Numerical Study of the acoustic characteristics of the entry diameter gas-liquid coaxial swirling injector

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Abstract. Linear acoustics is adopted to analyze the influence on the entry diameter of the gas inlet orifice on the acoustic damping of the injector. The impedance tube method is used to assess quantitatively damping capacity of entry diameter of the gas inlet in order to find the best structure parameter of the injector. We can draw the conclusion that the acoustic pressure amplitude of the injector entrance can serve as a criterion of the acoustic damping. The entry diameter of gas inlet orifice corresponds to an optimal injector length, but its damping capability remains unchanged.

1. Introduction

The high-frequency instable combustion of the liquid-propellant rocket engine is the interaction result of the release of combustion heat and the acoustic mode in the combustion chamber (Harrje & Reardon, 1972). A lot of research has been carried out, but effective prediction methods have not been established. Clapboards, acoustic cavities, acoustic liners and other devices are still used to dissipate the acoustic energy (Dravnovsky, 2007). Although findings suggest that these devices have good damping capacity (Kim et al., 2004; Nie & Zhuang, 1998), the installation of these devices will impose a negative influence on the performance of the engine.

The acoustic damping effect of the co-axial injector of the liquid-propellant rocket engine has also drawn attention (Yang & William, 1995; Kim & Chae, 2006). Soo Ho Kim et al. studied the influence of the injector's internal structure on the acoustic influence (Soo et al., 2014). ZHANG Mengzheng et al. employed a combustion chamber to conduct an experimental research into the acoustic characteristics of the gas-liquid co-axial injector (ZHANG, 2007); ZHOU Jin adopted the oxy-hydrogen co-axial injector for the acoustic experiment, finding that there is sharp squeal within certain scope of working parameters (ZHOU & HU, 1996). LI Longfei et al. used the simulated combustion chamber to study the influence of the gas-liquid co-axial injector's structure on the instability margin of the high-frequency combustion (WANG & ZHANG, 2012); In these tasks, the injector was proved to be a half-wave resonator which damped out acoustic oscillations effectively when the tuning length is satisfied. In this paper, linear acoustics is adopted to analyze the influence of the entry diameter on the acoustic damping of the injector.

2. The entry diameter of the injector

High-pressure after-burning liquid rocket engine adopts a pre-combustion chamber. The injector of the main combustion chamber is shown in Fig. 1. The high-temperature mixed gas of oxygen and kerosene in the pre-combustor is injected into the main combustion chamber in an axial direction. On the other hand, the temperature of the kerosene rises after going through the cooling channel. Mixed with the co-axial high-temperature oxygen after entering the injector along the circumferential and tangential injector at the end of the injector, it will reach its critical temperature. At the moment, the mixture features dense gas. The whole injector channel is filled with gas. Because of the shape changes of the section diameter within the injector and that the end retracting size is smaller than the feature size of the injector, the sectional changes and the end retracting are omitted. The injector is simplified into the cylinder with the equal internal diameter, which will not impose an essential influence on the injector's acoustic characteristics. In this way, the injector equals to a resonator, which is also called acoustic cavity injector. The gas inlet orifice is located at the entrance of the injector, and the entry diameter may have an effect on the acoustic damping capability of the injector.

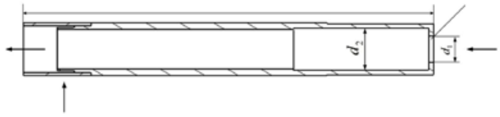


Fig. 1 Gas liquid coaxial injector

3. Numerical methods

3.1 Governing equation.

For a homogeneous and non-dissipative medium, the conventional wave equation is

$$\nabla^2 p' - \frac{1}{c^2}\frac{\partial^2 p'}{\partial t^2} = 0$$

where p´ =pressure fluctuation, c=sound speed in the medium, t=time.

$$\nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}$$

the pressure fluctuation is expressed $p' = p(x,y,z)\cdot e^{jwt}$, then Helmholtz equation is expressed in the form

$$\nabla^2 p(x,y,z) - k^2 p(x,y,z) = 0$$

where w=2π f=the angular frequency, k=w/c=2π f/c=wavenumber (DU et al., 2001).

3.2 Geometric models.

The impedance tube method is used to assess quantitatively damping capacity of entry diameter of the injector gas inlet in order to find the best combination of entry diameter and injector length and to better guide the injector design. The diameter of the resonance tube is 0.08m and the length is 0.12m. The length from the point 1 and point 2 to the outlet of the injector is 0.115m and 0.08m, respectively. The diameter of the injector is 16mm. The combustion region covers the area from the oxidizer manifold to the resonance tube. The number of computational grids is 116179. Through grid-dependency check of the numerical results, this grid system was found to give good accuracy of which error within 2%.

3.3 Calculation procedures.

The acoustic-pressure response is excited by the plane wave acoustic source located on the right of the resonance tube. To consider the boundary condition at wall, boundary absorption coefficient is defined as 0.005, which resulted from the experiment (Kim et al., 2004). The monitoring point 1 and 2 are located on the tube wall. The acoustic pressure amplitude of the two points are P1 and P2 respectively. Sound absorption coefficient is adopted to evaluate the damping capacity of the injector quantitatively.

4. Results and discussion

The diameter of rocket engine combustion chamber is 0.386m, the total mass flow rate of propellants is 0.408kg/s and total mixing ratio of oxidizer to fuel is 2.6. According to thermodynamic calculation, the sound speed in the chamber is 1294.7m/s and Mach number is 0.226. The gas in the real injector is used to be the medium, of which temperature, density and the speed of sound are 657.3K, 458m/s and103.3kg/m3. The 1st tangential mode of the chamber is estimated to be 1915Hz from Eq.(1). According to previous study (Sohn, 2009), the injector can be designed as a half-wave resonator in the acoustic aspect. Pressure oscillations in the combustion chamber can trigger longitudinal oscillations in gas passage of a injector which is applied to design geometric dimensions of gas passage of the injector from Eq.(2). So the length of the injector is calculated to be 119mm from Eq.(3).

$$f_{1T} = \frac{\alpha c_{ch}}{D_{ch}} \sqrt{1 - M_{ch}^2} \qquad (1)$$

$$f_{1L} = f_{1T} = \frac{c_l}{2(l + \Delta l)} \sqrt{1 - M_l^2} \qquad (2)$$

$$l = \frac{c_l}{2 f_{1L}} \sqrt{1 - M_l^2} \qquad (3)$$

where c=the sound speed in the chamber, D_{ch}=chamber diameter, l=injector length, M_{ch}= the Mach number in the chamber, M_l=the Mach number in the injector, f_{1L}=the first longitudinal mode and f_{1T} =the first tangential mode, l=injector length, $\triangle l$ =correction value.

4.1 Analysis of the acoustic damping of the entry diameter of the standard length.

Standard length refers to the injector length generally used by the rocket motor. In order to maximally damp the acoustic oscillation, the length is about half of the first-order longitudinal acoustic modal wave-length of the injector. The entry diameter ($n=d_1^2/d_2^2$) is defined as the ratio of the diameter square of the orifice to the inner diameter of the injector to study the influence on the acoustic damping capability of the injector. With the increase of the entry diameter of the injector, the sound absorption coefficient of the injector strengthens gradually (See Fig. 2). Meanwhile, it can be seen that the amplitude of the injector entrance decreases along with the increase of the entry diameter. From Fig. 3, it can be seen that the trend of acoustic pressure and the sound absorption coefficient of the injector entrance shows good consistence, which suggests that the acoustic amplitude of the injector entrance can serve as a criterion of the acoustic damping of the injector. This is different from findings of the literature review (Soo et al., 2014 & Sohn, 2009). We can see that, with the increase of the entry diameter of the injector, the acoustic pressure amplitude node of the injector exit moves outside the injector and lengthens the wave-length of the internal acoustic wave of the injector. The acoustic pressure of the injector entrance generates a correlation effect, so the oscillation amplitude decreases gradually.

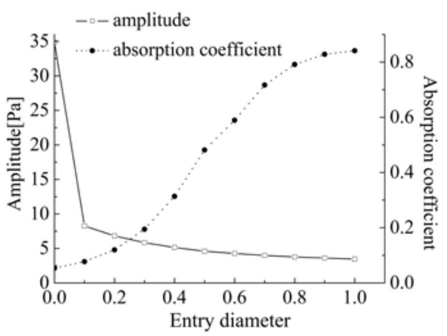
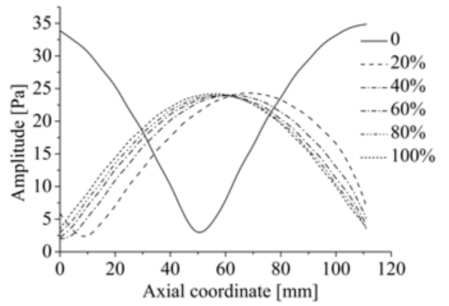
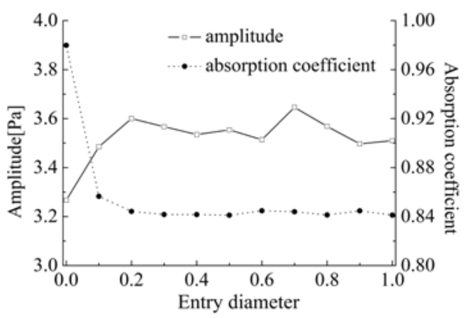
	

Figure 2. Effect of entry diameter on the amplitude and absorption coefficient	Figure 3. Different opening rate amplitude variations in the axial direction

4.2 Analysis of the acoustic damping of entry diameter of the optimal length.

The optimal length refers to an injector length when the damping capability is the greatest at the frequency of 1915Hz under certain entry diameter. The influencing of the entry diameter on the optimal length and damping capability of the injector is analyzed. Results show that every entry diameter corresponds to an optimal injector length. Besides, with the increase of the entry diameter, the increase rate of the optimal injector length gradually slows down. After the entry diameter exceeds 50%, the optimal growth rate of the injector quickly decreases. From Fig. 4, it can be seen that the variation trend of the acoustic pressure amplitude of the injector exit and the sound absorption coefficient along with the entry diameter shows consistence, suggesting that the acoustic pressure amplitude of the injector exit can serve as a criterion of damping capability. Through further analysis, when the entry diameter of the injector exceeds 20%, the acoustic pressure amplitude and the sound absorption coefficient basically remain the same. Therefore, the entry diameter of the injector should exceed 20%. As show in Fig. 5, when the entry diameter exceeds 20%, the internal acoustic pressure amplitude of the injector stays the same between the injector exit and the middle. This explains why the sound absorption coefficient remains the same. Therefore, with the increase of the entry diameter of the injector, when the entry diameter of the injector located at the optimal length exceeds 20%, its acoustic damping capability remains the same as a half-wave tube. During the design of the injector, the entry diameter should exceed 20% and the length should meet the respective optimal length.



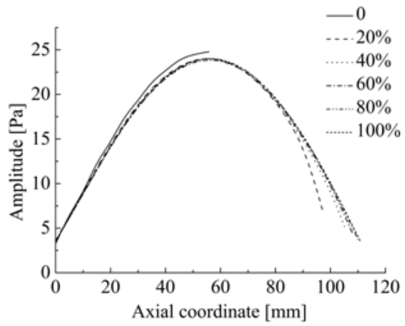


Figure 4. Effect of entry diameter on the amplitude and absorption coefficient	Figure 5. Different opening rate amplitude variations in the axial direction

5. Summary

By using linear acoustics to study the injector, we can draw a conclusion that: under the standard length, the damping capability of the injector strengthens gradually along with the increase of the entry diameter. The acoustic pressure amplitude of the injector entrance can serve as a criterion of the acoustic damping capability. Different entry diameter corresponds to different optimal length, which increases along with the increase of the entry diameter, but the injector's damping capability basically remains the same. The acoustic pressure amplitude of the injector exit can serve as a criterion of the acoustic damping capability.

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