Experiental ivestiatin of liui oxygen / CH_4 coaxil spray and fla e stabiiatin*

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Abstract Experimental investigation of cryogenic reactive coaxial sprays with liquid oxygen as oxidizer and gaseous methane as fuel was conducted in DLR Lampoldshausen, Germany. The sprays and the flames were investigated by visualization methods such as shadowgraphy and imaging the flame emission. The atomization and flame stabilization at different chamber pressures and injection dimensionless numbers, such as Weber number (We) and momentum flux ratio J-number, are discussed. It is shown that combustion pressure affects the jet atomisation appearance and the flame stabilization significantly. Increasing chamber pressure favors the flame anchoring close to the injection plane. No correlation between flame liftoff distance and Weber number or injection velocity has been found in this study. The liquid oxygen intact core length decreases with increasing gase-to-liquid momentum flux ratio. Atomization has significant effect on LOX / CH_4 coaxial flame stabilization.

Key words Liquid oxygen / methane+; Atomization; Flame stability; Optical diagnosis; Test

液氧 /甲烷同轴喷雾及火焰稳定的试验

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摘 要: 介绍了液氧和气态甲烷的低温同轴喷雾燃烧试验, 试验使用了光学诊断方法如阴影法和火焰分光光谱法记录了试验中的喷雾和火焰信息, 讨论了不同燃烧室压力和喷注无量纲数如韦伯数 (We) 和气液动量流率比下的雾化和火焰稳定情况。试验结果表明, 燃烧室压力对射流雾化和火焰稳定有显著影响, 增加燃烧室压力有利于火焰稳定于靠近喷注器面的地方, 研究中没有发现火焰吹离距离和韦伯数之间有明显的关系式。液氧射流核心长度随气液动量流率比的增大而下降。雾化质量对液氧 /甲烷同轴喷雾的火焰稳定性有明显的影响。

关键词: 液氧甲烷+; 雾化; 火焰稳定性; 光学诊断; 试验
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1 Introduction

There has been a particular interest of methane as a promising green propellant for rocket propulsion. The atomization and combustion characteristics of LOX / CH_4 propellant combination have been studied to exploit the potentialities. Spray combustion can be characterized by three processes as vaporization, mixing and chemical reaction processes. In most engine systems, the vaporization time is at the order of 1~10 ms, turbulent mixing time is about 0.1~1 ms and the chemical reaction time is only at the order of microseconds[1]. Vaporization of liquid propellant appears as the controlling process in spray combustion and vaporization process in turn is governed by atomization.

For atomization characterization of a shear coaxial injector, which is the typical injection element for cryogenic propellant combustion such as LOX / H_2 and LOX /

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CH_4, the non-dimensional numbers mainly used are the relative gaseous Weber number (We) and the gaseous to liquid momentum flux ratio J, defined by $We = \rho_g (u_g - u_l)^2 d_l / \sigma$ and $J = \rho_g u_g^2 / (\rho_l u_l^2)$. Weber number compares the aerodynamic force with the surface tension force acting on the liquid jet[2,3]. The size of droplets formed by coaxial atomizers is mainly controlled by Weber number. Sprays at higher Weber number can get smaller mean droplet size. Decrease in droplet diameter can greatly shorten the vaporization time because the vaporization time of a droplet is proportional to the square of the initial droplet diameter[4]. Other parameters such as chamber pressure p_c and gas-to-liquid density ratio have also been found affecting the atomization process[5-7].

Another important issue in non-premixed combustion is flame stabilization. The flame stabilization process has been studied extensively in the case of a gaseous fuel jet injected into an ambient quiescent atmosphere[8]. Cryogenic coaxial injector configuration differs in some notable ways from the previous gaseous fuel injection. The oxygen is injected as a liquid jet at cryogenic temperature, and then it requires breaking up into droplets and needs energy for vaporization. The oxygen jet from the central tube is at low speed while the coaxial fuel flows at high speed. So a low-velocity recirculation zone, which is essential for flame stabilization, may occur around the low speed central region, as shown in Fig. 1. For coaxial spray flame of LOX/H_2, it has been found that the flame is always anchored to the recirculation zone immediately after the liquid oxygen injector rim[5,6,9-11]. However, in this study it has also been observed for LOX/CH_4 at some conditions that a flame stands off at a distance from the injector plane and is anchored in the turbulent mixing layer of evaporated oxygen and gaseous fuel. Therefore LOX/CH_4 hot tests have been conducted at different combustion chamber pressures and Weber numbers in order to investigate the effects of injection and work conditions on atomization and flame stabilization. The results are discussed in this paper on the basis of spray and flame images photographed during the hot tests.

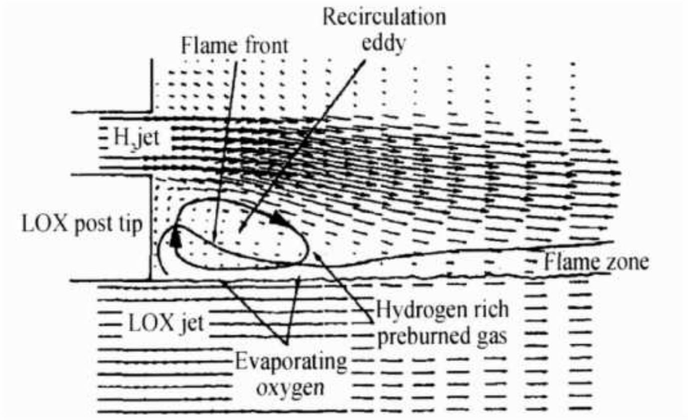


Fig. 1 LOX/H_2 flame stabilization mechanism in ref [9]

2 Experimental setup

The experimental investigation has been performed on the M3 test facility at DLR-Lampoldshausen, Germany. The test bench is equipped with a single-injector combustion chamber with 140 mm × 40 mm quartz windows as optical access for visualizing the spray and flame evolution (see Fig. 2(a)). The injector element is a shear coaxial injector as schematically shown in Fig. 2(b). The liquid oxygen is injected from the central pipe and gaseous CH_4 goes through the annular passage around the LOX post. The LOX pipe and the injector faceplate are changeable to get different dimensions of LOX and methane injection diameter d_l and d_g for achieving desired injection Weber-J number combinations. The LOX pipe thickness t keeps 0.4 mm for all the injector geometries and test conditions of this work for the sake of its effect on flame stabilization.

The methane tank was at ambient temperature and the LOX inlet temperature was 80 K. The combustion was initiated by a torch igniter. The duration for each test was 2 s since the optical windows were uncooled. The combustion chamber pressure investigated was 1.5

'Anchor' means a flame base to stabilize at somewhere. An anchored flame is a flame stabilized near the injector faceplate while a lifted flame stabilized at a distance downstream from the injection plane. A flame angle refers to the expansion angle in which the flame expands from the flame base to a wide flame region, as shown in Fig. 3. A jet breaks up means a continuous intact liquid core starts to disintegrate into discontinuous liquid blobs.

MPa, 3 MPa, 5 MPa respectively but the propellant mixture ratio in the combustor kept around 3.4. There was a convergent nozzle at the exit of the combustor (see Fig. 2(a)) to maintain the chamber pressures at steady combustion state and thus the p_c changed with the mass flow rate of propellant supply. We = 500~30 000, J = 0.2~2.0. There were at least two tests for one condition to check the experimental reproducibility.

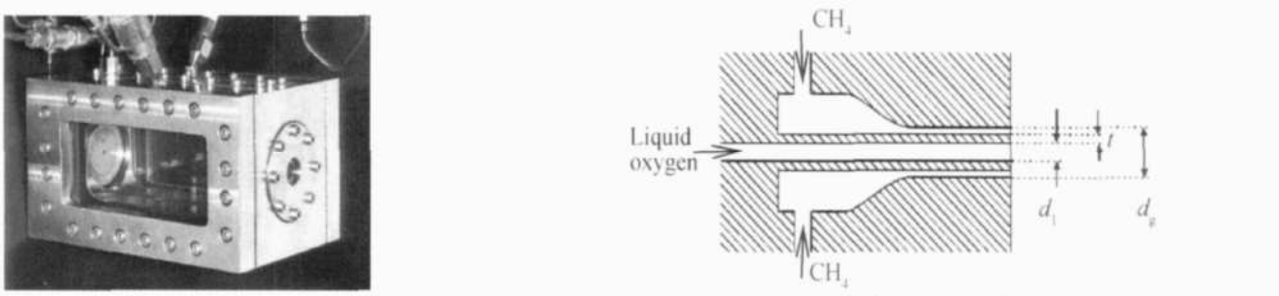
The detailed test conditions discussed in this paper were listed in Table 1. In order to investigate the effect of chamber pressure, test Case 1 and Case 2 were at similar Weber-J number combinations but the chamber pressure changed from 0.15 MPa to 0.3 MPa. The propellant mass flow rates increased at 0.3 MPa chamber pressure and the injector diameter d_1 had also to be changed correspondingly in order to achieve similar injection Weber-J numbers at different pressures.

When the chamber pressure kept unchanged, the injection We could be increased via changing injector dimensions too, Case 1 and Case 3 at 0.15 MPa for instance. In Case 4 for example, smaller outer diameter d_g of gaseous annular slit than that of Case 2 brought higher Weber number and relative velocity at 0.3 MPa pressure. Therefore the effect of We and other injection conditions on atomization and flame could be examined.

Test Case 5 was listed to show the results at 0.5 MPa combustion pressure. The propellant mass flow rates needed for 0.5 MPa were much higher than those at 0.15 MPa and 0.3 MPa, in consequence no similar injection We could be obtained in the case.

A high-resolution shadowgraph setup was used for recording the liquid oxygen spray information. The Kodak Flowmaster 2 K camera recorded the images at 0.055 mm/pixel high spatial resolution but only 4 frames/second acquisition rate. The shadowgraph image size was about 95 mm × 30 mm. The flow field was frozen by means of a back light from a nanolite with an 18ns flash duration in order to eliminate possible image blurring of high-velocity droplets because of long camera shutter time.

Flame evolution was visualized with an intensified high-speed CCD camera in a 9 kHz acquisition rate and a 256 × 128 pixel resolution. The camera was fitted with a UV lens and a narrow band filter (300~310 nm, the radiation band of OH radical in the flame) to record the OH radical emission during the combustion process. The OH emission image size was about 140 mm × 40 mm.



(a) The M3 Combustor (b) Sketch of the coaxial injector

Fig 2 Combustor and injector of LOX/CH_4 spray combustion tests

Table 1 Test conditions

Test case	p_c/MPa	We	J	d_1/mm	d_g/mm	$\dot{m}_l$/(g/s)	$\dot{m}_g$(g/s)	ρ_g/ρ_l	u_l/(m/s)	(u_g-u_l)/(m/s)	Re_l	Re_g
1	0.15	7260	0.47	1.4	5.7	23.7	7.0	8.0×10^{-4}	12.8	296.2	76 400	92 880
2	0.3	8417	0.46	1.6	5.7	31.9	9.4	16.1×10^{-4}	13.2	209.8	89 840	126 570
3	0.15	12504	0.79	1.4	5.0	23.7	7.0	8.0×10^{-4}	12.8	388.2	76 400	96 550
4	0.3	15747	0.84	1.6	5.0	31.9	9.4	16.1×10^{-4}	13.2	286.8	89 840	134 230
5	0.5	24593	0.51	1.6	5.0	52.6	15.5	26.8×10^{-4}	21.7	276.3	146 440	222 130

3 Results and discussion

3.1 Effect of combustion chamber pressure

The LOX/CH_4 coaxial spray flame has been found to be easily lifted off at low combustion pressure, i. e. 0.15 MPa chamber pressure. The flame does not stabilize in the recirculation zone close to the LOX pipe tip, as consistently observed for LOX/H_2 flame[5, 6, 9-11]. The LOX/CH_4 flame is lifted from the injector face plane and anchors in the mixing layer of gaseous oxygen and methane far downstream from the injector surface (see Fig. 3(a), Fig. 4). Figure 3 shows the photographed flame contours and the flame colors are related with the radiation intensity of OH radicals in the flame zone. Figure 4 mainly shows the liquid oxygen jet information. The flame is also visible in the shadowgraph image due to the Schlieren effect. The distance from the flame base to the injector exit is about 8 times of the liquid oxygen post diameter at the condition of test Case 1.

Fig. 3 Averaged OH emission images of LOX/CH_4 flame

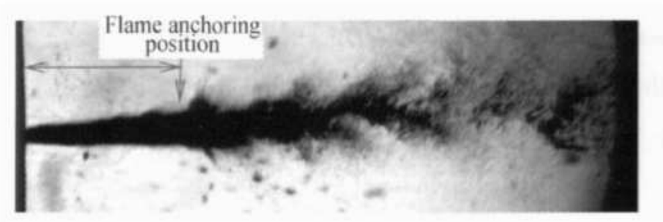


Fig. 4 Shadowgraph image of the reactive spray of test Case 1 with a lifted flame

Fig. 5 Spray and flame stabilization at p_c = 0.3 MPa (test Case 2)

The combustion pressure seems to affect the jet atomization appearance and the flame pattern greatly. In contrast with Case 1 at 0.15 MPa, the spray and flame of Case 2 at 0.3 MPa look very different (See Fig. 3(b) and Fig. 5), though the injection Weber-J numbers are similar in the two cases. The liquid core seems wavier and more droplets and liquid fibres are present than that in Case 1. The most significant difference is that the flame base moves upstream and anchors at the injector rim at 3 MPa.

When the combustion pressure raises up to 0.5 MPa, the flame anchoring position does not show big difference compared with that of 0.3 MPa (See Case 5 in Fig. 6). The flame at 0.5 MPa appears to be attached close to the injector exit. The liquid spray, however, seems rather different comparing with liquid jet at lower pressures. **Although the intact liquid core breaks up rather early, there is a long wavy liquid core till outside** of the image scope. The liquid core is surrounded by dense tiny droplet cloud and big droplets gradually become more clearly visible with the propagation of the liquid jet as the tiny droplets in the cloud are being consumed in the combustion process. Liquid lumps instead of clear liquid ligaments and fibers are visible in the illuminated region of the images. This may be due to the supply of much more liquid oxygen, i. e. higher liquid mass flow rate at 0.5 MPa.

One theory about the lift-off of a turbulent non-premixed flame has been proposed, that is, the position of the lifted flame concerns the matching between the local flow velocity at the position near stoichiometic ratio

Fig 6 Shadowgraph images of LOX/CH_4 at 0.5 MPa pressure (test Case 5)

contour and the turbulent burning velocity of a premixed flame[3,8]. Then the flame anchoring position mainly depends on where the stoichiometic ratio achieves and the comparison of the flow velocity and the turbulent burning velocity at that position.

Fig. 7 shows a typical spray pattern for a lifted LOX/CH_4 flame. A schematic diagram (see Fig 8) of the flame stabilization of LOX/CH_4 coaxial sprays is speculated based on images like Fig 7. Although there is similar recirculation wake in the near field of the injector as what is shown in Fig 1 for LOX/H_2, the low burning velocity of CH_4 cannot match the flow velocity near stoichiometic contour as H_2 does (laminar flame velocity 3.93 m/s for CH_4 and 10.7 m/s for H_2 at ambient conditions [12]). Another possible reason might be the narrow flammability limits of CH_4 (5.1% ~ 61% volume percent, in contrast with the 4% ~ 94% limits for H_2 [12]). Even if there is one point in the near field where the stoichiometic gaseous mixture of methane and vaporized oxygen is ignited, the narrow flammability region restricts the spread of the flame and the great heat absorption of cryogenic oxygen vaporization may quench the flame. Only at further downstream, the injection velocity rapidly relaxes to a much lower local velocity of the chamber flow and the oxygen vaporization rate is also sufficient to feed the flame, then the flame front can stand at some large turbulent eddies in the mixing layer. The reaction heat release from the flame base greatly increases the evaporation rate of oxygen thus a sudden expansion of dense oxygen immediately after the flame anchoring position can be seen from all the images with a lifted flame (shown as Fig 7).

The turbulent burning velocity S_T of a premixed flame in reaction-sheet regime, which is a typical engine flame regime, may be related to the laminar flame velocity S_L as $S_T/S_L = 3.5(v'_{rms}/S_L)^{0.7}$, where v'_{rms} is the root-mean-square flow fluctuating velocity[3]. The S_L was experimentally found to be proportional to $p_c^{-0.5}$[3], then the S_T may be related with p_c as $S_T \propto (v'_{rms})^{0.7} \cdot p_c^{-0.15}$. The Reynolds number at higher pressure is higher but the mean velocity in the combustion chamber becomes less. Then it might be reasonable to assume the pressure does not affect v'_{rms} greatly as it is the product of turbulent intensity and mean velocity. So the turbulent flame velocity S_T may not change obviously with combustion pressure at the test conditions of this study.

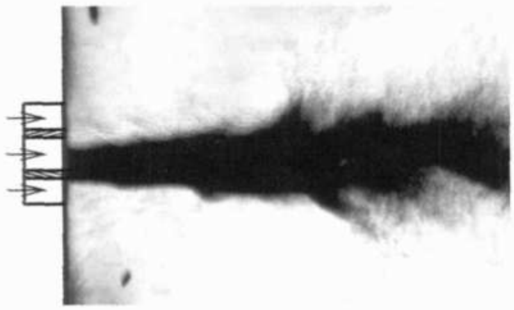


Fig. 7 Detail of the spray pattern from the injector to flame anchoring position for a lifted LOX/CH_4 flame

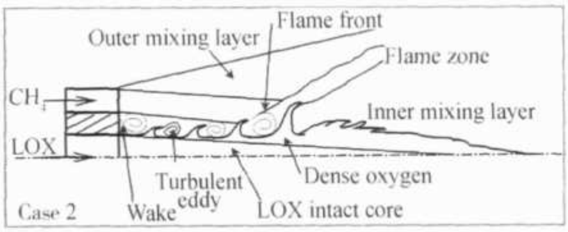


Fig. 8 Speculated schematic diagram of coaxial sprays and lifted flame of LOX/CH_4

The injection relative velocity between gas and liquid, however, is much lower at higher pressure if the injection Weber numbers are similar, Case 1 and 2 for instance. The injector exit flow velocities are about 35% ~ 40% lower at 0.3 MPa pressure but the oxygen vaporization rate might be similar because of similar Weber numbers. Thus it is possible at 0.3 MPa that the turbulent flame velocity can match the flow velocity in a thick enough region to resist flame quenching in the injector wake.

The p_c effect of above test results is coincident with the result derived by Juniper[13] from numerical investigations. A ratio, $\Phi = t/\delta_f$, of LOX pipe thickness t and the laminar flame thickness δ_f is considered as a control parameter for flame stabilization. A flame is easy to be anchored when the ratio is large ($\Phi > 1$). Considering flame thickness $\delta_f \propto \alpha / S_L = kRT / (p_c C_p S_L) \propto p_c^{-0.5}$ as $S_L \propto p_c^{-0.5}$, p_c increase can result in smaller flame thickness and thus greater thickness ratio Φ, which favors the flame anchoring.

3.2 Effect of injection conditions

When the injection nondimensional numbers, Weber-J numbers, are increased, the atomization appearance changes to some extent (See Case 3 at 0.15 MPa and Case 4 at 0.3 MPa in Fig. 9). The shorter intact liquid core and finer droplets are present at higher Weber and J numbers. Droplets are discernible in a wider region and thus bigger flame angle is also observed.

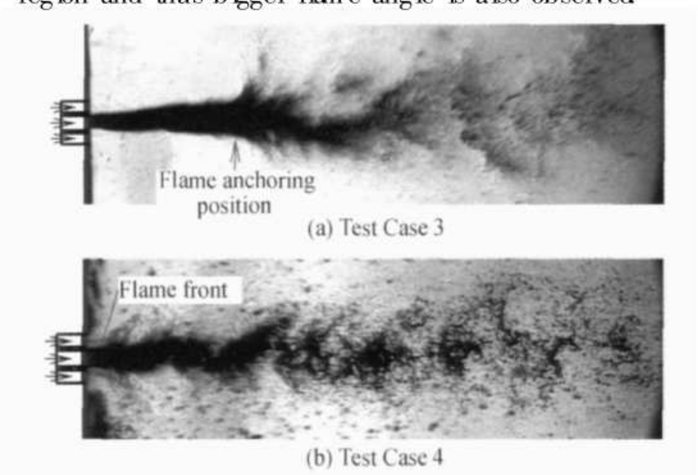


Fig. 9 Spray and flame stabilization at higher Weber and J- numbers

Flame stabilization, however, does not show obvious change correspondingly. The flame at 0.15 MPa is lifted off far from the injection plane again but the flame at 0.3 MPa is observed to anchor close to the injector as it occurs at lower Weber and J-numbers. And the flame lift-off distance does not change obviously with the Weber number or injection velocity too, Case 1 and Case 3 for instance. The reason may be although high injection velocity has the tendency to lift the flame off from the injection plane, high Weber number also favours the oxygen atomization and vaporization and thus favours the flame anchoring upstream (Note: Injection Weber number is proportional to the square of the injection velocity). The opposite effects of injection velocity and Weber number on flame stabilization may counteract with each other so a direct correlation of flame lift-off distance with Weber number or injection velocity cannot be obtained.

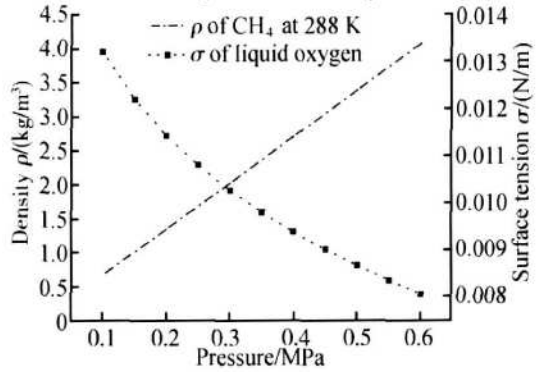


Fig 10 Thermal properties of LOX and CH_4

When relative injection velocities are similar, as shown in Case 1, Case 4 and Case 5, the flame stabilization patterns change when the combustion pressure and We increase. The flame anchors near the injector plane in Case 4 and Case 5. Greater oxygen vaporization rate due to high We at higher pressure may help the flame to propagate more upstream in the oxygen-lean mixing layer and to sustain the flame in the near injector field. As pressure increases, the density of the coaxial gaseous CH_4 increases and the surface tension of liquid oxygen decreases (see Fig 11)[14]. Then the We is much greater at higher pressure although the exit relative velocities are similar.

The liquid intact core length has been found to be mainly controlled by the gas-to-liquid momentum flux ratio J and is decreasing with the increasing J[7, 15-17]. The intact core lengths of liquid oxygen evaluated from the shadowgraph images are shown in Fig. 11 corresponding to the five tests cases discussed above. The intact core lengths in this study agree with above results except the test Case 2 at 0.3 MPa.

There are at least two tests for one condition and four images per test. The standard deviation of the core length from the mean at a condition is also shown in Fig 11. The great deviation mainly comes from the liquid jet pulsation itself during the disintegration process according to the data statistic analysis of Yang et al[12]. Compared to the effect on flame stabilization, chamber pressure does not show obvious impact on the intact core length of liquid oxygen. At higher pressure, the length shows greater deviation than that at 0.15 MPa.

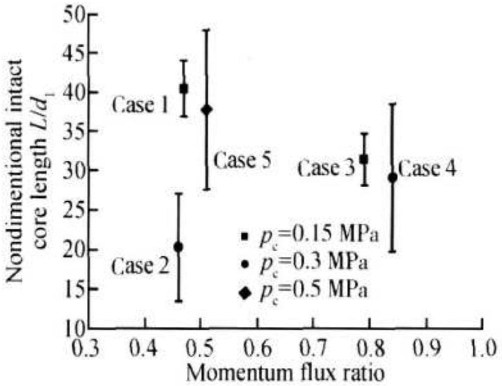


Fig. 11 Liquid intact core lengths of the five test cases

4 Conclusions

The atomization and flame stabilization of LOX/CH_4 reactive coaxial spray at different chamber pressures and Weber numbers are discussed in this paper. It is shown that combustion pressure affects the jet atomization appearance and the flame stabilization significantly. The LOX/CH_4 flame is prone to lift at 0.15 MPa. Increasing chamber pressure helps the flame anchor close to the injection plane. No correlation between flame lift-off distance and the Weber number or injection velocity has been found in this study. The liquid oxygen intact core length shows inverse relationship with the gaseous-liquid momentum flux ratio. Atomization has significant effect on flame stabilization. The chamber pressure affects flame stabilization mainly because it affects atomization quality by means of its effect on density, surface tension, injection velocity and Weber number.

References

[1] Snyder R, Herding G, Rolon J, et al. Analysis of flame patterns in cryogenic propellant combustion [J]. *Combust Sci and Tech.*, 1997, 124: 331~370.

[2] Lefebvre A H. Atomization and spray[M]. *London: Taylor & Francis*, 1989.

[3] Chigier N, Reitz R. Rigimes of jet breakup and breakup mechanisms; recent advances in spray combustion[M]. *Edited by Kuo K. Progress in Astronautics and Aeronautics, AIAA*, 1995.

[4] Turns S R. An introduction to combustion: concepts and applications (2nd ed) [M]. *Singapore: McGraw-Hill Companies*, 2000.

[5] Mayer W, Schik A, Vielle B, et al. Atomization and breakup of cryogenic propellant under high-pressure subcritical and supercritical condition[J]. *J. of Propulsion and Power*, 1998, 14(5): 835~842.

[6] Mayer W, Ivancic B, Schik A, et al. Propellant atomization and ignition phenomena in LOX/GH_2 rocket combustors[J]. *J. of Propulsion and Power*, 2001, 17(4): 794~799.

[7] Porcheron E, Carreau J L, Prevost L, et al. Effect of injection gas density on coaxial liquid jet atomization[J]. *Atomization and Sprays*, 2002, 12(1~3): 209~227.

[8] Burgess C P, Lawn C J. The premixture model of turbulent burning to describe lifted jet flames[J]. *Combustion and Flame*, 1999, 119: 95~108.

[9] Mayer W, Schik A, Schäffler M. Injection and mixing processes in high-pressure liquid oxygen/gaseous hydrogen rocket combustors[J]. *J. of Propulsion and Power*, 2000, 16(5): 823~828.

[10] Herding G, Snyder R, Scouflaire P, et al. Flame stabilization in cryogenic propellant combustion[C]. *26th Symposium (International) on Combustion*, 1996.

[11] Candel S, Herding G, Synder R, et al. Experimental investigation of shear coaxial cryogenic jet flames[J]. *J. of Propulsion and Power*, 1998, 14(5).

[12] Coward H F, Jones G W. Limits of flammability of gases and vapors[M]. *US Bulletin 503, Bureau of Mines*, 1952.

[13] Juniper M, Candel S. Edge diffusion flame stabilization behind a step over a liquid reactant[J]. *J. of Propulsion and Power*, 2003, 19(3): 332~341.

[14] Younglove B A, Ely J F. Thermophysical properties of fluids Ⓣ[J]. *J. Phys. Chem. Ref. Data*, 1987, 16(4): 577~598.

[15] Yang B, Cuoco F, Oschwald M. Atomization and flames in LOX/H_2 and LOX/CH_4 spray combustion[J]. *J. of Propulsion and Power*, 2007, 23(4): 763~771.

[16] Lasheras J C, Villermaux E, Hopfinger E J. Break-up and atomization of a round water jet by a high-speed annular air jet[J]. *J. of Fluid Mechanics*, 1998, 357: 351~379.

[17] Davis D W. On the behavior of a shear-coaxial jet, spanning sub-to super-critical pressures, with and without an externally imposed transverse acoustic field [D]. *The Pennsylvania State University*, 2006.

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