Large Eddy Simulations of Trans- and Supercritical Injection

H. Müller⋆, C.A. Niedermeier†, M. Jarczyk⋆, M. Pfitzner⋆, S. Hickel†, N.A. Adams†

⋆ *Institut für Thermodynamik, Universität der Bundeswehr München, 85577 Neubiberg, Germany*
† *Lehrstuhl für Aerodynamik und Strömungsmechanik, Technische Universität München, Boltzmannstr. 15, 85748 Garching b. München, Germany*

1 Introduction

Although liquid rocket engines have been used for several decades, the numerical simulation of mixing and combustion in a rocket combustion chamber still poses a challenge that has not been satisfactorily resolved. This is mainly due to the elevated pressures combined with cryogenic injection temperatures of the propellants. Molecular interactions can not be neglected and the related real-gas effects need to be modeled properly. Furthermore, the corresponding steep density gradients require robust numerical algorithms. The demand for computational fluid dynamics (CFD) solutions is, albeit the mentioned difficulties, for various reasons ever increasing. Shortened development cycles due to the growing international competition in the space transportation sector as well as restricted budgets and increasing requirements in terms of reliability and efficiency are just a few. In this context, the Technische Universität München (TUM) and the Universität der Bundeswehr München (UniBW) started a joint effort to develop CFD tools, which are capable of predicting the flow in a rocket combustion chamber. While the TUM promotes the in-house code INCA[1] (density-based) the UniBW extends the capabilities of the open-source CFD program OpenFOAM[2] (pressure-based). For validation, Large Eddy Simulations (LES) have been performed for the injection of trans- and supercritical nitrogen jets. Both codes yield similar results and are in excellent agreement with the experimental data.

2 Numerical and Physical Modeling

The conservation equations for a single component flow can be written as follows:

$$\frac{\partial \rho}{\partial t} + \frac{\partial \left(\rho u_j\right)}{\partial x_j} = 0 \tag{1}$$

$$\frac{\partial \left(\rho u_i\right)}{\partial t} + \frac{\partial \left(\rho u_i u_j + p\delta_{ij}\right)}{\partial x_j} = \frac{\partial \tau_{ij}}{\partial x_j} \tag{2}$$

$$\frac{\partial \rho h}{\partial t} + \frac{\partial \left(\rho h u_j\right)}{\partial x_j} = -\frac{\partial q_j}{\partial x_j} + \frac{\partial \tau_{ij} u_i}{\partial x_j} + \frac{Dp}{Dt} \tag{3}$$

[1]www.inca-cfd.org
[2]www.openfoam.com

Investigated Cases	Case3	Case4	Case11
Injection velocity, m/s	4.9	5.4	4.9
Injection temperature, K	126.9	137	128.7
Chamber pressure, bar	39.7	39.7	59.8
Chamber temperature, K	298	298	298

Table 1. Initial and boundary conditions for trans- and supercritical jet flows.

Here x_j are Cartesian coordinates, t is the time, ρ is the density, u_i is the velocity component in direction i, h is the enthalpy and p is the thermodynamic pressure. q_j is the heat flux vector and τ_{ij} represents the viscous stress tensor. The heat flux has been modeled using Fick's law.

The thermodynamic properties, i.e., heat capacity and enthalpy, have been calculated as the sum of an ideal reference state and a departure function which accounts for real-gas effects.

$$h\left(T,p\right) = h_0\left(T\right) + \int_{p_0}^{p} \left(V - T\left(\frac{\partial V}{\partial T}\right)_p\right) \mathrm{d}p \tag{4}$$

$$c_p\left(T,p\right) = c_v\left(T,p\right) - \frac{T\left(\frac{\partial p}{\partial T}\right)_V^2}{\left(\frac{\partial p}{\partial V}\right)_T} \tag{5}$$

The derivatives in the departure functions need to be calculated with an appropriate equation of state. In the present work both codes use the cubic Peng-Robinson equation [5] with an additional volume correction of Harstad *et al.* [2].

$$p = \frac{RT}{V-b} - \frac{a\left(T\right)}{V^2 + 2Vb - b^2} \tag{6}$$

While the INCA code uses the Adaptive Local Deconvolution Method (ALDM) [3] to model the subgrid scale (SGS) contribution, in OpenFOAM the Smagorinsky model has been used. The transport properties, i.e., the viscosity and the thermal conductivity, have been modeled with the empirical correlation for dense fluids of Chung *et al.* [1].

3 Case Setup and Preliminary Results

To validate both codes, Large Eddy Simulations have been performed for trans- and supercritical injection of nitrogen into a supercritical pressure and ambient temperature environment. The configuration has been chosen to match the experimental setup of Mayer *et al.* [4]. The mixing chamber of the experiment is a square duct with the dimensions 60x60 mm^2 and the injector has a diameter of 2.2 mm. Mayer *et al.* examined several cases with different combinations of injection velocity, temperature and chamber pressure of which three have been simulated in the

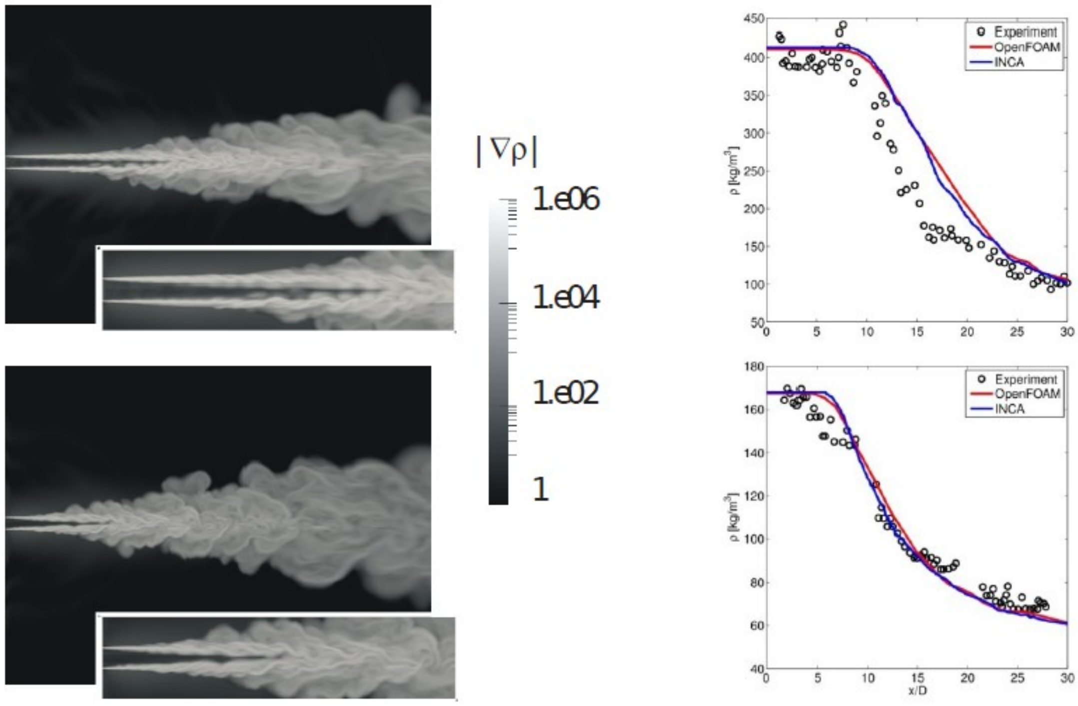

Figure 1. LES results for Case3 (upper) and Case4 (lower) of Mayer *et al.*. Numerical schlieren picture (left) and axial density distribution(right).

current work. The boundary conditions for the considered cases are summarized in Table 1, the nomenclature follows the experiments.

Figure 1 shows the results of the LES for Case3 and Case4. Snapshots of the density gradient magnitude are shown on the left side. The axial density distributions on the right hand side show excellent agreement of both codes with the available experimental data. The only deviation can be found in the mixing region of the transcritical jet (Case3). Further analysis of the results and additional plots for Case11 will be included in the final paper.

References

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