ParCFD'2020
32^{nd} International Conference on Parallel Computational Fluid Dynamics
May-11-13 2020, Nice FRANCE

NON-PREMIXED TURBULENT COMBUSTION IN CRYOGENIC JET FLAMES AT ELEVATED PRESSURES

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Key words: High Pressure Combustion, Non-premixed Flames, Real Fluids, CFD.

Abstract. This study presents a numerical framework to simulate non-premixed turbulent combustion at high pressures. Improved real fluid approach has been used to accommodate for non-ideal thermodynamic effects. A steady laminar flamelet model is adopted for supercritical combustion. An open source code, OpenFOAM has been employed for Computational Fluid Dynamics (CFD) analysis. Comparisons with existing experimental and numerical works in literature show reasonable agreement.

1 INTRODUCTION

Non-premixed (or diffusion) combustion occurs in all systems where fuel and oxidizer are not perfectly premixed before entering the combustion chamber. Various combustion systems have non-premixed flames in the presence of turbulent flows [1]. The combustion chamber pressures in rockets, gas turbines, and diesel engines are very high in order to enhance thrust, power and efficiency. In these conditions the injected fluid(s) can experience ambient pressures exceeding their critical pressures [2]. Today's main stage liquid-propellant rocket engines (LPRE) typically operate at supercritical pressures and at cryogenic injection temperatures. The mixing, ignition and combustion are affected by non-ideal thermodynamic effects. In particular, the thermodynamic and transport properties are highly non-linear functions of temperature and pressure. Moreover, the experiments of Mayer et al. [3] showed that the surface tension between liquid and vapor is diminished at sufficiently high pressures and mixing is characterized by continuous-phase diffusion rather than by two-phase spray atomization. Near the critical point, propellant mixture properties exhibit liquid-like densities, gas-like diffusivities, and pressure-dependent solubilities.

2 Review of Literature

The highly non-linear behavior near the critical point results in inability of the ideal gas law to relate the thermo-physical states. The Peng-Robinson equation of state [4]

performs well near the critical temperature, however, in the transcritical regime considerable deviations from experimental data can be observed [5]. The volume-translated Peng-Robinson method [6] considerably improves the accuracy of the density prediction.

An appropriate model for simulating combustion under these conditions has to be chosen. The assumption of infinitely fast chemistry simplifies the chemical kinetics such that all scalars such as temperature, concentrations and density are uniquely related to the mixture fraction [7]. However, in turbulent flows, the non-equilibrium effects must be taken into account with at least one additional "progress" variable and the equations for its moments are to be modelled. According to the steady laminar flamelet model, the turbulent flame is considered to be an ensemble of small laminar diffusion flames, generally referred to as flamelets [7].

3 METHODOLOGY

The open source code OpenFoam has been used for present work. In this implementation, the cubic Peng-Robinson equation of state was chosen to model real fluid behavior. The k-ϵ Reynolds-averaged Navier-Stokes (RANS) model has been employed to account for the turbulence in the flow. For flamelet model, the Flamemaster software of Pitsch [8], which solves the flamelet equations in order to tabulate mixture fraction, mixture fraction variance and scalar dissipation rate has been used. The limitations of Peng-Robinson equation of state in density prediction at transcritical conditions will be discussed in this study and improvements will be suggested at the time of the conference.

4 VALIDATION

Two cold flow test cases [9] have been chosen to investigate the characteristics of a cryogenic, axisymmetric liquid nitrogen jet flowing into a combustion chamber. These benchmarks separate the effects of the real-gas modeling and turbulent mixing from combustion. They represent the simulation of injection of a dense cryogenic jet of liquid nitrogen into the gaseous nitrogen. The first case is supercritical, in which the chamber pressure was about twice the critical pressure of nitrogen; while the second case is transcritical, in which the pressure of chamber was nearly equal to the critical pressure value. The validation results for the supercritical and the transcritical cases are shown in Figures 1 and 2, respectively. Flow density has been compared with experimental and numerical data in the literature [9, 10]. For the supercritical case in shown in Figure 1, present work compares well with the numerical work in literature. However, in transcritical case shown in Figure 2, computed density values are lower as compared with numerical work in literature [9] in high density region. This is due to the fact that Peng-Robinson equation of state does not perform well in transcritical regime [5]. Results with improved Peng-Robinson equation of state will be presented at the time of the conference. In both cases there is a deviation in results in comparison with the experimental data [9], especially in higher density region. Raman scattering was used in the measurement of density in these experiments which is known to be error-prone in high density flows [9]. Numerically

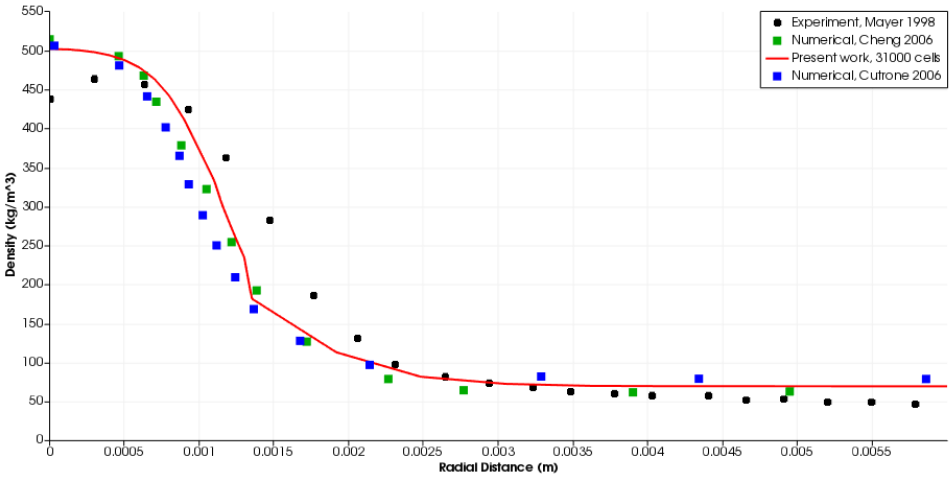

Figure 1: Density plot in supercritical cold flow case

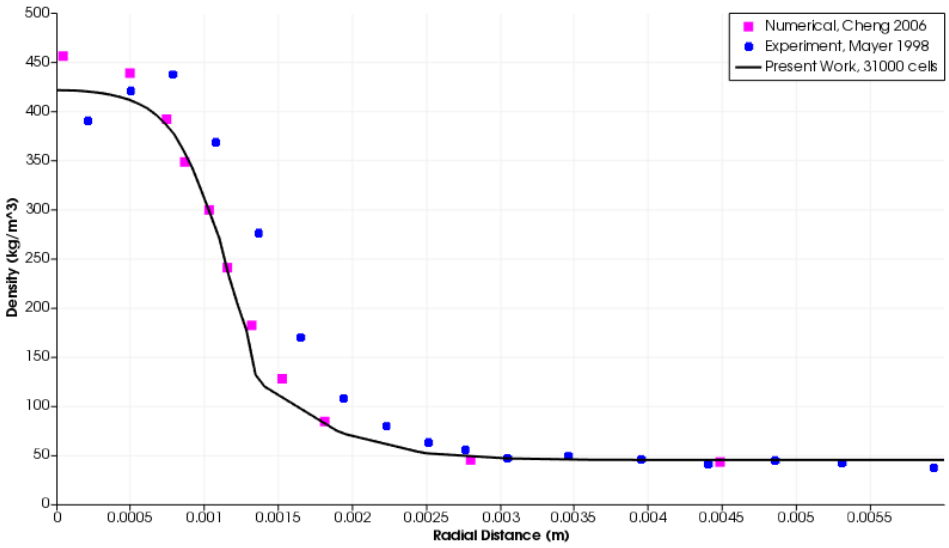

Figure 2: Density plot in transcritical cold flow case

calculated densities from this study as well as from literature are slightly lower than experimental values in the medium-density region.

In order to validate our choice of combustion model, the injection and combustion of LOX/GCH4 has been simulated, at the experimental operating conditions of Singla et al. [11]. OpenFoam is extended to use the laminar flamelet model for this case. The outcomes of this case will be presented at the conference. Since the problem is transient in nature, parallel computations are necessary even though the flamelet model has been used to simplify the solution of chemical kinetics.

5 CONCLUSION

Real fluid model employed for non-idealities in thermophysics performed well.The whole chemical kinetics was solved as a pre-processing step in order to tabulate the scalar and progressive variables for combustion. This became possible only because of decoupling of combustion and flow simulation enabled by Steady Laminar Flamelet approach which reduced the high computational cost involved in the CFD analysis of reacting flows. This study will support the design and development of combustion chambers with high pressures.

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