Modeling of Turbulent Spray Combustion under Cryogenic and Elevated Pressure Conditions

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Abstract

The paper concerns the modeling of turbulent liquid oxygen/hydrogen spray combustion for elevated subcritical pressure and cryogenic inlet temperature conditions. In particular, the combustion in the single injector combustion chamber is modeled where experimental data are available for gas phase temperature and both droplet size and velocities. The model uses an Eulerian–Lagrangian formulation for the gas and the liquid phase, respectively. Detailed models for droplet heating and vaporization in a convective flow field are employed, and detailed gas phase reactions are accounted for through use of a flamelet model for turbulent spray combustion. The results show a very good agreement between experimental and computational spray characteristics. The computed gas phase temperature lies above the experimental values which is associated with CARS single shot measurements and incomplete data for the initial conditions of the combustion process.

Introduction

An improved understanding of the physical and chemical processes occurring in liquid rocket engines is required to ensure the stability, reliability, and efficiency of their performance. The gaseous hydrogen and the liquid oxygen (LOX) are injected at cryogenic inlet temperatures, and the turbulent combustion occurs in both the sub- and supercritical domain. Therefore, the models for the processes in systems such as the Ariane V or the Space Shuttle main engine are very complex. In the present study the combustion process in a single injection combustion chamber is investigated for elevated pressure and cryogenic inlet temperatures. Experimental data are available for an elevated pressure situation of 5 bar, and the experimental data are published by Sender *et al.* [1].

The combustion in liquid rocket propulsion typically occurs in the flamelet regime of turbulent combustion [2] which enables the use of the flamelet model for turbulent spray diffusion flames [3, 4]. Structures of laminar hydrogen/oxygen flames are precalculated at 5 bar and for cryogenic inlet temperature of 100 K for hydrogen [5, 6], and they are incorporated into the turbulent spray combustion model which allows the computation of all chemical species that are included in the detailed chemical reaction mechanism for the hydrogen/oxygen system that includes 8 reactive species and 38 chemical reactions [7].

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Model

A dilute LOX spray is considered that is injected into a turbulent gaseous hydrogen stream where the inlet temperatures are cryogenic. The pressure of the system is 5 bar. The model includes an Eulerian description of the gas phase and Lagrangian equations for the dilute spray. The $k-\epsilon$ turbulence model is employed where additional terms account for the interaction with the spray [3, 4]. The chemical reactions are described through a flamelet model for turbulent spray diffusion flames. The conservation equations for the mixture fraction and its variance also account for mass gain through vaporization of the liquid [3].

The convective heating and vaporization is described through a model developed by Abramzon and Sirignano [8]. The equation for droplet motion accounts for turbulence effects through use of a Gaussian distribution for turbulent fluctuations [9]. The total spray and its distribution is described through the discrete droplet model.

For the computation of the gas phase characteristics in the cryogenic temperature regime, data from JSME tables [10] for pressures up to 200 bar and temperatures between 80 and 300 K are used. Moreover, the pressure (and temperature) dependence of the vaporization rate and of the binary equilibrium composition at the liquid/gas interface [11] is included.

Results and Discussion

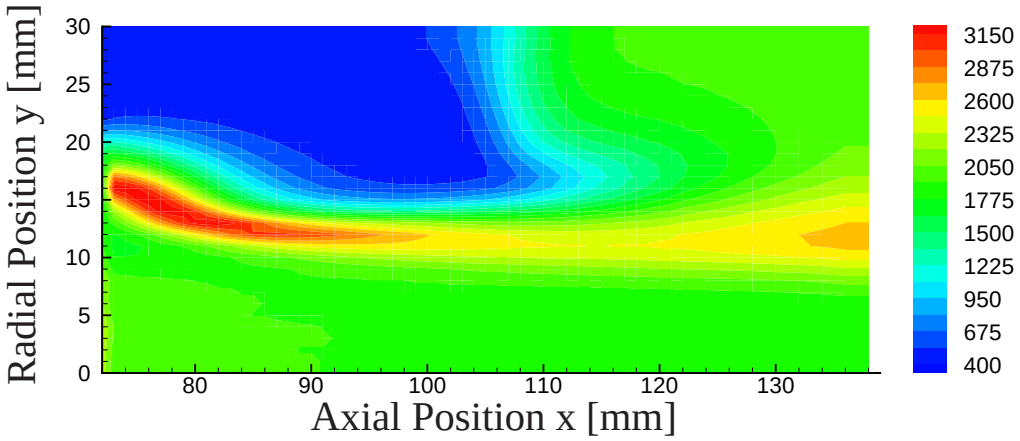

Figure 1: Contour plot of the gas temperature.

Figure 1 shows the overall structure of the spray flame in terms of the gas phase temperature. The main chemical reaction zone is located at the boundary of the spray jet where vaporized oxidizer meets the surrounding hydrogen stream. The maximum flame temperature is about 3000 K which is typical for these high-pressure flames.

A more detailed investigation of the gas temperature is shown in Fig. 2 where the calculated and experimental radial profiles are shown for three different axial positions. Symbols show experimental data and lines are computational results.

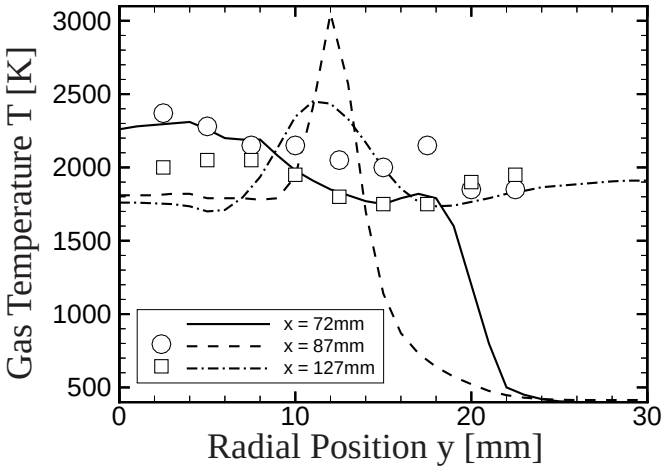

Figure 2: Radial profiles of the gas temperature for three different axial positions: Symbols present experimental data and lines show computational results.

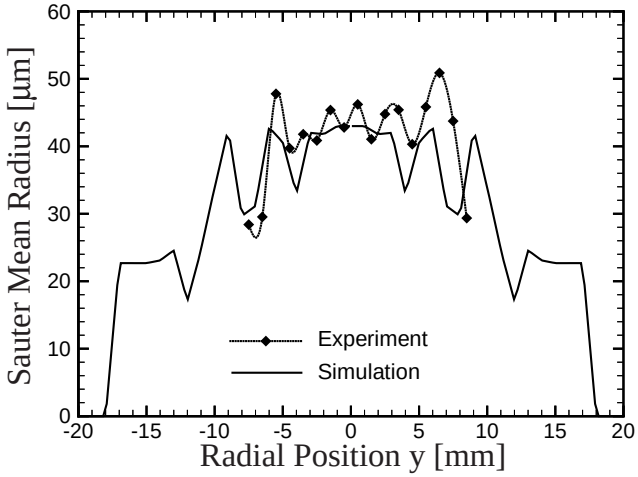

Figure 3: Experimental and computational results of the Sauter mean radius at $x = 104$ mm.

At $x = 72$ mm, there are no experimental data, and the inlet conditions for the gas temperature have been obtained from interpolated experimental data at two surrounding positions. Moreover, the experimental data has been extrapolated into the outer regions where no experimental data are available.

Figure 2 shows that the gas temperature in the main reaction zone is overpredicted by the computations. This may be attributed to both experimental and computational uncertainties. First the experiments employed CARS single shot measurements, and the averaging procedure of these values typically leads to an underprediction of the measured gas temperatures. Moreover, the initial gas phase profiles needed for the computations

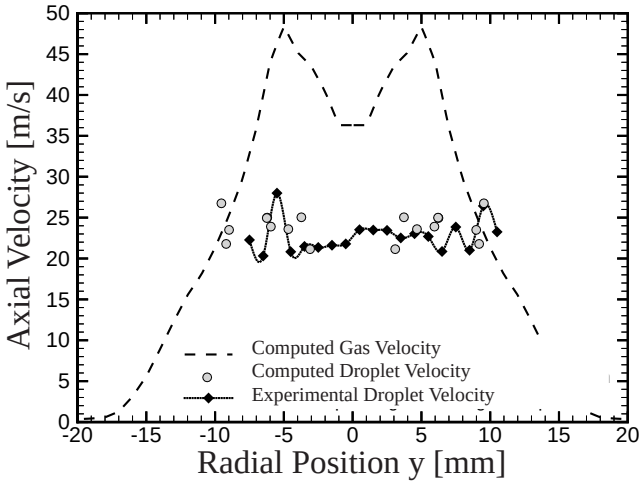

Figure 4: Experimental and computational results of the droplet velocities as well as calculated gas velocities at $x = 104$ mm.

is estimated from the gas temperature profile, and this procedure is somewhat arbitrary. Another reason is to be found in the incomplete liquid phase data. The experiments usually are able to capture only up to 10–20% of the total liquid flux. The computations use the uncorrected data from measurements so that the vaporization of the neglected liquid would reduce the gas phase temperature. Therefore, the discrepancies of computed and measured temperature profiles in the gas phase is reasonable.

Figures 3 and 4 show a comparison of liquid phase characteristics. Figure 3 displays the radial profile of the Sauter mean radius at $x = 104$ mm. Symbols show experimental results, and the agreement between experiment and computation is excellent. The same is true for the profiles of axial velocities at the same axial position shown in Fig. 4. Thus it is shown that the present model is suitable to correctly predict the liquid phase properties.

Summary and Future Research

The combustion process in the micro combustion chamber M3 has been studied by means of numerical computations. The Eulerian/Lagrangian model is suitable to predict the processes in the dilute spray regime of the combustion chamber. In particular, the prediction of the spray distribution and evolution is very good.

Calculated gas phase temperatures are higher than the experimental values which is explained by various reasons. First, the experimental data are somewhat underpredicted which is typical for CARS single shot measurements. Moreover, only a small portion of the total liquid flux was captured by the experimental techniques so that the energy consumed by droplet vaporization is underpredicted leading to too high values of gas temperature.

Future studies should include the dense spray regime, and an extension of the present model into that region will be developed.

Acknowledgments

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