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Numerical study on the combustion characteristics of a fuel-centered pintle injector for methane rocket engines

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ABSTRACT

A pintle injector is a movable injector capable of controlling injection area and velocities. Although pintle injectors are not a new concept, they have become more notable due to new applications such as planet landers and low-cost engines. However, there has been little consistent research on pintle injectors because they have many design variations and mechanisms. In particular, simulation studies are required for bipropellant applications. In this study, combustion simulation was conducted using methane and oxygen to determine the effects of injection condition and geometries upon combustion characteristics. Steady and two-dimensional axisymmetric conditions were assumed and a 6-step Jones–Lindstedt mechanism with an eddy-dissipation concept model was used for turbulent kinetic reaction. As a result, the results with wide flame angles showed good combustion performances with a large recirculation under the pintle tip. Under lower mass flow-rate conditions, the combustion performance got worse with lower flame angles. To solve this problem, decreasing the pintle opening distance was very effective and the flame angle recovered. In addition, a specific recirculation zone was observed near the post, suggesting that proper design of the post could increase the combustion performance, while the geometry without a recirculation zone had the poor performance.

1. Introduction

A pintle injector is a kind of variable area injector with a specific moving part for controlling the injection area. Because the injection area and velocity can be controlled optimally at any throttling condition, deep throttling is possible without large losses in combustion efficiency [1,2]. The pintle injector was first developed to use hypergolic propellants and was applied to a moon landing module in the Apollo mission [3,4]. Since its development in the 1950s, the pintle injector has been studied only by a few groups [5–9]. Recently, this technology has gained new attention as a low-cost bipropellant injector that can control large quantities of propellant using only one element [10–12]. There are few publications, whereas the injector has many geometric variations; thus more fundamental studies are required. Two spray experiments have been carried-out by Son, et al. with a center-controlled pintle injector to explain its spray characteristics for a liquid rocket engine under various injection conditions [13,14]. In that study, a unique recirculation zone was observed near the injector post and this recirculation affected the breakup and spray characteristics. Simulation studies of liquid rocket combustion mostly concerned coaxial and swirl injectors [15–18]; for the pintle injector, there have been a few simulation publications. In addition, most researchers focused on hydrogen fuel simulations [19,20]. Betelin et al., validated a integration methodology to overcome stiffness of hydrogen reaction [21]. Smirnov et al. studied accumulation of errors which comes from different simulation methods [22]. They also validated supersonic combustion simulation using acetylene and oxygen mixture [23]. Son et al. [24] tried to verify the two-phase spray using multiphase simulation and Yue et al. [25] conducted combustion simulation of the pintle injector combustion using hypergolic propellants; however, detailed parametric studies using bipropellants have not been performed. In this study, the combustion simulation pintle injector was performed using methane and oxygen. Methane is recently attracted as the rocket fuel because it can be refueled to interplanetary vehicle engine in other planets and there are lots of advantages for reusable engines [26,27]. The simulation was conducted focusing on the effect of a fundamental injection condition with different geometries, especially the recirculation zone near the post. In consequence, a couple of design guidelines for the pintle injector have been suggested based on the simulation results.

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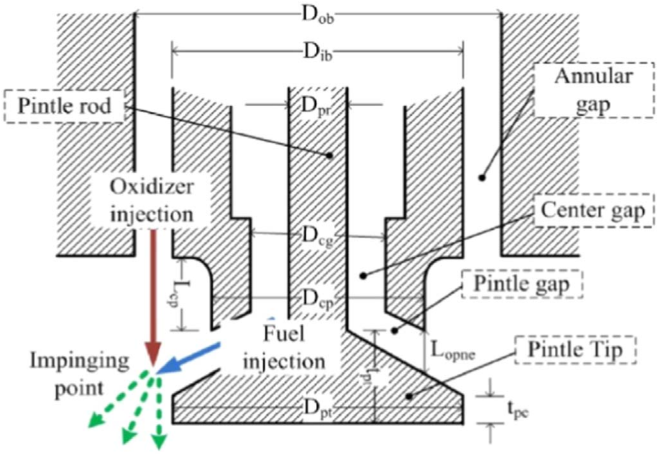

Fig. 1. Schematic of a pintle injector [12].

Table 1
Dimensions of a pintle injector [12].

Outer body diameter, mm	D_{ob}	13.5
Inner body diameter, mm	D_{ib}	12.0
Center gap diameter, mm	D_{cg}	4.0
Center post diameter, mm	D_{cp}	8.0
Pintle rod diameter, mm	D_{pr}	3.0
Pintle tip diameter, mm	D_{pt}	12.0
Center post length, mm	L_{pt}	5.0
Pintle tip thickness, mm	T_{pt}	3.0
Pintle end thickness, mm	T_{pe}	1.0
Pintle opening distance, mm	L_{open}	0.2, 0.6
Pintle tip angle, deg	θ_{pt}	40

2. Numerical methodology

2.1. Numerical method

The configuration of the pintle injector was the same as in the previous study [13]. A schematic of a pintle injector is shown in Fig. 1 with its dimensions in Table 1, and the pintle tip angle was fixed at 40°. A simplified two-dimensional (2D) axisymmetric model of a pintle injector was constructed, as shown in Fig. 2. This model had a throat diameter of 10 mm and the total length of the combustion chamber with the nozzle was 242 mm. The diameter and length of the cylindrical part were 60 mm and 66 mm, respectively. In order to compare the distributions of species in the chamber, four axial points were chosen with a 20-mm-interval based on the pintle tip end. The FLUENT commercial software package was used for the simulation. The flow variables in the computational domain were calculated using the continuity, momentum, and energy equations for 2D axisymmetric geometries. Unstructured grids with quadrilateral cells were used for meshing the model with an average number of 73,000 cells. In the present work, the gaseous methane in the central gap and oxygen in the annular gap were injected as propellants at 300 K. A pressure-based solver was used for steady calculation and a 2D axisymmetric condition was assumed. A standard K-epsilon model, where the standard wall functions as the near-wall treatment, was used for turbulent modeling and the density was calculated by the ideal gas assumption. The boundary conditions of the combustion chamber wall and nozzle were fixed at a constant temperature of 600 K, and the adiabatic condition was assumed for the remaining walls. The pressure-velocity coupled solver was used and spatial discretization was conducted with a second-order upwind method.

Table 2
Jones–Lindstedt mechanism modified by Frassoldati.

Reactions	A	B	Ea (cal /mole)
$CH_4 + 0.5\ O_2 => CO + 2\ H_2$	3.06e10	0.0	30,000
$CH_4/0.50\ /O_2/1.3/$			
$CH_4 + H_2O => CO + 3\ H_2$	3.84e09	0.0	30,000
$CO + H_2O <=> CO_2 + H_2$	2.01e09	0.0	20,000
$H_2 + 0.5\ O_2 <=> H2O$	8.06e16	−1.0	40,000
$H_2/0.3\ /O_2/1.55/$			
$O_2 <=> 2\ O$	1.50e09	0.0	113,000
$H_2O => H+OH$	2.30e22	−3.0	120,000

For the turbulent combustion analysis, an eddy-dissipation concept model (EDC) was applied. In the EDC, the reaction rates were calculated by formulating small-scale eddies in the turbulent flow, which was governed by the turbulent kinetic energy (K) and the turbulent dissipation energy (ε). Generally, the EDC calculates the reaction rate for every reaction individually and is good for predicting the temperature and flame length. Giorgi et al. compared various types of turbulent combustion models for the coaxial rocket injector [28]. They revealed that the numerical results obtained with the EDC were better and numerically cheaper than those obtained with the probability density function method (PDF). Instead of using detailed full-step mechanisms, a reduced Jones–Lindstedt 6-step mechanism (JL6) was used with 6 equations and 9 species, as shown in Table 2. The simulation results of rocket

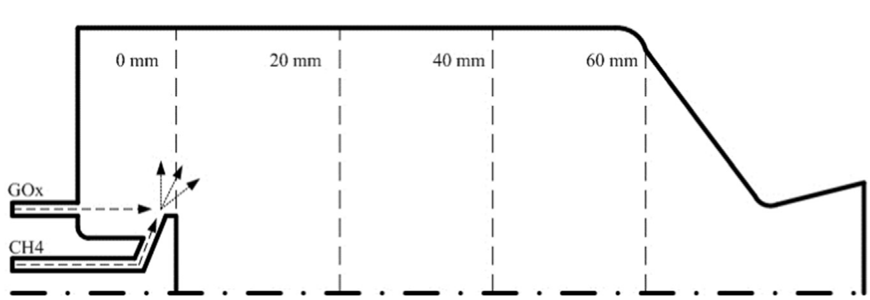

Fig. 2. 2D axisymmetric simulation model.