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Coupled heat transfer analysis of thrust chambers with recessed shear coaxial injectors

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ABSTRACT

To investigate the effects of recessed lengths on combustion performance and heat loads in LOX/methane thrust chambers with shear coaxial injectors, a coupled numerical methodology is developed to solve the combustion and heat transfer in thrust chambers with regenerative cooling. In this methodology, the transcritical turbulent combustion is modeled by a validated non-adiabatic flamelet model considering real-fluid properties; turbulent flows within the thrust chamber and cooling channels are computed by a pressure-based coupled algorithm. The validation indicates that the prediction with detailed chemistry mechanism and the Chung method confirms quantitatively to literature experimental data. The results reveal that the recess causes an increase of wall heat flux in the whole thrust chamber and makes the heat flux peak in the combustion chamber moves downstream. Furthermore, both the heat flux peaks in the combustion chamber and nozzle increase first and then decrease as recessed lengths increase. Meanwhile, chamber pressure, hot-gas temperature, and the averaging heat flux of the combustion chamber wall are positively correlated with recessed lengths. However, the heat loads are more sensitive to the recessed lengths than chamber pressure and hot-gas temperature. Much attention should be paid to the protection of chamber wall.

1. Introduction

To substantially reduce the launch expenditure, many countries have focused on Reusable Launch Vehicle (RLV) for the past several decades [1]. Liquid Rocket Engine (LRE) is regarded as a candidate for the propulsion system of RLV due to mature technology, high thrust, and low cost [2]. The propellant combination of liquid oxygen (LOX) and methane has attracted much attention in recent years because of its advantages over conventional propellant combinations, such as high density specific impulse, non-toxic, and convenient for production [3]. As an essential assembly of LRE, the injector discharging propellants has a great effect on the performance of thrust chambers, including combustion efficiency, combustion stability, and heat loads. Therefore, the determinations of injector types, injector geometries, and injection conditions are crucial in the design of LRE [4].

The shear coaxial injector which has been widely applied to conventional LOX/hydrogen rocket engines [5–9] is considered as an ideal injector type for LOX/methane rocket engines. For the LOX/methane thrust chamber working over supercritical pressures, the transcritical flow behavior of injected oxygen in the near-injector region [10] results in dramatic changes of properties such as density and specific heat capacity even with small changes of temperature and pressure [11]. Many experimental and numerical studies have been published on the mixing, combustion, and heat transfer of LOX/Methane thrust chambers with shear coaxial injectors [12–16]. Singla et al. [17] conducted experimental investigation on transcritical oxygen/supercritical methane combustion and continuous mixing of propellants instead of atomization and vaporization was observed. Kim et al. [10] used a real-fluid flamelet model to study the transcritical flame of a single LOX/Methane shear coaxial injector. They concluded that the mixing and combustion of LOX/methane are greatly influenced by the so-called pseudo-boiling phenomena. In our recent work [18], the heat transfer of combustion and regenerative cooling in LOX/methane thrust chambers with multi-element injectors was solved with a conjugate manner. The proposed method leaded to results more consistent with practical situations than traditional methods, and the results demonstrated that the transcritical flames have a strong influence on the heat flux of combustion chamber wall.

As a key parameter of shear coaxial injectors, the recessed length is defined as the axial distance from LOX post tip to the injector face. Many researchers have studied the role of the recess on the mixing and combustion processes of propellants. Lux and Haidn [19] performed a experimental investigation on the near-injector flame structure and combustion response of a recessed LOX/methane shear coaxial in-

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Nomenclature

D, d	diameter, mm
E	total energy, J/kg
k	turbulence kinetic energy, m^2/s^2
L, l	length, mm
$\dot{m}$	mass flow rate, kg/s
P	pressure, Pa
q	heat flux, W/m^2
T	temperature, K
$\boldsymbol{u}$	velocity vector, m/s
z	axial position, m
ρ	density, kg/m^3
τ	stress tensor, Pa
λ	thermal conductivity, W/(m K)
ε	turbulence energy dissipation rate, 1/s
μ	dynamic viscosity, Pa s
σ	standard deviation

Subscripts

c	combustion chamber
eff	effective value in turbulent flows
F	the fuel stream
O	the oxidizer stream
r	recess
t	turbulent parameter

jector. They found a recessed LOX post led to a smooth combustion. Tani et al. [20] observed that a sufficiently large recessed length of LOX post promoted the mixing of jets at supercritical pressures. Muto et al. [21] performed Large-Eddy Simulations (LES) on a recessed injector to investigate the effect of recess on coaxial jet mixing under supercritical pressure. The results indicated that the mixing improvement was achieved by the recess and effects were dependent on injection conditions. To our knowledge, only a few studies have been published on the combustion, in particular, heat loads of LOX/methane thrust chambers with recessed shear coaxial injectors, which may have a large impact on the performance and lifetime of Reusable LRE. Locke et al. [22] carried out wall heat flux measurements in LOX/methane thrust chambers with recessed shear coaxial injectors. The results suggested that the heat flux levels in the near-injector region with recessed injectors were higher than those with flushed injectors. However, the mechanism of effects were unknown and the authors indicated that CFD simulations would help to explain the wall heat measurements. Ranuzzi et al. [23] performed a CFD simulation of combustion flows for the LOX/methane thrust chamber in [22]. The computed wall heat flux was qualitatively consistent with corresponding experimental data, but the effects of the injector recess on wall heat flux were not discussed.

In this paper, we investigate the effects of recessed lengths on combustion performance and heat loads in high-pressure thrust chambers with shear coaxial injectors of LOX/methane rocket engines. The combustion and heat transfer in regeneratively-cooled thrust chambers with flushed or recessed injectors are solved by an improved coupled numerical methodology. In this methodology, the transcritical LOX/supercritical methane turbulent combustion is simulated by a validated non-adiabatic flamelet model considering real-fluid properties; turbulent flows within the thrust chamber and cooling channels are solved by a pressure-based coupled algorithm. With this methodology, the flow fields and heat loads in the thrust chamber influenced by recesses of different lengths are discussed. The discussion should help to explain how recessed lengths of shear coaxial injectors affect the wall heat flux in the LOX/methane thrust chamber working at supercritical pressures. Consequently, the investigation here may promote the design and optimization of LOX/methane thrust chambers with shear coaxial injectors in industry.

2. Computational methodology

2.1. Governing equations

The flow and heat transfer in the thrust chamber of LRE involve the following three essential processes: (1) the mixing and combustion of propellants and the flow of hot gas, (2) the heat transfer between the hot gas and the inner wall, (3) the heat conduction across the chamber wall. For the thrust chamber with regenerative cooling, the convective heat transfer between the chamber wall and the coolant is also included. The purpose of this paper is to predict the flow fields and heat flux distributions of the thrust chamber during stable operation phase. Because the numerical domain includes a supersonic nozzle and the densities of fluids dramatic change, the flow cannot be assumed as incompressible. Thus, the equations governing the compressible three-dimensional flow involving heat transfer of the hot gas and coolant are the Navier-Stokes equations including conservation equations for mass, momentum, and energy. The mass and momentum conservation equations for the coolant flow and the chemically reacting flow within the thrust chamber can be written as follows:

$$\nabla\cdot(\rho\boldsymbol{u}) = 0 \tag{1}$$

$$\nabla\cdot(\rho u_i\boldsymbol{u}) = -\nabla P + \nabla\cdot\tau_{eff} \tag{2}$$

The conservation of energy for the fluid is described by

$$\nabla\cdot[(\rho E + P)\boldsymbol{u}] = \nabla\cdot[\lambda_{eff}\nabla T - (\tau_{eff}\cdot\boldsymbol{u})] \tag{3}$$

Where λ_{eff} is the effective conductivity, and τ_{eff} is the deviatoric stress tensor. λ_{eff} and τ_{eff} are defined as Eqs. (4) and (5), where λ_t and μ_t are determined according to the turbulence model.

$$\lambda_{eff} = \lambda + \lambda_t \tag{4}$$

$$\tau_{eff} = (\mu + \mu_t)\left(\nabla\boldsymbol{u} + \nabla\boldsymbol{u}^T - \frac{2}{3}\nabla\cdot\boldsymbol{u}I\right) \tag{5}$$

For compressible turbulent flow, Eqs. (1)–(3) should be converted into Favre-averaged Navier-Stokes equations, in which these equations are mass-averaged to regard density fluctuations [24]. For the chamber wall, the heat conduction is governed by a Fourier's equation:

$$\nabla\cdot(\lambda\nabla T) = 0 \tag{6}$$

2.2. Numerical treatments

In general, The flows of the hot gas and the coolant in the thrust chamber of LRE is fully turbulent. The standard $k-\varepsilon$ (SKE) model was coupled to treat turbulent fluid flow because of the trade-off between its accuracy and economy in turbulent combustion modeling [25]. The SKE model is a two-equation turbulence model closing the governing equations by solving the transport equations for turbulence kinetic energy and its dissipation rate. More details for the equations and constants of SKE model can be found in [26]. The turbulent flow and heat transfer in the thrust chamber are significantly impacted by the presence of the chamber wall. Thus, a modified standard wall function approach including the effects of viscous dissipation and wall roughness [27] based on the work in [28] was adopted in the present numerical model to accurately capture the large gradients of solution variables in the near-wall region. This approach uses semi-empirical formulas to link the viscous sublayer and the fully-turbulent layer.