Research Note

Off-Design Combustion in Liquid-Propellant Rocket Engine with High-Frequency Instability*

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1. Introduction

High-frequency combustion instability is one of the traditional problems of liquid-propellant rocket engines. It damages and melts the engines instantaneously. Related phenomena such as injection, mixing, vaporization and combustion have been studied to elucidate the mechanism of instability.^{1–9)} It is revealed that the characteristic time of reaction is significantly shorter than that of high-frequency instability and that of vaporization is on the same order of magnitude.¹⁰⁾ The instability is divided into a transverse mode and a longitudinal mode. The longitudinal mode was analyzed,¹¹⁾ and will not cause serious damage to engines. Though it is caused by the transverse mode, the mechanism of energy transfer from combustion to vibration and the mechanism of the cyclic motion of the instability are still unclear and unidentified.

Most liquid-propellant rocket engines utilize an impinging-jet injector or a coaxial/concentric injector to supply propellants. For both injection methods, a base space is formed on the faceplate, as shown in Fig. 1, surrounded by the propellant jets and fans.^{12,13)} The base space connects each other and forms a corridor on the faceplate. The base space is filled with vapor and droplets of propellant. However, the combustion chamber is not designed to burn propellant in this space.

If combustion progresses in the base space under a high-pressure condition, the faceplate will melt easily. This paper introduces the concept of a high-frequency combustion instability mechanism using the off-design combustion, which can seriously damage the engines. Herein, the off-design combustion is used as combustion in the base space shown in Fig. 1. The characteristic time related to the off-design combustion is estimated to judge whether or not the combustion can be a cause of the high-frequency instability.

2. Off-Design Combustion

Table 1 shows the injection and instability conditions of some engines.^{3,7,9)} Typical injection styles (i.e., concentric and impinging injections) and propellants are selected. Δp_{p-p}

Fig. 1. Schematic of off-design combustion.

is the pressure change from peak to peak. There are variations in Δp_{p-p} and frequencies. In concentric injectors, the oxidizer injector is inside of the fuel injector and the diameter of the fuel injector, D_f , is larger than that, D_o , of the oxidizer injector. Pitch or spacing between the injectors are on the order of magnitude of 10 mm.

2.1. Mechanism of pressure change

The proposed mechanism of the high-frequency pressure change resulting from the off-design combustion is as follows.

(1) Injected propellant merges and forms the fan and mixing region. This region has large inertia and behaves like a wall for gas in the base space because the density of the fluid in the region is larger than that of the gas in the base space. In addition, the volume or thickness of the region is larger than that of the base space. For example, in the F-1 engine, the thickness of the mixing region is roughly three times larger than that of the base space.⁴⁾

(2) Ignition of mixture in the base space initiates the off-design combustion. For example, flame is anchored to the injectors.¹⁴⁾ The combustion flame will propagate in the corridor of the base space.

(3) Pressure increases due to the off-design combustion in the base space. The volume of the base space is almost constant during combustion because of the short characteristic time of the reaction and the large inertia of the fan and mixing region.

(4) When pressure in the base space becomes higher than that in the propellant manifold, propellant supply to the combustion chamber stops.

(5) The high pressure in the base space cause the propellant fan and mixing region to move, and the off-design com-

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Table 1. Injection and instability conditions.

	Fuel	Oxygen	p_c , MPa	Δp_{p-p} , MPa	Freq., kHz	Injection style	D_f , mm	D_o , mm	Spacing, mm
NASA Lewis	H ₂	O ₂	2.07	1	1.5, 3–3.5, 3.8, 5	Concentric	3.6	1.3	11.6
F-1	RP-1	O ₂	7.76	12	0.44–0.54	Like impinging	7.14	6.15	11
JPL	Aniline/Furfuryl alcohol	Nitric acid	2.07	1.1–10	1.8–3.5	Unlike impinging	2.5	4.4	30

bustion gas flows out. The pressure in the base space decreases as the gas flows out.

(6) After pressure in the base space becomes lower than that in the propellant manifold, propellant is injected into the combustion chamber again, filling the base space with propellant vapor and droplets. After sufficient vaporization and mixing, the off-design combustion starts again.

In the above scenario, the mixture in the base space is ignited by the anchored flame. Ignition may be attained other ways; for example, a hanging-down combustion flame from the primary combustion region.

2.2. Characteristic time of off-design combustion gas

Here, the characteristic time related to the off-design combustion is estimated. Once the off-design combustion initiates, high pressure in the base space, p_b , pushes the propellant fan and mixing region. The force acting on the region is the product of a difference between p_b and chamber pressure of p_c and a surface area. The motion of the region is discussed as a unit volume here. The pitch between the injector elements, l , shown in Fig. 1, is used as a reference length. Then, using the reference length of l , the surface area pushed by $(p_b - p_c)$ is represented by l^2 . The volume of the mixing region to be moved is represented by l^3 . Then, the acceleration of the propellant mass in the mixing region, a_p , is

$$a_p \approx C_1 \cdot (p_b - p_c) / (\rho_p \cdot l) \quad (1)$$

ρ_p is propellant density, and C_1 is a constant. The motion of the region occurs simultaneously in other places.

For the off-design combustion gas to flow out of the base space, the propellant fan and mixing region must move. When the distance of the region to be moved is represented by l , then

$$a_p t_1^2 / 2 \approx l \quad (2)$$

Then the time from initiation of the off-design combustion to when the fan and mixing region is moved, t_1 , is

$$t_1 \approx l \sqrt{2\rho_p / \{C_1 \cdot (p_b - p_c)\}} \quad (3)$$

When, $l = 0.01$ m, $p_c = 10$ MPa, $p_b = 30$ MPa, $\rho_p = 1000$ kg·s⁻¹, and $C_1 = 1$, then t_1 is 0.1 ms. When the pressure on the injector faceplate becomes higher than that in the propellant manifold, propellant jet stops in the actual engines. The present study estimates characteristic time, therefore the stop time is ignored for simplicity.

Once the propellant fan and mixing region has moved, the off-design combustion gas flows away from the base space. The mass in the base space, m_b , is

$$m_b = C_2 \rho_b l^3 \quad (4)$$

ρ_b is density of the off-design combustion gas, and C_2 is a

constant. The volume of the base space is represented by l^3 . When the off-design combustion gas in the base space flows out at sonic speed, u_{bs} , flow-out time, t_2 , is

$$t_2 \approx \frac{m_b}{\rho_{bs} u_{bs} A_{bs}} = C_2 l \{(\gamma + 1)/2\}^{\frac{\gamma+1}{2(\gamma-1)}} / \sqrt{\gamma R_b T_b} \quad (5)$$

Here, the flow-out cross-section, A_{bs} , is represented by l^2 . The gas constant of the off-design combustion gas, R_b , is 400 J·kg⁻¹·K⁻¹, and the ratio of the specific heat, γ , is 1.3, which refers to the combustion condition of RP-1/LOX at O/F = 1.6.¹⁾ When the temperature in the base space, T_b , is 1000 K and C_2 is 1, then t_2 is 0.02 ms. The sum of t_1 and t_2 is 0.12 ms. C_1 and C_2 are specified using experimental results.

In addition to t_1 and t_2 , the time required for mixing and vaporizing the propellant is required to complete a cycle. Though it is longer than the time required for a reaction, the time required for vaporization is within the characteristic time of the high-frequency instability.¹⁰⁾ Therefore, the characteristic time caused by the off-design combustion will be less than 1 ms and within the time of the high-frequency instability listed in Table 1.

3. Conclusion

This paper introduces the idea that the mechanism for the high-frequency instability in liquid rocket engines is the off-design combustion progressing between the face-plate and the propellants injected. The characteristic time related to the off-design combustion is within that of the high-frequency combustion instability. Therefore, the off-design combustion can be a cause of the instability.

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