Comparative investigation of numerical modelling techniques for cryogenic flashing oxygen.

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Abstract

Liquid oxygen (LOX) is a commonly used oxidizer for multi-stage rockets of space launch vehicles [1]. The delivery of LOX in the combustion chamber is realized either at near-atmospheric (e.g. lower-stages) or at near-vacuum (upper stages) pressure conditions, where due to the low ambient pressure, LOX becomes superheated and flash evaporation occurs. The present study was funded by the HAoS-EU project [2] and **demonstrates the applicability of two different numerical approaches with regard to modelling the phase-change and flashing of LOX and the subsequent spray formation at low ambient pressure conditions.** Initially, phase-change rate has been modelled with the Hertz-Knudsen equation [3], whereas, for the second approach the fluid properties have been obtained by look-up tables derived from REFPROP [4],[5]. A 2D Unsteady Reynolds-averaged Navier-Stokes (URANS) framework was used for both approaches.

Introduction

Regardless of the fuel combination, LOX prevails as the oxidizer for most rocket engines [1]. Depending on the stage of operation the delivery of LOX to the combustion chamber can be realized in near-vacuum pressure conditions and thus LOX phase-change is expected. Although there are cases of experimental cryogenic research [6], [7], **due to the technical challenges that cryogenic temperatures pose, especially at supercritical pressures [8], there are relatively limited available experimental studies that focus on flows of cryogenic oxygen.** This study, presents a comparative investigation on the predictive accuracy of different methods regarding in-nozzle phase-change and the formation of a spray. The numerical results regarding the spray cone angle are compared to available experimental data [6] .

Figure 1. LOX storage tank (left). RP-1/LOX fueled rocket (right)

Table 1. List of modelled cases and corresponding boundary conditions

Case	p_{in} [kPa]	p_{out} [kPa]	T_{init} [K]	Superheat degree, R_p
1	1700	20.6	113	**32.26**
2	1700	14.14	113	**47.00**
3	1700	9.10	113	**73.03**
4	1700	2.75	113	**241.66**

Methodology

The governing equations solved comprise the mass, momentum and energy conservation. Two approaches have been used in this investigation regarding phase-change and fluid properties. **A)** A two-phase mixture approach was implemented including an additional equation for the vapour transport, as follows:

$$\frac{\partial(a\rho_v)}{\partial t} + \nabla(a\,\rho_v\,\vec{u}) = \dot{R}\,.$$

The source term $\dot{R}$, corresponding to the phase-change rate, was modelled using the Hertz-Knudsen equation [3]:

$$\dot{R} = \frac{\lambda\, A_{int}\,(p_{sat} - p)}{\sqrt{2\,\pi\, R_g\, T_{int}}}\,,$$

where R_g is the ideal-gas constant, T_{int} is the bubble-interphase temperature and A_{int} is the overall vapour interface surface area. λ reflects the degree of deviation from thermodynamic-equilibrium [3], [9]. **B)** A single-fluid approach, where the fluid properties are extracted from a thermodynamic table deriving from the REFPROP dataset [4], [5]. The geometry and dimensions of the simulation domain are presented in Figure 2.

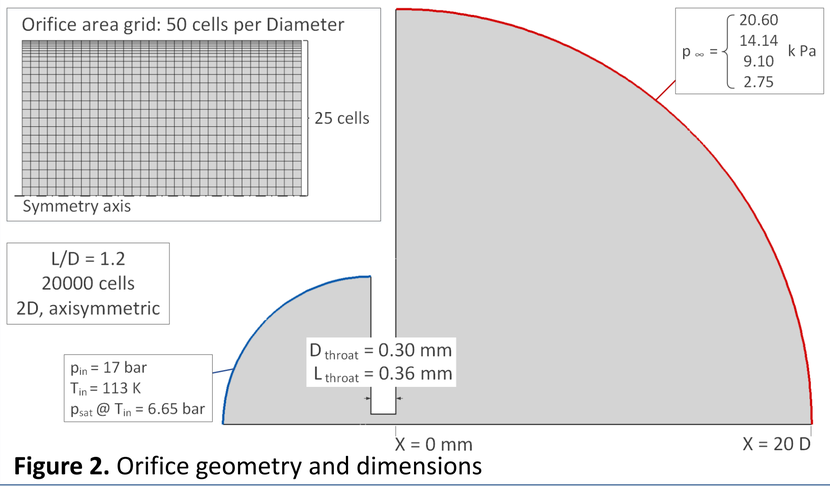

Figure 2. Orifice geometry and dimensions

Results

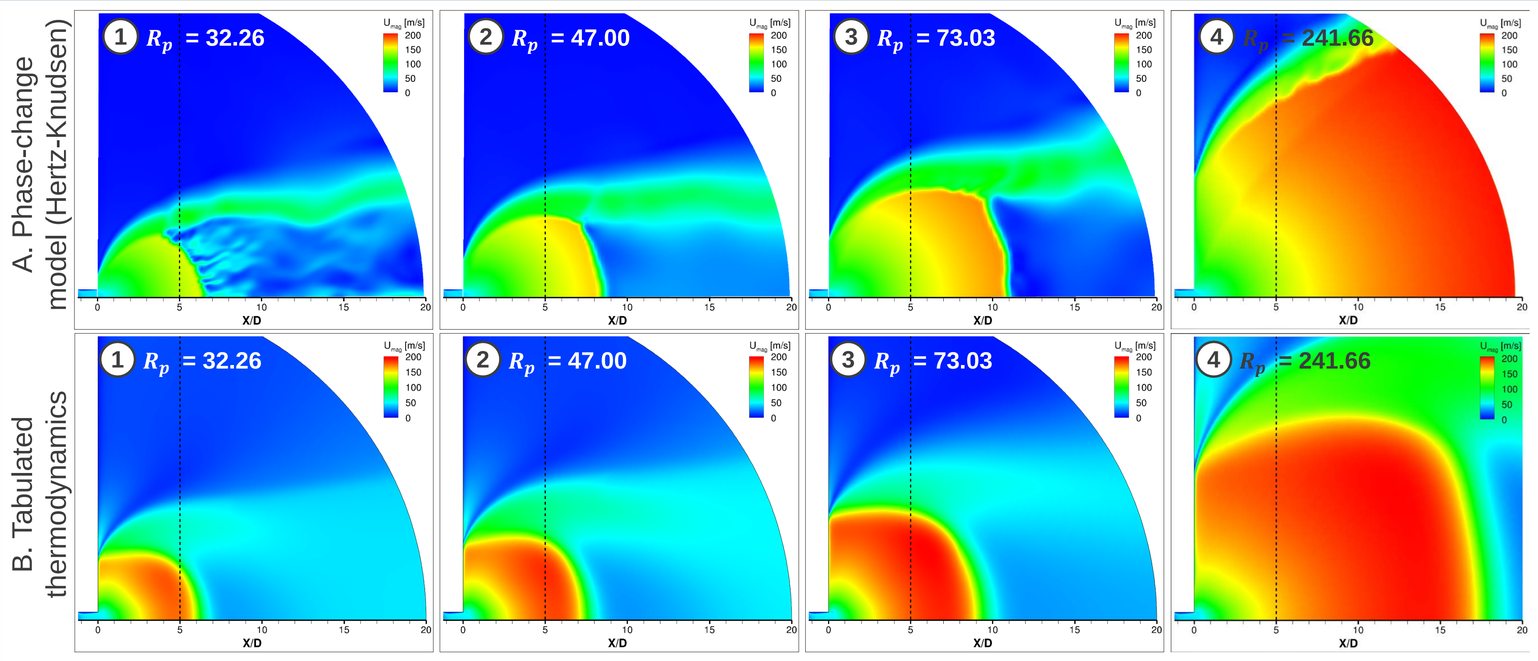

Figure 3. Contour plots of velocity magnitude (m/s) on the vertical plane of symmetry of the nozzle for case 1 to 4 (increasing superheat degree towards the right) using a phase change model (above) and tabulated thermodynamics (below).

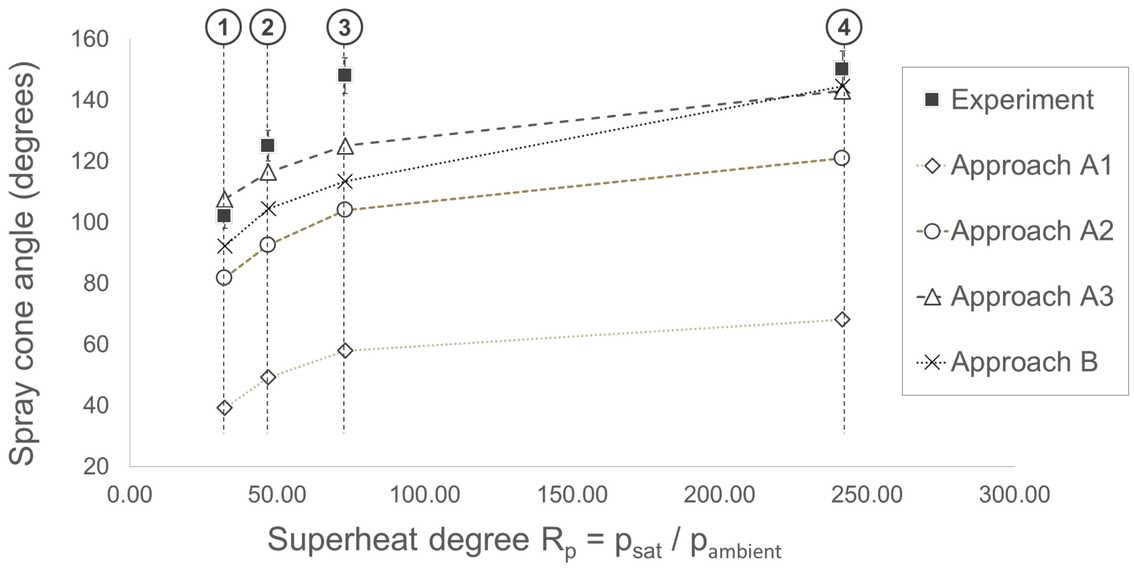

Figure 4. Spray cone angle in degrees for conditions of increasing superheat degree. All angles calculated at an axial distance of 5 times the diameter of the orifice. $X = 0\ m$ at the orifice exit.

Approach A1, A2: Use of Hertz-Knudsen model with the assumption of A_{int} = 10 m^2/m^3 for A1 and A_{int}= 10^2 m^2/m^3 for A2. The spray cone angle is underestimated in both cases.

Approach A3: Use of Hertz-Knudsen model, assuming a value of A_{int} = 10^3 m^2/m^3. The spray cone angle is predicted accurately for the area of transition to flashing (1,2) and the fully flashing regime (4).

Approach B: Use of tabulated thermodynamics. Spray cone angle is well predicted for the area of transition (1) and the fully flashing regime (4).

Discussion

This research has demonstrated that the phase-change process and atomization of cryogenic LOX can be accurately modelled by employing two different methodologies. **Both the use of a phase-change model (Hertz-Knudsen) and the tabulated thermodynamics were proven able to capture the topologies that appear in the fully flashing regime.** The main findings of this study are applicable not only to propulsion components of space vehicles but also to other cryogenic liquid applications, e.g. CO_2 for refrigeration systems and flash boiling applications in internal combustion engines which is a subsequent focal point of this research.

Conclusions

Two-phase oxygen flow was numerically investigated under a 2D, URANS framework. Phase-change of the superheated liquid was modelled by utilizing the Hertz-Knudsen equation with a pressure-based solver, and a parametric study was conducted regarding the total area of interface between the liquid and vapor phase, A_{int}, in order to the assume a realistic value for the model. Furthermore, tabulated thermodynamics deriving from the REFPROP dataset was used in order to feed a density based-solver with accurate properties of the cryogenic fluid. For both approaches, it was demonstrated that **the flashing process can be accurately captured for an increased degree of superheat as well as for conditions that are considered transitional towards the flash boiling onset.** Moreover, both solvers were able to capture the topologies that are reported in experimental investigations of cryogenic fluids ([6],[10]), namely the lateral expansion of a shockwave that is formed so that the pressure just after the outlet of the orifice to be restored to the ambient values. Numerically, future work will focus on the improvement of the phase-change model and the tabulated thermodynamics process.

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References

1. Harstad, K., Bellan, J.,1998, International journal of heat and mass transfer, 41 (22), 3551-3558
2. http://haos-itn.eu/
3. Karathanassis, I. K., Koukouvinis, P., Gavaises, M., 2017, International Journal of Multiphase Flow, 95, 257–270
4. Schmidt, R., Wagner, W., 1985, Fluid Phase Equilibria, 19, 175-200.
5. Lemmon, E. W., Jacobsen, R. T., 2004, International Journal of Thermophysics, 25 (1).
6. Lamanna, G., Kamoun, H., Weigand, B., Manfletti, C., Rees, A., Sender, J., Oschwald, M., Steelant, J., 2015, Atomization and Sprays, 25 (10).
7. Banuti DT, Hannemann V, Hannemann K, Weigand B., 2016, Combustion and Flame, 168, 98-112.
8. Habiballah, M., Orain, M., Grisch, F., Vingert, L., Gicquel, P., 2006, Combustion Science and Technology, 178 (1-3), 101-128.
9. Karathanassis, I., Koukouvinis, P., Gavaises, M., 2016, Atomization and Sprays, 26 (12), 1307-1336.
10. Andreas Rees, A., Salzmann, H., Sender, J., Oschwald, M., 2019, Proceedings of the 8th European Conference for Aeronautics and Space Sciences (EUCASS)

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