Influence of Pseudo-Boiling Phenomenon and the Mass Flux Ratio on the Dynamics of Transcritical Shear Flame

Hamed Zeinivand,[1] **and Hadi Rezaei.**[2] **Mohammad Farshchi**[1]

1 Aerospace Engineering Department, Sharif University of Technology, Tehran, Iran

2 Iranian Space Research Institute, Tehran, Iran

ABSTRACT

In the present paper, the effects of the interaction of a high-density liquid oxygen jet with a high-velocity hydrogen in the presence of a pseudo-boiling phenomenon are investigated. Pseudo-boiling phenomenon causes a sudden expansion in the flame, which leads to the formation of recirculation zone. Different turbulence models have been investigated and it has been shown that the selection of a suitable turbulence model for the trans-critical reacting flow is much more important than subcritical and supercritical flames. Also, contrary to expectations, the dense core of liquid oxygen disappears faster in the non-reacting case than the reacting flow, which is due to the displacement of the mixing layer in the reacting flow due to the intense expansion (because of the pseudo-boiling phenomenon). The effects of mass flux ratio were also investigated and it was observed that by increasing the mass flux ratio from 5 to 24, a strong recirculation is formed at the flame front and the flame becomes like a bubble, similar to LOX-GCH$_4$ flame. Increasing the mass flux ratio leads to an increase in the strength of the shear layer that causes the pseudo-boiling phenomenon occurring at a higher rate. Finally, increasing conversion of the liquid-like oxygen to gas-like conditions leads to the formation of a strong vortex in the flame front.

KEYWORDS

Cryogenic propellants, Transcritical injection, Pseudo-boiling phenomenon, supercritical combustion

1. Introduction

Cryogenic propellants, used in high performance space propulsion systems, are injected in a liquid-like state at a temperature, which is below their critical temperature, and in an environment, where the pressure exceeds their critical pressure [1]. The propellants are heated to a supercritical temperature before combustion takes place. This process is often referred to as “transcritical injection”, and it is far more complicated than a straightforward supercritical injection and the subsequent combustion process. The largest thermodynamic gradients in the transcritical regime occur as the fluid undergoes a transition from a liquid-like high density fluid to a gas-like low-density fluid when crossing the “pseudo-boiling line” [2]. The pseudo-boiling line is characterized by a local peak in specific heat capacity as well as large gradients in density and transport properties. Due to the anomalous thermodynamic and transport properties of the propellants, the phenomena underlying the transcritical injection and the subsequent combustion are not well-understood. Kim et al. [3] numerically investigated the influence pseudo-boiling phenomenon in GCH_4/LOX transcritical flame. They showed that the pseudo-boiling phenomenon is the main reason for the sudden flame expansion and central flow recirculation. They argued that by increasing inlet temperature or pressure beyond the critical point of liquid oxygen, the pseudo-boiling phenomenon is weakened and the flame becomes longer. The applicability of typical RANS turbulence models, which were developed for gaseous flows, to transcritical and supercritical flows are not well known. To answer this question, we have conducted a detailed study of the influence of several RANS turbulence models to the development of a transcritical flame. On the other hand influence of mass flux ratio of the fuel and oxidizer regarding to pseudo-boiling phenomena has been studied numerically. To validate the present physical and numerical models and study the mixing and combustion processes of the GH2/LOX coaxial jets at supercritical pressures, the RCM-03 A-60 case (Fig.1) has been selected [4].

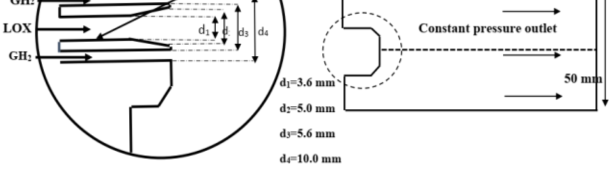

Fig. 1 schematic geometry of injector and chamber of RCM-03

2. Methodology

In the present study three eddy-viscosity turbulence models have been employed to model the Reynolds stress terms in the momentum equation. The Eddy Dissipation Combustion (EDC) model with detailed chemistry has been employed for turbulent combustion modeling. The hydrogen-oxygen chemistry mechanism suggested Li et al. consisting of 19 reversible reactions between eight species has been used for GH_2/LOX and GRI.3.0 kinetic mechanisms has been selected for GCH_4/LOX flame. The Soave-Redlich-Kwong (SRK) equation of state [5] is used for thermodynamic flow properties under supercritical conditions.

$$p = \frac{R_u T}{V - b} - \frac{a(T)}{V^2 + bV} \tag{1}$$

Thermodynamic properties such as enthalpy, internal energy and specific heat can be expressed as the sum of ideal-gas properties at the same temperature and departure functions which take into account the dense-fluid correction. Thus. Transport properties such as the mixture viscosity ($\boldsymbol{\mu}$) and the thermal conductivity ($\boldsymbol{\lambda}$) are determined by the method proposed by Chung et al. based on the Chapman-Enskog theory with a dense-fluid correction. ANSYS FLUENT® software was employed for the analysis. The governing equations are discretized and solved using a second order finite volume method on a staggered grid and a pressure-based coupled algorithm. The second order upwind scheme is used for discretizing convective terms. Pressure-velocity coupling is achieved using SIMPLEC algorithm. Real gas thermophysical properties of the propellants and products embedded in the CFD solver by user defined functions (UDF) during computation. The convergence criterion is set to $\mathbf{1 \times 10^{-5}}$ for all transport variables.

3. Results and Discussions

Comparisons of the present numerical simulation results with available experimental data reveal a reasonably good prediction of a transcritical axial shear hydrogen-oxygen flame using the standard k-ε turbulence model and the eddy dissipation concept combustion model. The standard k-ε model has reasonable agreement with the experimental data, however, the SST k-ω and realizable k-ε models predict a stretched flame with as much as one hundred percent error in prediction of the location of maximum temperature (Fig.2). It is conjectured that not only effects of turbulent mixing, but also the pseudo-boiling phenomenon have influenced the flow field dynamics. The radial heat transfer to the oxygen jet core, generated by the standard k-ε model, provides the appropriate conditions for the massive pseudo-boiling of the liquid-like oxygen core, leading to the sudden expansion of the flame at the vicinity of the maximum turbulent conductivity.

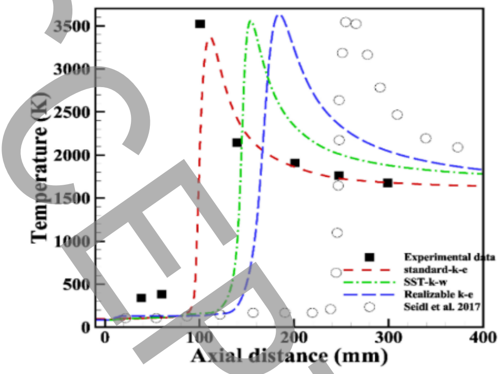

Fig. 2 Axial distribution of temperature along the centerline

In the non-reacting case, the eddy viscosities predicted by the all turbulence models have a very similar behavior (Fig.3). The reason is that in the non-reacting case the high speed hydrogen stream and the low speed oxygen stream form a high velocity gradient shear layer, while in the reacting case expansions caused by pseudo-boiling and chemical reactions push the hydrogen jet away from the centerline toward the chamber corner, causing a drastic drop in the turbulent mixing of the two streams. Hence, in spite of the steep temperature gradients generated by the heat release in the reacting case, the turbulent mixing and heat transfer processes between the co-flowing hydrogen and oxygen streams in the non-reacting case are much stronger than the reacting case.

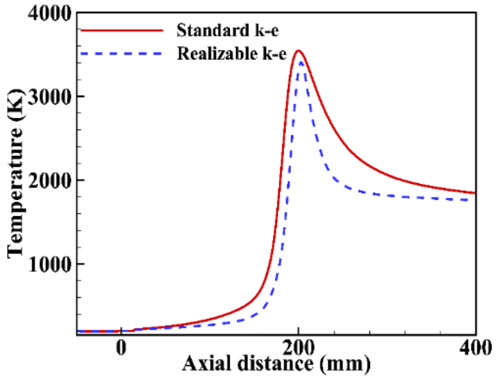

Fig. 3 Axial temperature for two turbulence models for $T_{ox,in}$=200K

On the other hand, by increasing the fuel and oxidizer mass flux ratio from 5 to higher ratios, the flame length decreases. As the mass flux ratio increases, the length of the dense oxygen core decreases, and it is also observed that the streamlines become more perpendicular to the longitudinal axis of the chamber around a longitudinal distance of 70 to 100 mm. At mass flux ratio of 19.5, the flame becomes very short, and finally at a mass flux ratio of 24, the flame converts to a bubble shape form. These conditions are similar to the form of liquid oxygen and methane in the RCM03-V02 combustion chamber. With increasing of the mass flux ratio, the hydrogen velocity and shear layer turbulent viscosity increase drastically. Accordingly the amount of energy transfer from more energetic hydrogen layers to dense oxygen layers increases remarkably.

4. Conclusion

In the present paper, the effects of the interaction of a high-density liquid oxygen jet with a high-velocity hydrogen in the presence of a pseudo-boiling phenomenon are investigated. Different turbulence models have been investigated and it has been shown that the selection of a suitable turbulence model in the trans-critical reaction flows are much more important than subcritical and supercritical flames. Also, contrary to expectations, the dense core of liquid oxygen disappears faster in the non-reactive flow than the reactive flow. The cross flow (transverse) heat transfer in the non-reacting transcritical injection and mixing is much stronger than in the reacting case, resulting in a very short cryogenic oxidizer core. The effects of mass flux ratio were also investigated and it was observed that by increasing the mass flux ratio from 5 to 24, a strong recirculation is formed in the flame front and the flame becomes a bubble that is similar to LOX-GCH$_4$ flame.

5. References

[1] M. Oschwald, J.J. Smith, R. Branam, J. Hussong, A. Schik, B. Chehroudi, D. Talley, Injection of fluids into supercritical environments, Combustion Science and Technolgy, 178(2006) 49-100.

[2] D. T. Banuti, Crossing the widom-line-supercritical pseduo-Boiling, Journal of Supercritical Fluids, 98 (2015) 12-16.

[3] T. Kim, Y. Kim, S. K. Kim, Effects of pressure and inlet temperature on coaxial gaseous methane/liquid oxygen turbulent jet flame under transcritical conditions, Journal of Supercritical Fluids, 81(2013) 164-174.

[4] S. Candel, M. Juniper, G. Singla, P. Scouflaire, C. Rolon, Structure and dynamics of cryogenic flames at supercritical pressure, Combustion and Science Technology, 178(2006) 161-192.

[5] G. Soave, Equation constants from a modified redlich-kwong equation of state, Chem. Eng. Sci. 27 (6) (1972) 1197-1203.