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# Study on atomization and combustion characteristics of LOX/methane pintle injectors

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## ABSTRACT

Influences of main structural parameters of the LOX/methane pintle injectors on atomization cone angles and combustion performances were studied by experiments and numerical simulation respectively. In addition, improvement was brought up to the structure of the pintle injectors and combustion flow fields of two different pintle engines were obtained. The results indicate that, with increase of the gas-liquid mass flow ratio, the atomization cone angle decreases. In the condition of the same gas-liquid mass flow ratio, as the thickness of the LOX-injection gap grows bigger, the atomization cone angle becomes smaller. In the opposite, when the half cone angle of the LOX-injection gap grows bigger, the atomization cone angle becomes bigger. Moreover, owing to the viscous effects of the pintle tip, with increase of the 'skip distance', the atomization cone angle gets larger. Two big recirculation zones in the combustor lead to combustion stability of the pintle engines. When the value of the non-dimensional 'skip distance' is near 1, the combustion efficiency of the pintle engines is the highest. Additionally, pintle engines with LOX injected in quadrangular slots can acquire better mixing efficiency of the propellants and higher combustion efficiency as the gas methane can pass through the adjacent slots. However, the annular-channel type of pintle injectors has an 'enclosed' area near the pintle tip which has a great negative influence on the combustion efficiency.

## 1. Introduction

Toxic propellants are used frequently in modern space activities. Through decades of continuing development, the toxic propellant rocket engines can achieve high performance. However, the toxicology and corrosiveness of the propellants lead to many problems, like high costs and environmental pollution [1]. Non-toxic propellants have the advantages of environment-friendly, high safety, good maintainability and low cost, etc. With enhancement of people's awareness of environmental protection and rapid development of astronautical technology, using non-toxic propellants in space vehicles begins to be an inexorable trend. Development of green propellants depends on two characteristics: high performance and low cost [2]. Many researches had been conducted to figure out the possibility of methane being used in rocket engines. The results indicate that methane has the advantages of safety, low cost, low corrosiveness [3], high cooling performance [4] low carbon deposition [5]. Additionally, Masters A I et.al pointed out that methane can overcome the weakness of low specific impulse of kerosene and low density of hydrogen, but has both the advantages of them [6]. Thus, rocket engines using liquid oxygen (LOX) and methane in combination as propellants developed rapidly under that background [7–10].

On the other hand, Goddard R H had raised the necessity of controlling the thrust of rocket engines in early 20th century. There are two basic ways to control the thrust of rocket engines, one of which is to control the thrust itself, and the other is to control the duration of the thrust. To control the thrust itself, the most important way is to control the mass flow rate of the propellants. Although the mass flow rate varies from different injection pressure-drop of the propellants, it is difficult to achieve high thrust variation or high performance by this manner, as the combustion efficiency can be significantly affected by the injection pressure-drop. Therefore, one practicable way is to alter the area of the injection channel of the injectors in order to maintain constant injection pressure-drop. Thus, pintle injectors, which use a removable component named 'needle' to alter the area of injection channel in order to change the mass flow rate of both oxidizer and fuel, were applied widely, especially in Apollo project [11,12]. Pintle injectors, originating from experiments at the Caltech Jet Propulsion Laboratory (JPL) in 1957, were once used to characterize the reaction rates of candidate rocket propellants [13]. Then, after improvement of

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**Nomenclature**

| | |
|---|---|
| $\pi$ | Pi |
| LOX | Liquid Oxygen |
| $\dot{m}_{CH4}$ | Mass flow rate of gaseous methane, kg/s |
| $\dot{m}_{LOX}$ | Mass flow rate of liquid oxygen, kg/s |
| $L_s$ | Length of needle in combustor or ‘skip distance’, mm |
| $D_{fo}$ | Outside diameter of methane channel, mm |
| $D_p$ | Outside diameter of pintle tip, mm |
| $L_s/D_p$ | Non-dimensional ‘skip distance’ |
| $D_{pi}$ | Inside diameter of needle, mm |
| $h_o$ | Thickness of LOX-injection gap, mm |
| $\alpha_o$ | Half cone angle of LOX-injection gap, ° |
| $L_c$ | Cylindrical section length of combustor, mm |
| $D_c$ | Diameter of combustor, mm |
| $D_t$ | Diameter of nozzle throat, mm |
| $L^*$ | Characteristic length of combustor, m |
| $N$ | Number of quadrangular slots |
| $\delta_o$ | Circumferential size of quadrangular slots, mm |
| $L_o$ | Axial size of quadrangular slots, mm |
| $BF$ | Blockage Factor, $BF = (N\delta_o)/(\pi D_p)$ |
| $\eta$ | Combustion efficiency |
| $C^*$ | Characteristic velocity, m/s |
| $C_{th}$ | Theoretical characteristic velocity, m/s |
| $P_{c,s}$ | Stagnation pressure in the combustor, Pa |
| $A_t$ | Throat area, mm$^2$ |
| SMD | Sauter Mean Diameter, μm |
| TMR | Total Momentum Ratio |
| R-R distribution | Rosin-Rammler distribution |

the structure, pintle injectors have the characteristics of deep throttling, fast response and ‘face shut off’ [14]. Over 60 different pintle engines have been developed at least to the point of hot fire characterization testing in TRW (Thompson-Ramo-Wooldridge Inc.) and over 130 bipropellant engines using pintle injectors have flown successfully [15]. In addition, pintle injectors were used in gel propellants tactical missiles [16] and cryogenic propellants rocket engines [17–23].

However, fundamental research about pintle injectors is little. The conical liquid sheet of the pintle injectors is more stable if the inner face of the injection channel is longer than the outer face [24]. Numerical simulation results about inner flow process of the pintle injectors, which have been demonstrated by experiments [25], indicate that manufacturing process tolerance has a great influence on flow state of the conical liquid sheet in the exit of the injectors [26]. Moreover, effects of environmental pressure, gas-liquid momentum ratio and Weber number on atomization characteristics of the pintle injectors were studied experimentally [27–29]. The combustion flow fields of the pintle injectors which are important to understand the combustion characteristics of the pintle engines were rarely studied.

In the present study, the influences of main structural parameters of the pintle injectors on atomization cone angles are studied experimentally, and combustion flow fields inside the pintle engines are obtained through numerical simulation. Finally, a comparison of combustion flow fields of two different pintle engines is given to come up with the improved structure of the pintle injectors. The results provide a reference for the structural optimization of the pintle engines.

## 2. Experimental facilities

### 2.1. Experimental platform

The atomization experimental platform used in this research is shown in Fig. 1. The nitrogen resource works as pressurization bottle. Due to bad atomization characteristics of liquid/liquid pintle injectors, the gaseous methane rather than liquid methane was chosen as fuel, mainly because the gaseous methane can improve the atomization characteristics of the pintle injectors. A combination of water and air is selected as simulant of the LOX and gaseous methane respectively. The water and air are marked as simulant No. 1 and No. 2.

The pressure of the simulants is controlled by a gas pressure regulator which is installed in the gas distribution board. The injected water is collected by collecting system and pumped out by the air draft system. The measurement system is independent from the experimental apparatus. A Tamron high speed camera with a lens of Nikon 80–200 mm is used to obtain atomization images in the experiments. The frame frequency in this research is 10,000 f/sand the exposure time is 1/40,000 s. To measure the Sauter Mean Diameter (SMD) distribution of the pintle injectors, the Malvern measurement system is used in the experiments. The SMD distribution results provide references to the inflow parameters of the numerical simulation.

### 2.2. Pintle injector

Fig. 2(a) presents the pintle injector used in the experiments. The pintle injector is mainly composed of installation fixture, pintle, needle and base. The needle can be positioned along the axial direction. It is achieved by replacing the gaskets which have different thickness. There are two pressure sensors in the pintle injectors to measure the injection pressure of the water and air respectively. The pintle and needle form the injection channel of the water, while the base and needle form the injection channel of the air. The physical configuration of the pintle injector is shown in Fig. 2(b).

In the experiments, the total momentum ratio (TMR) is the same between the simulants and the real propellants. The TMR is defined by Eq. (1) in which $\rho$ represents density, $v$ represents velocity and $A$ represents the area of injection channel. The subscript index “g” and “l”

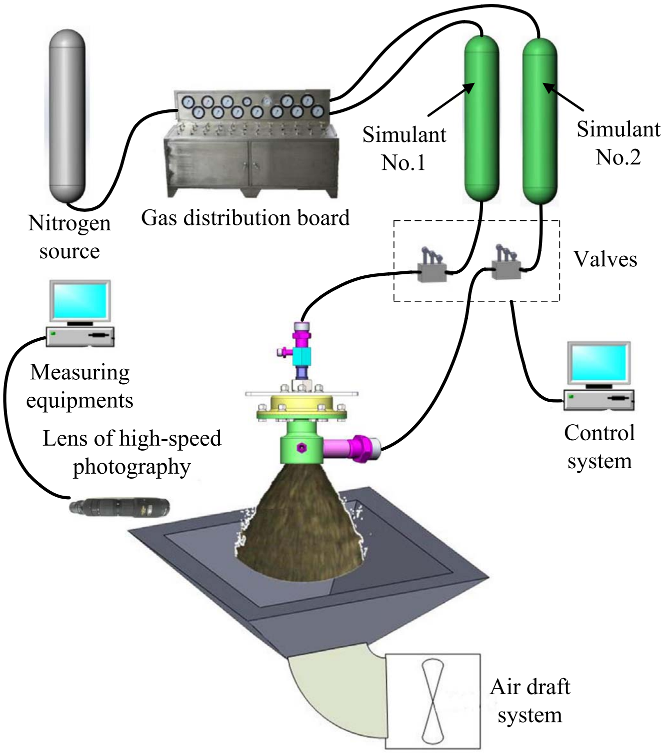

**Fig. 1.** Schematic configuration for experimental platform.