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Full Length Article

Experimental investigation of the atomization behavior of ethanol and kerosene in acoustic fields

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HIGHLIGHTS

- Small droplets easily followed the propaganda direction of the acoustic disturbance.
- The main flow of the spray followed a trend toward the side without speaker.
- The presence of the acoustic field affected more on the spray of ethanol than that of kerosene.
- Smaller droplets are more sensitive to the pressure fluctuation.

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ABSTRACT

Working conditions of advanced aircraft engines are developing from conventional to ultra-conventional conditions, and it should enhance the basic research on the atomization and combustion of the aviation fuel. Combustion instability leads severe vibration to the engine combustion device and even the entire system, and it also causes significant damage to the system components. The fuel atomization and evaporation is the controlling process of combustion rate, and it is an important mechanism of the combustion instability. This paper is planned to experimentally measure the spatial fuel atomization characteristics in an environment of acoustic field by high-speed imaging. Using multi-threshold image processing to analyze the effect of the high frequency oscillation on the fuel break-up, mixing mechanism during each stage of the fuel atomization, to explore the physical description and thermodynamic control mechanism of fuel droplet atmospheric environment, to illustrate how the acoustic excitation influences atomization characteristics of the fuels under different conditions, so as to find a way for a controlled operation of such sprays or droplets.

1. Introduction

Working conditions of advanced aircraft engines are developing from conventional to ultra-conventional conditions, in order to further promote the development of aircraft engines, and it should enhance the fundamental research on the atomization and combustion of the aviation fuel and related key technologies. Combustion instability leads severe vibration to the engine combustion equipment and even the entire system, and it also causes significant damage to the system components. The atomization and evaporation is the controlling process of the fuel combustion rate, and it is an important mechanism of the combustion instability [1].

Combustion instability has been considered as one of the most important but difficult problems in the development of engines [2]. According to the current common understanding of the combustion instabilities, the turbulent combustion in the aircraft engine causes acoustic oscillations, and the propagation and reflection of the pressure wave interacts with the heat release in a fixed geometry of the combustion chamber. Until now, many researchers have carried out a large number of experiments and numerical simulation on the study of combustion instability [3], and have obtained some important results. For example, by changing the dynamic characteristics of the supply system, increasing the fuel injection pressure, adjusting the volume of the combustion chamber, and adding acoustic damping devices to solve the problem of low frequency combustion instability. However, theoretical issues concerning the mechanism of intermediate frequency and high frequency combustion instability excitation of aircraft engines are still required to be solved.

In the combustion chamber of the aircraft engine, the aviation kerosene requires forming dense suspended droplets through

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Nomenclature

Symbol	Definition, Unit
d_e	exit orifice diameter, m
DAQ	data acquisition
I	image graysacle intensity
N	number of pixels
TH	threshold value
Z	vertical coordinate, m
Θ	half spray angle, °

atomization, and then evaporating and combust, and there is a time delay between the fuel injection into the combustion chamber and the start of combustion. The combustion system tends to be unstable and generates pressure oscillation when this delay is in the specific region to meet the Rayleigh criterion. According to the pressure fluctuation frequency, the combustion instability in the aircraft engine can be divided into low frequency instability, intermediate frequency instability and high frequency instability. The combustion instability with high frequency (>1000 Hz) is caused by the acoustic response of the continuous turbulent fluctuation within the small geometry of the combustion chamber, although the energy of which is relatively low, it still cannot be ignored.

In 1997, Dubey et al. [4] experimentally investigated the effect of the acoustic field on the combustion characteristics of an ethanol spray flame by phase-Doppler particle analyzer (PDA) in a Rijke-tube combustor. The acoustic field is sinusoidal and controlled in the combustor with a frequency of 80 Hz and a sound pressure level of 155 dB. Experiments were performed to study the effect of oscillations on the Sauter mean diameters (SMD), droplet number density, and droplet velocity for the oscillating and non-oscillating operating conditions of the Rijke-tube combustor. The SMD of the ethanol spray decreased by 15% with the existence of the acoustic field due to the enhanced evaporation. In 1998, McQuay et al. [5] analyzed the influence of variable acoustic fields on the evaporation characteristics of a nonreacting ethanol spray in a vertical tube by PDA. Droplet diameters decreased between 13% and 31%, where the sound pressure level was 150 dB and the frequencies were 54 Hz, 106 Hz and162 Hz. In 2005, Sujith [6] investigated the influence of axial acoustic fields on air-atomized ethanol sprays. They showed that a high-amplitude acoustic field (160 dB) reduced the penetration length of the spray. The spray velocity domain was mapped by particle image velocimetry (PIV) measurements. The spray velocities were greatly reduced with the existence of the acoustic field, which indicated the droplets were smaller compared to those without acoustic oscillation. Also, the presence of acoustic oscillations increased the spray cone angle, when there was considerable entrainment of air into the spray with the presence of acoustic fields. They concluded that the acoustic velocity primarily affected the spray characteristics rather than the acoustic pressure. Gajan et al. [7] implemented the phase-averaged technique to analyze the air velocity field and flow pattern oscillations for the spray produced by an airblast atomizer. The spray showed a droplet density wave formed mainly with smaller droplets. This wave had two origins: the first was linked to the atomization process and the second was from the transportation of droplets by the oscillating airflow. The presence of this wave played an essential role in the pressure and heat release coupling which was the source of combustion instabilities. Gurubaran et al. [8] experimentally investigated the distilled water spray – swirl – acoustic interactions. They found that the existence of a swirl flow field greatly altered the characteristics of water spray. In the presence of acoustic fields, the phase averaged droplet diameter variation was larger at the axial locations compared with the off axis locations. The phase averaged axial velocity variation of the droplets was higher compared to those of phase averaged radial and tangential velocities with in an acoustic cycle. Periodic grouping of droplets in the spray field is observed with the existence of acoustic field. In the process of fuel atomization, due to the small droplet size, the frequency of the unstable wave on the fluid surface is high during the breakup process, whose coupling degree is low with the medium and low frequency of the acoustic excitation. Based on this principle, Eckstein et al. [9] implemented small disturbance linearization processing method to analyze the drop size distribution under the steady state, and they obtained the instability characteristics of the combustion chamber under the disturbance of low frequency acoustic disturbance and the predicted results similar to the experimental results. Therefore, the real impact on the excitation frequency of the liquid fuel atomization and evaporation should be the high-frequency oscillation which is corresponding with the droplet size. Choutapalli [10] experimentally studied the effect of Strouhal number on the flow field of a turbulent pulsed jet with the Reynolds number varied from 0.97×10^5 to 3.25×10^5, they concluded that the thrust of the free pulsed jet was increased with increasing the Strouhal number of primary jet.

However, most of these studies have focused on a single droplet or the ethanol spray interacting with an acoustic field whose frequency is lower than 1 k Hz and little is found in the literature that takes into account the interaction of a full spray of kerosene with an acoustic field. This study is planned to experimentally analyze the atomization characteristics of aviation kerosene in an environment of pressure oscillation with the acoustic excitation frequency larger than 1 k Hz, with comparisons to those of ethanol. Using multi-threshold image processing to analyze the effect of the high frequency oscillation on the fuel break-up, mixing mechanism during each stage of the fuel atomization, to illustrate how the acoustic excitation influences atomization characteristics of the fuels under different conditions, so as to find a way for a controlled operation of such sprays or droplets.

2. Experimental setup and methodology

This section introduces the spray visualization system consisting of the fuel injection facility and acoustic generation system, and it also explains the multi-threshold algorithm for the image analysis to characterize the fuel spray.

2.1. Spray visualization system setup

An experimental setup of the fuel injection, acoustic generation and spray visualization facility is shown in Fig. 1. In the fuel injection system, a 1.0L stainless steel sample cylinder with a working pressure of 15 MPa is adopted as the fuel container, which is equipped with a pressure gauge and a pressure relief valve to display and control the gas pressure (injection pressure) inside the cylinder. The fuel (ethanol or kerosene) is injected by the pump (HONGSEN JS-320) into the sample cylinder. A 40L high pressure nitrogen vessel is connected to provide constant pressure inside the sample cylinder to mimic the fuel injection pressure. In practice, a 10L stainless steel cylinder is connected to the high pressure nitrogen vessel as a pressure stabilizer to reduce the pressure fluc-