Cavitation coupled atomization

Aqeel Ahmed, Julien Reveillon, F.X. Demoulin

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Aqeel Ahmed [(1)]; Julien Reveillon [(1)]; Francois-Xavier Demoulin [(1)]
[(1)] CNRS-UMR 6614 CORIA, Saint-Etienne du Rouvray, France

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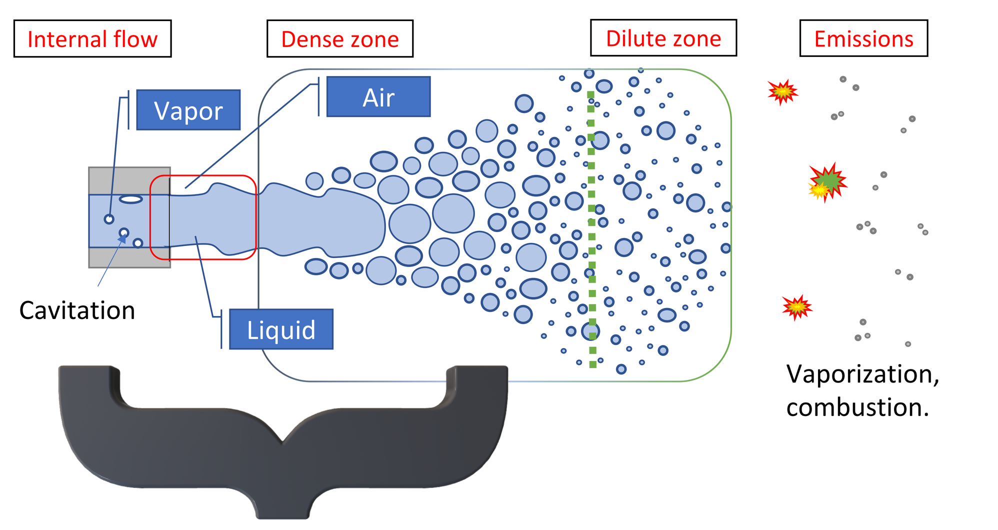
Abstract

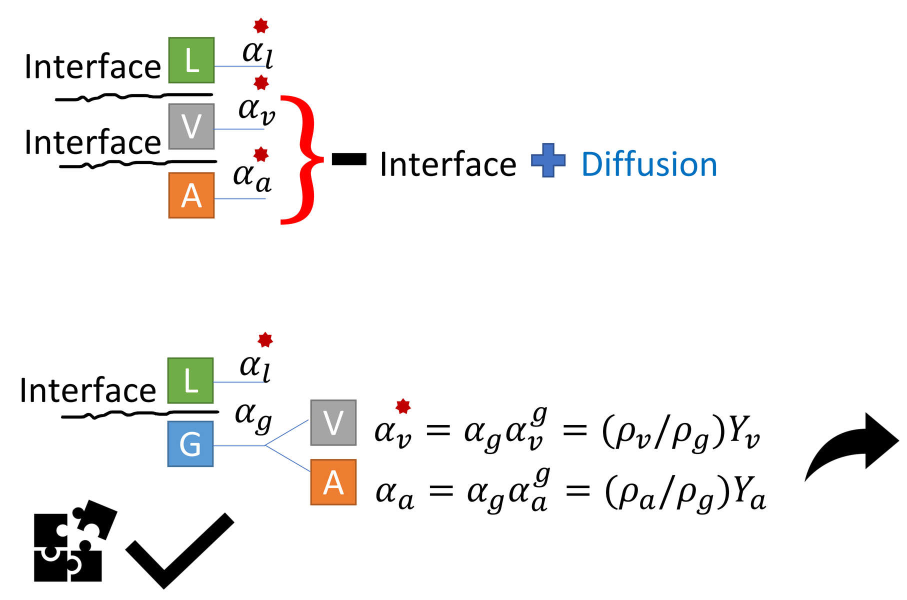
In modern high pressure fuel injection systems for internal combustion engines, cavitation inside the injector is frequently observed. In contrast to the cavitation encountered by pure fluid, the cavitation process in a typical fuel injection system is affected by the ambient non-condensable gas. Since the fuel is directly injected in a chamber full of air, a typical two-phase approach for modeling pure liquid cavitation (liquid-vapor) is not sufficient. To this end a three-phase system is typically considered with fuel liquid, fuel vapor and non-condensable gases (NCG, for instance air). In the context of interface resolved numerical methods, one of the options is to treat each phase separately. This, however, comes at a cost, as such multiphase formulations consider each phase immiscible, thus preventing mixing between vapor and NCG. In reality there are only two phases; liquid and gas. As soon as vapor comes in contact with any other NCG , they belong to one phase: the multi-component gas phase. In this work, we have treated cavitation of fuel in an inert gas environment using multiphase formulation, with interface only between liquid and gas. The model is validated and then tested on three dimensional model experiment.

Objectives



- Consistent formulation for in nozzle phase change (cavitation) and atomization.
- Maintain sharp interface between liquid and gas to predict atomization.
- Such that the same formulation can be extended for phase change (evaporation) in the external spray.

Numerical Work



* Solve Equations
L:Liquid, V:Vapor, A:Air, G:Gas

α : Volume faction
Y : Mass fraction

- Multi-phase formulation
- Mass transfer model to predict phase change [1,2]
- Surface tension incorporated for liquid gas interaction [3,4]

$$\frac{\partial \alpha_l}{\partial t} + \nabla \cdot (\bar{\mathbf{U}} \alpha_l) = \frac{\dot{m}}{\rho_l}$$
$$\frac{\partial \alpha_v}{\partial t} + \nabla \cdot (\bar{\mathbf{U}} \alpha_v) = -\frac{\dot{m}}{\rho_v}$$

Conservation of liquid and vapor mass with constant density in each phase

$$\alpha_g = 1 - \alpha_l = \alpha_v + \alpha_a$$
$$\rho = \alpha_l \rho_l + \alpha_v \rho_v + \alpha_a \rho_a = \alpha_l \rho_l + (1 - \alpha_l) \rho_g$$
$$\frac{\partial \rho \bar{\mathbf{U}}}{\partial t} + \nabla \cdot (\rho \bar{\mathbf{U}} \bar{\mathbf{U}}) = -\nabla p + \nabla \cdot \left(\rho \nu_{eff} \left(\nabla \bar{\mathbf{U}} + \nabla \bar{\mathbf{U}}^T \right) \right) + \underbrace{\sigma k \delta (\mathbf{x} - \mathbf{x_s}) \mathbf{n}}$$

Surface tension force defined at liquid-gas interface only

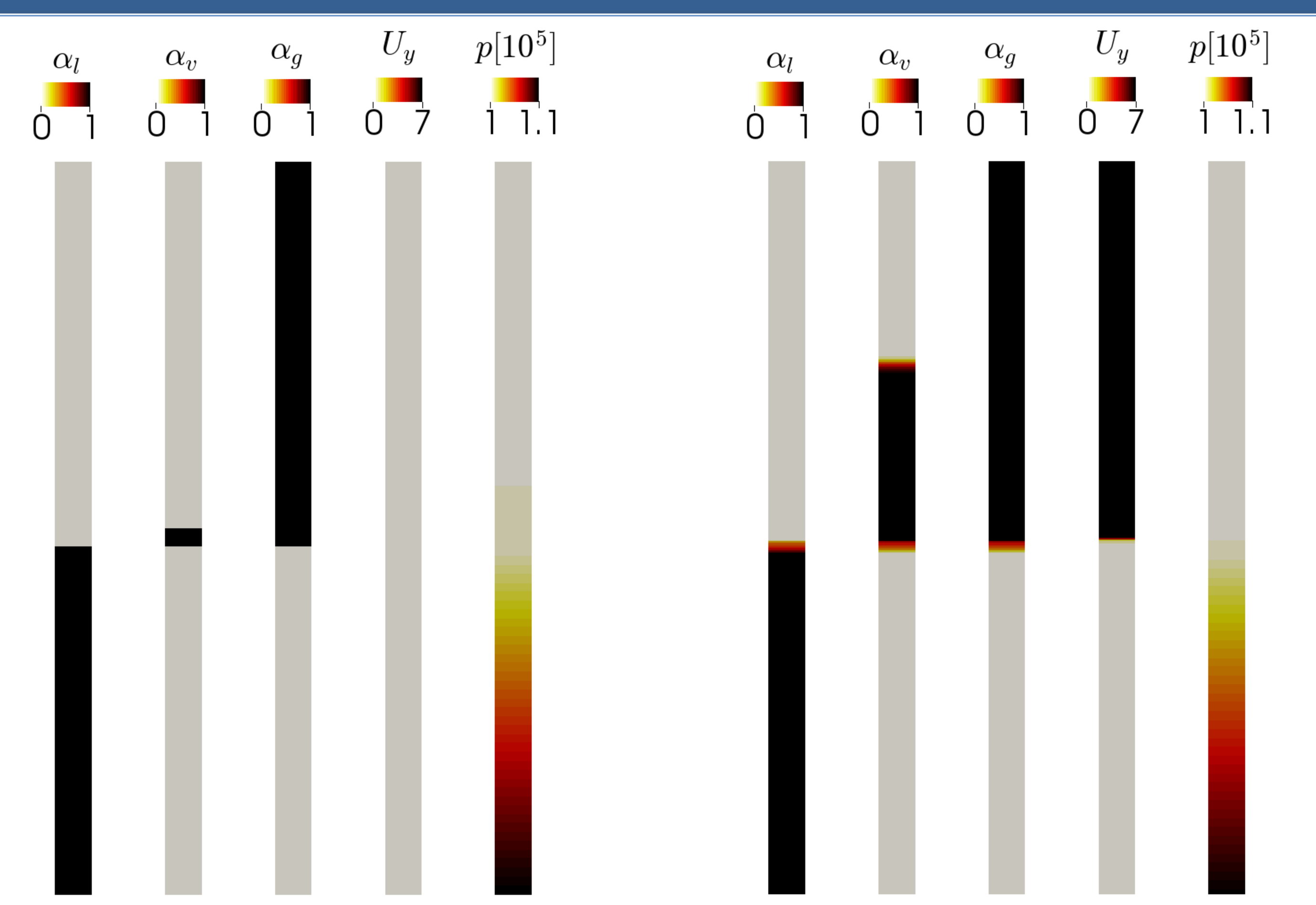
$$\nabla \cdot \bar{\mathbf{U}} = \dot{m} \left(\frac{1}{\rho_l} - \frac{1}{\rho_v} \right)$$

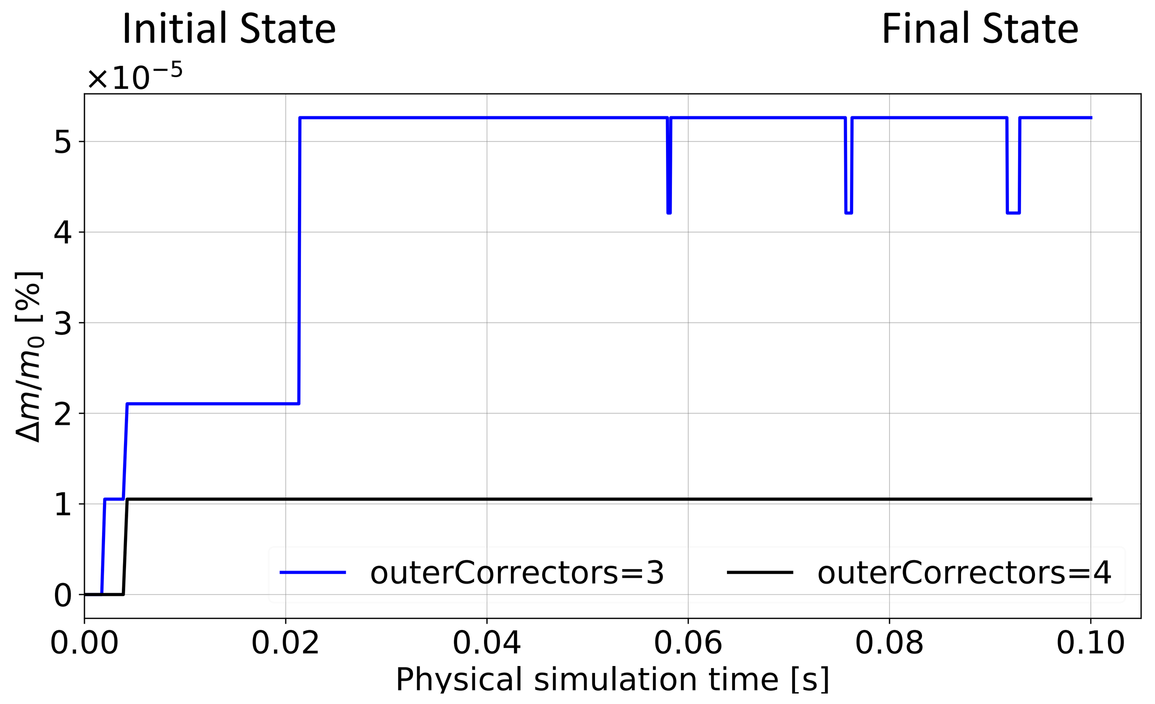
Velocity is not divergence free as long as there is phase change

$$\nabla \cdot \nabla p = f\left(\bar{\mathbf{U}}, \dot{m}(\alpha_l, \alpha_v, p), \rho(\alpha_l, \alpha_v, \alpha_a)\right)$$

Pressure Poisson equation: strong coupling with mass transfer terms

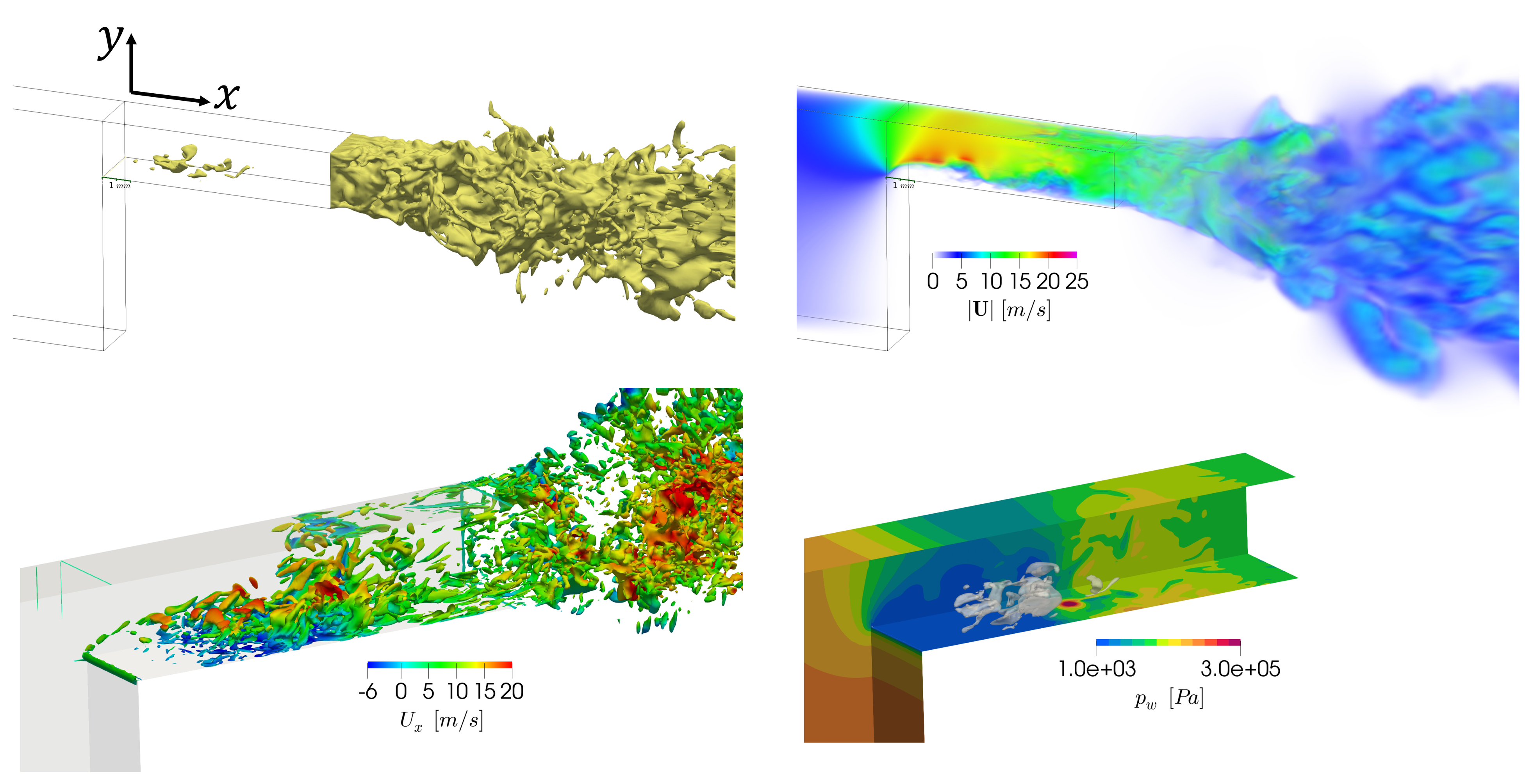
Validation

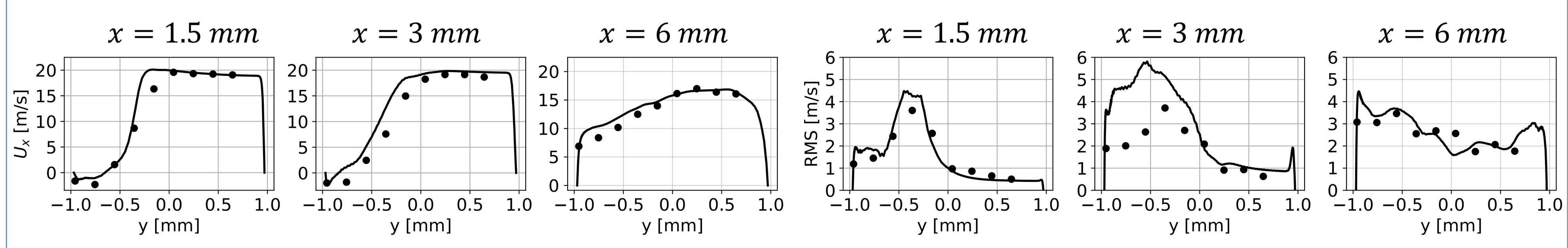




A column of liquid and gas (air and vapor) is set with hydrostatic pressure distribution initially (top right). After the onset of cavitation, the total mass of liquid and vapor is compared (bottom), as the liquid changes to vapor (top left). Mass is conserved with good accuracy.

3D Application: LES of Cavitating Water Jet [5]





Exp. [5] and numerical (solid lines) streamwise velocity and fluctuations at x=1.5, 3 and 6 mm.

Conclusions

- Multiphase formulation with liquid, vapor and air to predict in nozzle cavitation and external jet atomization
- Surface tension dominated primary and secondary atomization is well captured
- LES has the potential to predict the complex internal nozzle flow

Contact

Aqeel Ahmed
CNRS UMR 6614 CORIA
Email: aqeel.ahmed@coria.fr
Website: http://haos-itn.eu/

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