ARTICLE IN PRESS

Chinese Journal of Aeronautics, (2018), **xxx**(xx): xxx–xxx

Chinese Society of Aeronautics and Astronautics
& Beihang University

Chinese Journal of Aeronautics

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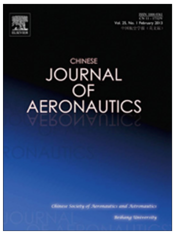

Periodic atomization characteristics of simplex swirl injector induced by klystron effect

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Received 15 March 2017; revised 19 September 2017; accepted 1 November 2017

KEYWORDS

Atomization;
Combustion stability;
Klystron effect;
Liquid rocket engine;
Simplex swirl injector

Abstract The atomization dynamic characteristics of a simplex swirl injector was investigated experimentally by using a hydrodynamic mechanical pulsator and the shadow photography technique. The frequency response characteristics of the fluid film and atomization fluctuations and their correlations with pressure fluctuations were obtained by using an in-house code of image processing. It is demonstrated that the klystron effect induced by periodic pressure fluctuations results in periodic liquid film fluctuation with large amplitudes, periodic superposition of droplets and reduction of the breakup length. It was found that the atomization of the simplex swirl injector only responds to the pressure fluctuation in frequency range approximately from 0 to 300 Hz, and it is particularly sensitive to pressure fluctuations at frequencies from 100 to 200 Hz. According to this experiment, the responsive frequency limitation is merely affected by injector configuration, rather than the supply line.

1. Introduction

Combustion instabilities generated by the coupling of heat release and acoustic pressure in the combustor are very complicated and dangerous phenomena in rocket engines. This problem is particularly troublesome in rocket engines, because it interrupts original energy supplies, generates undesired intense pressure fluctuations, and leads to excessive heat that transfers to combustor walls and injector plates. Although tremendous human, material, and time resources have been invested by many countries since the 1940s to determine ways to manage this problem,[1,2] because of the complexity of the problem, the generally inaccessible environment of the rocket engine combustion chamber, and the lack of appropriate diagnostic techniques available to study the problem, this problem has not yet been resolved.

It is known that the combustion process can add energy to the system in the occurrence of combustion instabilities. The energy transfer is mathematically expressed in terms of the so-called Rayleigh criterion.[3] According to the Rayleigh criterion, interaction between the combustion heat release and the acoustic field is the strongest if heat is added in a region of space while the pressure fluctuation is being up to the highest.

It should be noted that there are two significant characteristics of pressure fluctuations in the unstable combustion chamber: their large amplitudes and obvious periodicity.[4,5]

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Peer review under responsibility of Editorial Committee of CJA.

Production and hosting by Elsevier

https://doi.org/10.1016/j.cja.2018.02.016
1000-9361

Please cite this article in press as: YANG A et al. Periodic atomization characteristics of simplex swirl injector induced by klystron effect, *Chin J Aeronaut* (2018), https://doi.org/10.1016/j.cja.2018.02.016

That feature could be crucial to understand combustion instabilities, since the combustion heat release needs to be periodic to catch a stable phase angle to the periodic pressure fluctuation, which is required by Rayleigh criterion. Periodicity of combustion heat release in the occurrence of combustion instabilities has been certified in previous literatures experimentally[6,7]and numerically.[8–10] However, there are many other processes in the liquid engine combustion chamber, including injection, atomization, vaporization, mixing and reaction. They all might have an effect on the heat release and might be influenced by pressure fluctuations. Thus, a further question should be asked that whether the other processes also feature the similar periodicity in the occurrence of combustion instabilities.

The best way to find out the answer to this question is to observe all the component processes in rocket engines when combustion instability phenomenon occurs. Unfortunately, any successful observed case does not exist in previous literatures, although Miller et al.[4] achieved strong spontaneous longitudinal instabilities with peak-to-peak amplitudes of 0.69–1.38 MPa in a model combustor without observation.

Another way to examine the feedback of these processes to combustion instabilities is to set up an environment with large oscillations to observe and analyze the dynamic responses of the processes. This environment should approach that of naturally occurring combustion instabilities in real engines.[11] Hardi et al.[12] conducted an experiment in which a condition similar to unstable combustors' was provided. The breakup and atomization behavior of the central LOx jet was characterized using the high-speed shadowgraph imaging. There was not evident periodicity displayed by injection or atomization in their experiment. Nevertheless, there are three differences between their experiment and the spontaneous combustion instability cases. First, in their experiment, the large acoustic oscillations were excited by a toothed exciter wheel rather than the heat release. Second, the injectors allocated near the pressure node and velocity antinode were mainly impacted by the transverse acoustic velocity, rather than acoustic pressure. Third, there was only one single acoustic oscillation of approximate 4200 Hz frequency at which the first transverse resonance occurred. Referring to previous studies,[4,13] a specific injector configuration under a specific working condition features a certain limited frequency range in which the combustion instability occurs. For this reason, it is not sure that whether the frequency of 4200 Hz is appropriate to the injectors used in Hardi et al.'s experiment[12] to trigger combustion instabilities. Hence, it is difficult to determine whether the injection and atomization are periodic during a real combustion instability process through Hardi et al.'s experiment.

Among all the component processes in rocket engines, the injection and atomization processes dominate other subsequent processes to a great extent and they are relatively convenient for measurement. A characteristic time analysis was performed by Anderson et al.[13] to identify which component contributes to instability. It was found that atomization processes, such as a jet breakup, had similar time scales to the acoustic time scales associated with resonant frequencies of representative combustion chambers. However, this similarity always exists but does not always lead to combustion instabilities. Besides, there are two obvious differences between the primary atomization frequencies and the acoustic resonance frequencies. First, the primary atomization frequencies are acquired by measuring the distances between two adjacent ligaments ranging from d to $10d$, where d is the injector's orifice diameter. Thus, to the primary atomization, there were not strict frequencies or periodicities which could be identified by FFT analysis. So those primary atomization frequencies could only be regarded as some kind of 'mean frequency'. Second, this 'mean frequency' of primary atomization was about twice the maximum combustion instability frequency predicted by the Hewitt Stability Correlation,[14] although the two frequencies had the similar varying trend with respect to U/d, where U is the jet velocity. Nevertheless, the primary atomization can present strict periodicities if some driver periodically forces it as that is suggested in Santoro et al.'s study.[15] It was also showed that the periodic primary atomization at 5500 Hz frequency which is equal to the maximum combustion instability frequency. This frequency is much lower than the free primary atomization frequency leading to the oscillating chamber pressure of the peak-to-peak 0.138 MPa amplitude. It means that the primary atomization in the unstable combustion chamber features utterly different state from the free primary atomization. Those differences could attribute to injection pressure oscillations of large amplitude. The injection pressure oscillations accompany the flow oscillations that modulate the velocities of the liquid particles with time. Then a large proportion of fluid particles are superposed together at certain point where the liquid particles with high velocities overtake those with low velocities. This phenomenon called the klystron effect was reported in impinging jet injectors[1,16] and swirl injectors.[17,18] Besides, the backpressure oscillation, with the frequency approximating the fundamental frequency of sheet waves, enhances the wave amplitude and the atomization angle, which accelerates the sheet's breakup and decreases the mean size of the droplets downstream of the impingement point.[19]

The stochastic characteristics of the primary atomization frequency are based on the case of unforced turbulent impinging jets. For combustion instability cases, the state of atomization is possibly unusual, since the amplitude of back pressure fluctuations in combustion chambers is always the same order of magnitude as the pressure drop of injectors.[4] In that case, the effect of back pressure fluctuations on injection and atomization should not be neglected. Nevertheless, this effect has not been investigated systematically.

In some particular cases, injection and atomization could present periodic characteristics due to self-pulsations that might originate from the feed lines or the hydraulic and aerodynamic instabilities. Bazarov and Yang[18] studied the effect of pressure fluctuations excited by self-pulsations between the feed lines and the injectors on the atomization of the swirl injectors. The self-pulsation characteristics of a gas/liquid swirl coaxial injector were investigated by measuring spray patterns, acoustic characteristics, spray oscillation characteristics, and the self-pulsation boundary under ordinary[20] and high[21] back pressure respectively. However, combustion instabilities caused by self-pulsations can generally be avoided by changing dynamic characteristics of the feed system (such as adding a restrictor ring in the feed line) or limiting working range. Besides, frequencies of combustion instabilities are not always equal to those of self-pulsations just right. Hence, the injection and atomization under extrinsic fluctuations rather than self-pulsations should be paid more attention to.

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