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Review on pressure swirl injector in liquid rocket engine

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ABSTRACT

The pressure swirl injector with tangential inlet ports is widely used in liquid rocket engine. Commonly, this type of pressure swirl injector consists of tangential inlet ports, a swirl chamber, a converging spin chamber, and a discharge orifice. The atomization of the liquid propellants includes the formation of liquid film, primary breakup and secondary atomization. And the back pressure and temperature in the combustion chamber could have great influence on the atomization of the injector. What's more, when the combustion instability occurs, the pressure oscillation could further affects the atomization process. This paper reviewed the primary atomization and the performance of the pressure swirl injector, which include the formation of the conical liquid film, the breakup and atomization characteristics of the conical liquid film, the effects of the rocket engine environment, and the response of the injector and atomization on the pressure oscillation.

1. Introduction

Liquid-propellant rocket engines have been used as the primary propulsion systems in most launch vehicles and spacecraft since the late 1920's [1,2], such as the planet landers and low-cost engines [3]. The performance of liquid rocket engine is determined not only by the propellant selection but also by fuel and oxidizer atomization performance [4,5], evaporation and ignition of droplets [6–8]. The atomization performance of propellants is determined by the injector. And there are many types of injector, for example the liquid centered gas-liquid pintle injector [9,10], liquid-liquid pintle injector [11], liquid centered swirl coaxial injector [12,13], etc.

Pressure swirl injectors are extensively used in liquid rocket engines [14], gas turbine engines [15], internal combustion engines [16,17], and many other combustion applications [18]. The pressure swirl injector can be divided into hollow cone injector [19], solid cone injector [20], and spill-return injector [21]. And the swirling motion of liquid can be formed by either tangential inlet ports [22] or a swirler [19]. In liquid rocket engine, the injector configuration should been as simple as possible to ensure the reliability and stability. Thus the pressure swirl injector with tangential inlet ports is widely used in liquid rocket engine. Commonly, this type of pressure swirl injector consists of tangential inlet ports, a swirl chamber, a converging spin chamber, and a discharge orifice [23], as depicted in Fig. 1. And it can be further divided into converge-end swirl injector and open-end swirl injector based on whether there is a converging spin chamber, as depicted in Fig. 2. The liquid is injected through the tangential ports, forming an air core along the centerline due to high liquid swirl velocity. The liquid flow at the discharge end presumes a hollow conical swirling film. Then the swirling film becomes unstable and breaks up into droplets, as shown in Fig. 1.

The pressure swirl injector is used to atomize the liquid propellants through the formation of liquid film, primary breakup and secondary atomization. Atomization is a process during which the interfacial area of liquid increases gradually because the bulk liquid is transformed into small droplets. So, the evaporation of liquid propellants can be facilitated by atomization significantly. From the energy point of view, atomization is a process during which the potential energy of the supplied liquid finally converts into the needed surface energy, as shown in Fig. 3. Jedelsky and Jicha [21] studied the energy conversion in atomization of a spill-return pressure swirl injector, they found that 58% of the pressure drop converts into the kinetic energy of the rotational motion in the swirl chamber, and the energy loss includes hydraulic loss and friction loss. The kinetic energy of the spray near the injector exit is 32–35% of the inlet energy, which contains the droplet kinetic energy (21–26%) and the entrained air kinetic energy (10–13%). Atomization efficiency is defined as the ratio of surface energy and the inlet energy. It decreases with the increase of pressure drop because the viscous loss increases faster than the surface energy. Commonly, the atomization efficiency is less than 0.3%. For the pressure swirl injector, most of the energy loss occurs in the swirl chamber.

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Nomenclature

A_t	Total area of the tangential ports, m^2
A	Geometry characteristic constant
α	Converge angle of the swirl chamber, deg
β	Spray cone angle, deg
β_r	Spray cone angle at a distance L from the injector exit, deg
C_d	Discharge coefficient
d_l	Ligaments diameter, m
d	Droplet diameter produced by the breakup of the ligaments, m
D_t	Tangential ports diameter, m
D_0	Injector diameter, m
D_s	Swirl chamber diameter, m
D_a	Air core diameter, m
D_{at}	Air core diameter at the tangential inlet, m
ΔP_l	Liquid pressure drop, Pa
η	Small disturbance, m
η_{bu}	Critical amplitude of the disturbance waves, m
η_0	Initial amplitude of the disturbance waves, m
F_s	Centrifugal force, N
F_{scr1}	The critical centrifugal force for judging air core, N
F_{scr2}	The critical centrifugal force for judging stable air core, N
$GSMD$	Global Sauter Mean Diameter, μm
GLR	Gas liquid ratio
γ	Opening coefficients
h	Film thickness, m
h_0	Film thickness at the injector exit, m
h_t	Film thickness at the inlet of the tangential ports, m
K	Injector constant
K_v	Velocity correction coefficient
K_s	Wave number correspond to the maximum growth rate
L_0	Orifice length, m
L_s	Swirl chamber length, m
L_{bu}	Slant breakup length, m
L_v	Vertical breakup length of the conical liquid film, m
λ	Wavelength of the surface wave, m
$\dot{m}_l$	Liquid mass flow rate, kg/s
μ_l	Dynamic viscosity, $Pa{\cdot}s$
ν_l	Kinematic viscosity, m^2/s
ω	Angular frequency of the surface wave, Hz
ω_s	Maximum surface wave growth rate
ω_i	Surface wave growth rate
PDA	Phase doppler anemometry
P_c	Chamber pressure, Pa
Q	Volume flow rate, m^3/s
R	Radius, m
Re	Reynolds number
R_s	Radius of the swirl chamber, m
R_g	Gas constant
R_t	Tangential inlet radius of the injector, m
R_0	Orifice radius of the injector, m
Ro	Rossby number which characterize the ratio of the axial velocity and the rotational velocity
Re_t	Reynolds number at the tangential inlet
Re_{th}	Theoretical Reynolds number of the liquid film at the injector exit
R_{sw}	Swirling radius of the pressure swirl injector, m
ρ_l	Liquid density, kg/m^3
ρ_g	Gas density, kg/m^3
SMD	Sauter Mean Diameter, μm
S_n	Swirl number
σ	Surface tension coefficient
σ_{cr}	Critical pressure ratio
τ_{bu}	Breakup time, s
φ	Filling coefficient
ϑ	Angle of the tangential ports, deg
We	Webber number
We_l	Liquid Webber number
W	Tangential velocity, m/s
W_t	Velocity of the tangential inlet, m/s
X	Dimensionless air core diameter

The operating principle of liquid rocket engine is quite different from other combustion applications, making the operation condition of pressure swirl injector in liquid rocket engine quite different. For example, in automobile engine, the spray is pulse and the pressure drop is really high. And the research focuses on the atomization of biofuel [24–26], secondary injection [27] and the effects of injector geometry [28–30] for energy-saving and emission reduction. However, in liquid rocket engine, the spray is stable, both the pressure drop and the ambient temperature are high. What's more, when throttling process or combustion instability occurs, the pressure drop and chamber pressure will also vary. These characteristics indicate that the liquid propellants could be super critical and the pressure in supply system and combustion chamber could be oscillating.

Although the pressure swir injector has been reviewed before. For example, Vijay et al. [31] reviewed the injector geometrical parameters, fluid properties and operating conditions' influence over the air core stability, breakup length, spray cone angle and Sauter mean diameter. The effects of the rocket operating environments on the atomization mechanism and spray characteristics of the pressure swirl injector has not been summarized before. In this paper, a more comprehensive review on the pressure swirl injector in liquid rocket engine has been conducted. The internal flow characteristics, conical film formation, primary breakup and spray characteristics has been discussed. Then the effects of rocket operating environments on the spray characteristics have been discussed further. These operating environments include back pressure, super critical injection and pressure oscillation.

2. Discussion

2.1. Formation of conical liquid film

In the pressure swirl injector, the liquid is injected through the tangential ports, forming an air core and an annular liquid film along the centerline due to high liquid swirl velocity. Then, the annular liquid film develops into hollow conical swirling film when it flows out of the injector exit. The formation of conical liquid film is strongly related with the internal flow characteristics which includes the air core formation [31], the boundary layer development [23], the film thickness and the growth of the unstable wave at the interface between the gas and liquid, as shown in Fig. 4.

2.1.1. Air core formation

An air core is formed when the centrifugal force of the swirling flow overcomes the viscous force and a low-pressure area near the injector exit is created by the centrifugal motion of liquid within the swirl chamber [23]. The centrifugal force can be calculated by $dF_s = dm\frac{W^2}{r}$, and is proportional with the square of the tangential velocity W. The tangential velocity at a specific radius position W is proportional with the velocity at the tangential inlet ports W_t for the angular momentum conservation $Wr = W_tR_{sw}$. It means that the centrifugal force increases with the increase of the tangential inlet velocity W_t, the tangential inlet Reynolds