rage of the turbine flowmeter, the mass flow rate was measured by a calibrated venturi. The pressure at the inlet of the venturi was measured by a pressure sensor with an accuracy of 0.5% FS, and the full scale output for the pressure sensor is also 5 MPa.

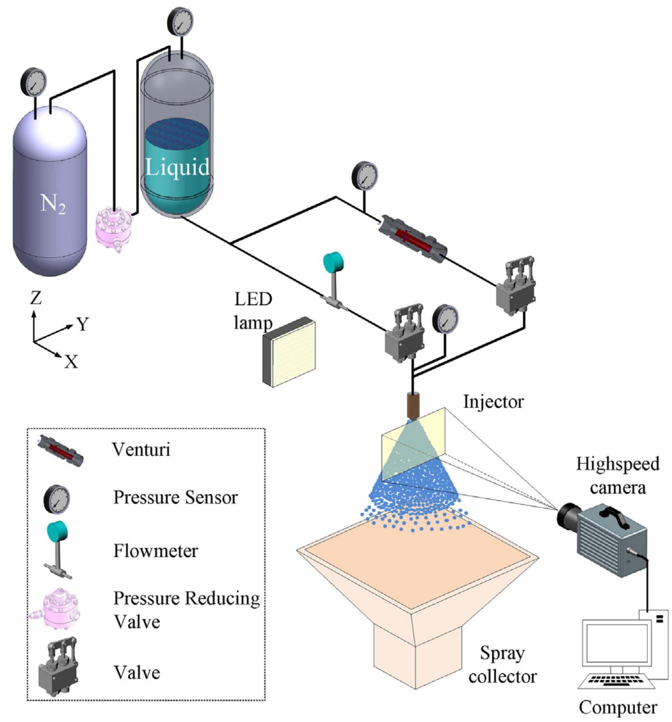


**Fig. 1.** Experimental facilities and setup.

Schematic of the pressure swirl injector is featured in Fig. 2. The pressure swirl injector has the same configuration as the injector of Kang et al. [12,13,27], which adopts four tangential entries, located every 90°, to form a swirl motion of the liquid. A conical liquid sheet at the injector exit and a gas core in the injector are produced with the centrifugal effect. Key sizes are listed in Table 1.

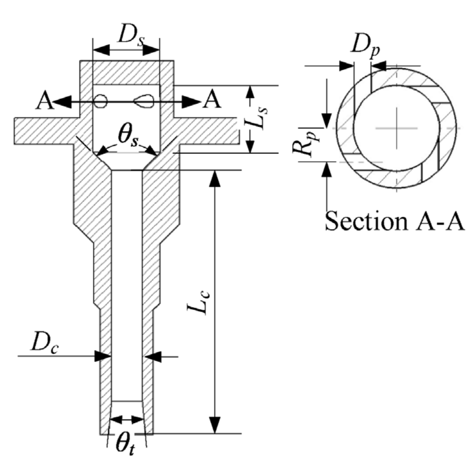


**Fig. 2.** Schematic of the GLSC injector.