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Near-field flame dynamics of liquid oxygen/kerosene bi-swirl injectors at supercritical conditions

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ABSTRACT

The flame dynamics of liquid bi-swirl injectors are numerically investigated using the large eddy simulation technique. Liquid oxygen (LOX) and kerosene at subcritical temperatures are injected into a supercritical pressure environment. The theoretical framework is based on the full conservation laws and accommodates real-fluid thermodynamics and transport theories over the entire range of fluid states. Turbulence/chemistry interaction is modeled with a laminar flamelet library approach, the validity of which is demonstrated in the present work. The near-field flow and flame characteristics are carefully studied. The flame is anchored in the wake of the inner injector post by two counter-rotating vortices, and further stabilized by center and corner recirculation zones in the downstream region. Differences in the flow patterns between the cold-flow and combustion cases are recognized. Various geometric parameters, including recess region, post thickness, and kerosene annulus width, are examined in depth to explore their influence on flame characteristics. A recess region is found to be necessary to achieve efficient mixing and combustion. The absence of a recess region increases the penetration depth of the kerosene stream in the downstream region and reduces the thermal protection provided to the injector faceplate. On the other hand, a thicker LOX post or a wider kerosene annulus protects the faceplate more efficiently, and introduces larger recirculation zones near the LOX post surface and thus higher flow residence time to better anchor the flame. However, the flame attachment for thicker post and wider annulus induces a stronger heat flux to the post surface, and thus increases the risk of thermal failure of the injector device. The dynamic characteristics of the flame field are also discussed. The flow oscillations within the injector are found to be dominated by a quarter acoustic wave, while the oscillatory field near the injector exit is characterized by vortex shedding. The characteristic frequency of the vortex shedding is similar for different LOX post thicknesses and annulus widths, and is determined by the exit velocity profiles.

1. Introduction

This paper deals with the combustion characteristics of bi-swirl injectors of liquid oxygen (LOX) and kerosene under supercritical conditions typical of contemporary rocket engines. Figure 1 shows schematically the injector considered in the present study, which mimics the bipropellant injectors used in the RD-0110 engine [1]. LOX and kerosene are tangentially introduced into the inner and outer swirlers, respectively. The centrifugal force induces the LOX film to flow along the solid surface of the inner swirler and form a thin liquid sheet, which exits and impinges onto the surrounding kerosene stream in the recess region. The interaction of LOX and kerosene determines the quality of subsequent mixing and combustion process.

Swirl is widely adopted to achieve efficient mixing and combustion in gas-turbine [2,3] and liquid-propellant rocket engines [4,5]. Understanding of the flow and flame dynamics of swirl-stabilized gas turbine combustors has been significantly improved with the implementation of large eddy simulation (LES) over the last few decades [6–9]. Studies of swirl injectors in rocket engines, however, are much less documented. Rocket engines, especially those for the first-stage or booster applications, operate at much higher pressures, often exceeding the critical pressures of propellants, a situation known as supercritical conditions [10]. Such extreme operating conditions pose severe challenges to experimental diagnostics and numerical simulations. Several theoretical [4,11] and numerical studies [12,13] have been conducted to explore various underlying mechanisms dictating flow instabilities in swirl injectors.

Numerous experimental studies have been performed to examine the effects of injector geometry and flow conditions on mixing and combustion characteristics [14–18]. It has been found that an elevation in the chamber pressure increases the liquid film

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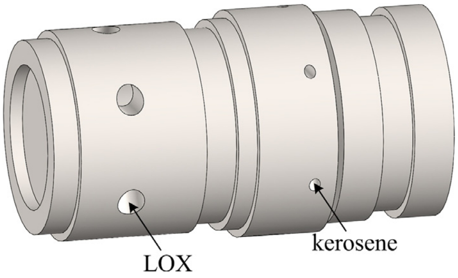

Fig. 1. Bi-swirl injector of liquid oxygen and kerosene.

thickness but decreases the spreading angle [19,20]. Ahn and coworkers [21,22] studied the effect of recess length and pressure on combustion characteristics at both subcritical and supercritical pressures. The discharge coefficient was found to increase with chamber pressure, and decrease with increasing recess length. The presence of a recess region facilitates the interaction of propellants and enhances mixing efficiency. As the recess length increases, the mixing pattern gradually shifts from external to internal mode, improving the propellant interaction and combustion performance.

These investigations provide valuable data, but are not sufficient to gain direct insight into the underlying physics. In particular, optical diagnostics currently available for use in the flame zone do not enable detailed examination of the detailed flow and flame evolution, and especially the flame stabilization mechanisms. The fundamental processes driving combustion instabilities are still not well understood. Other important injector attributes, such as post thickness and annulus width have also not been experimentally examined. A comprehensive study, considering more geometric parameters, is needed to obtain high-fidelity representation of injector flow and combustion dynamics.

An alternative approach is to use advanced numerical tools to illuminate the detailed structures and flow dynamics in swirl injectors. Direct numerical simulations (DNS) resolve all turbulent scales and steep gradient layers, but they are restricted to simple flows with low Reynolds numbers and low density ratios [23,24], and become computationally prohibitive for practical devices with complex geometries and high Reynolds number flows. Although there are still many unresolved issues in modeling unclosed subgrid-scale (SGS) motions [25,26], the LES technique has been widely employed to simulate practical systems at supercritical pressures [27–30], resulting in good agreement with existing experimental data, and is thus employed in the present study.

Wang and Yang [31] recently conducted an LES-based numerical investigation of the combustion characteristics of LOX/kerosene bi-swirl injectors at supercritical conditions, and revealed for the first time the flame stabilization mechanism. The kerosene annulus width was found to significantly affect the flow evolution, and increasing the width may introduce unstable burning in the annulus. Wang et al. [32] explored the effects of injector geometries, including recess length, LOX post thickness, and annulus width, on the LOX/kerosene mixing characteristics. A larger post thickness or annulus width was found to lead to a higher spreading angle of the LOX film and more efficient intersection with the kerosene stream, thereby facilitating propellant mixing in the recess region. Improved mixing efficiency, however, does not guarantee better injector performance; the thermal load on the post surface may increase and in consequence reduce the injector life.

The present paper investigates the flame dynamics of liquid bi-swirl injectors under various geometric conditions using the LES technique. A laminar flamelet approach is implemented to model turbulence/chemistry interaction. The flow and flame evolution in the injector near field is explored extensively. The differences in the flowfield under conditions with and without combustion are examined systematically. The paper is structured as follows: Section 2 summarizes the theoretical and numerical framework; Section 3 describes the numerical setup and flow conditions; and Section 4 presents the results and detailed discussion.

2. Theoretical and numerical formulation

The theoretical basis of the present study is described in Oefelein and Yang [33], which deals with supercritical fluid flows and combustion over the entire range of fluid thermodynamic states of concern. Turbulence closure is achieved using the LES technique. The Smagorinsky eddy viscosity model proposed by Erlebacher et al. [34] is employed to represent the effects of SGS motions. Thermodynamic properties, including density, enthalpy, and specific heat at constant pressure, are evaluated based on fundamental thermodynamic theories and the modified Soave–Redlich–Kwong (SRK) equation of state (EOS) [10]. Transport properties, including thermal conductivity and dynamic viscosity, are estimated using an extended corresponding-state principle. Mass diffusivity is obtained by the Takahashi method calibrated for high-pressure conditions [35]. The evaluation of thermodynamic and transport properties has been validated and implemented in previous studies [10,36–38].

Note that filtering EOS produces an unclosed SGS term, which appears to be negligible for ideal gases and is assumed to be insignificant for most real-gas LES simulations. However, several studies [25,39,40] have shown that this SGS term may be substantial in regions of steep property gradients. Several SGS models were proposed through a priori analysis of the DNS non-reacting database. The extension of the SGS models to reacting flows is, however, still an open question. An alternative approach is to tabulate thermochemistry with a presumed subgrid probability density function (PDF) [41,42], but this has not been thoroughly examined for LES-based simulations. Because of these uncertainties, adding an existing EOS SGS model to the current framework would not necessarily improve the numerical results. Therefore, the filtered density is directly evaluated using the filtered pressure, compressibility factor, and temperature (i.e., $\bar{\rho} = \bar{p}/\tilde{Z}\tilde{R}\tilde{T}$). Modeling of the SGS term and its impact on the filtered density should be explored in the future.

Modeling of turbulence/chemistry interaction remains a critical issue, and an accurate and efficient treatment is yet to be established, even for ideal-gas mixtures. The situation is more challenging for real fluids in the transcritical regime because of thermodynamic nonidealities and transport anomalies [10]. In the present study, both LOX and kerosene are injected at subcritical temperatures and become supercritical in the flame zone. A precise classification of turbulent diffusion flame regimes is still an open question, because diffusion flames do not have well-defined length, time, and velocity scales [43]. The local flame scales depend on local flow conditions. The chemical kinetics of kerosene combustion involve hundreds of species and thousands of elementary reaction steps, rendering direct simulation of detailed chemistry computationally prohibitive.

A steady laminar flamelet model is implemented in the present study. The underlying assumption is that the local Damkohler number ($Da = \tau_f/\tau_c$) is sufficiently large and the chemistry is sufficiently fast to follow the flow changes; τ_f and τ_c denote the local flow time and chemical time, respectively. Unsteady effects and flame extinction occur when Da is low. A priori study showed that the local strain rate in the current flowfield is much smaller than the extinction strain rate ($\sim 10^7$/s at 100 atm) for oxygen/kerosene counterflow diffusion flames [38]. This implies that Da is sufficiently large in the present study to justify the validity of the flamelet model. Instead of solving species transport equations, which encounter stiffness issues due to the range of chemical time