Cavitation erosion assessment of a wobbling high-pressure fuel injector

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Introduction

The flow inside high-pressure fuel injectors is prone to cavitation triggered by local pressure values below the vapor pressure. Repetitive violent collapse events of vapor structures can finally alter the geometry via material loss. This cavitation induced erosion affects the performance of the injectors and may lead to operating failures [1].

There are previous cavitation studies investigating different types of dynamic mesh motion approaches such as cartesian cut-cell [2], node interpolation [3] and Arbitrary Lagrangian–Eulerian (ALE) [4] methods. To the best of our knowledge, there is no study that applies the overset mesh methodology and examines cavitation erosion for wobbling needle motion. Despite the comparatively high time cost for mesh and topology construction, overset mesh technique is a promising approach as it allows to simulate very low needle positions with non-skewed cells unlike the aforementioned approaches.

Here, needle lift and off-axis motion effects are investigated with the overset mesh methodology. Cavitation erosion is assessed with a combined approach [5,6] using different post processing erosion indicators.

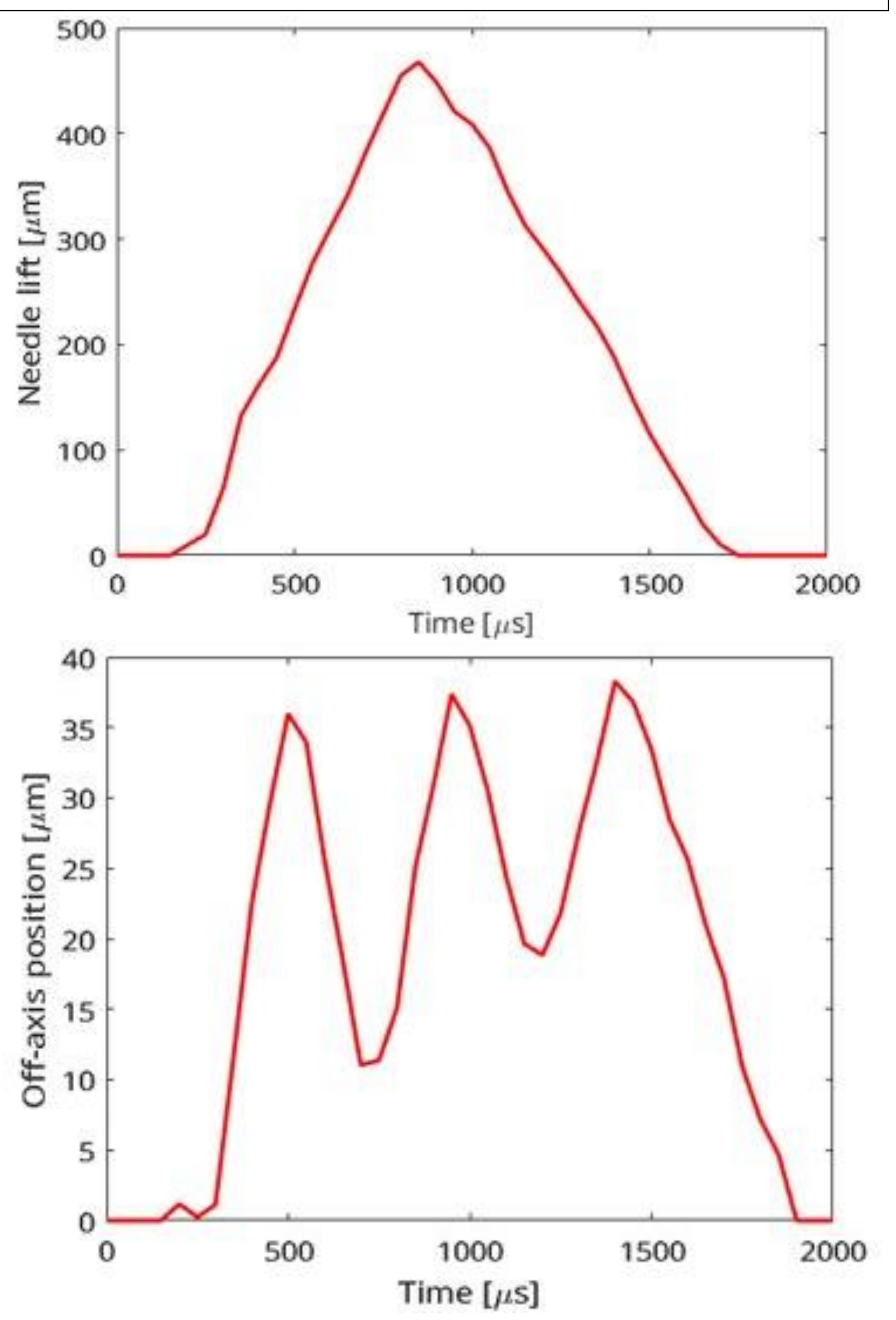

Figure 1. (Top) Needle lift and (bottom) off-axis motion profiles

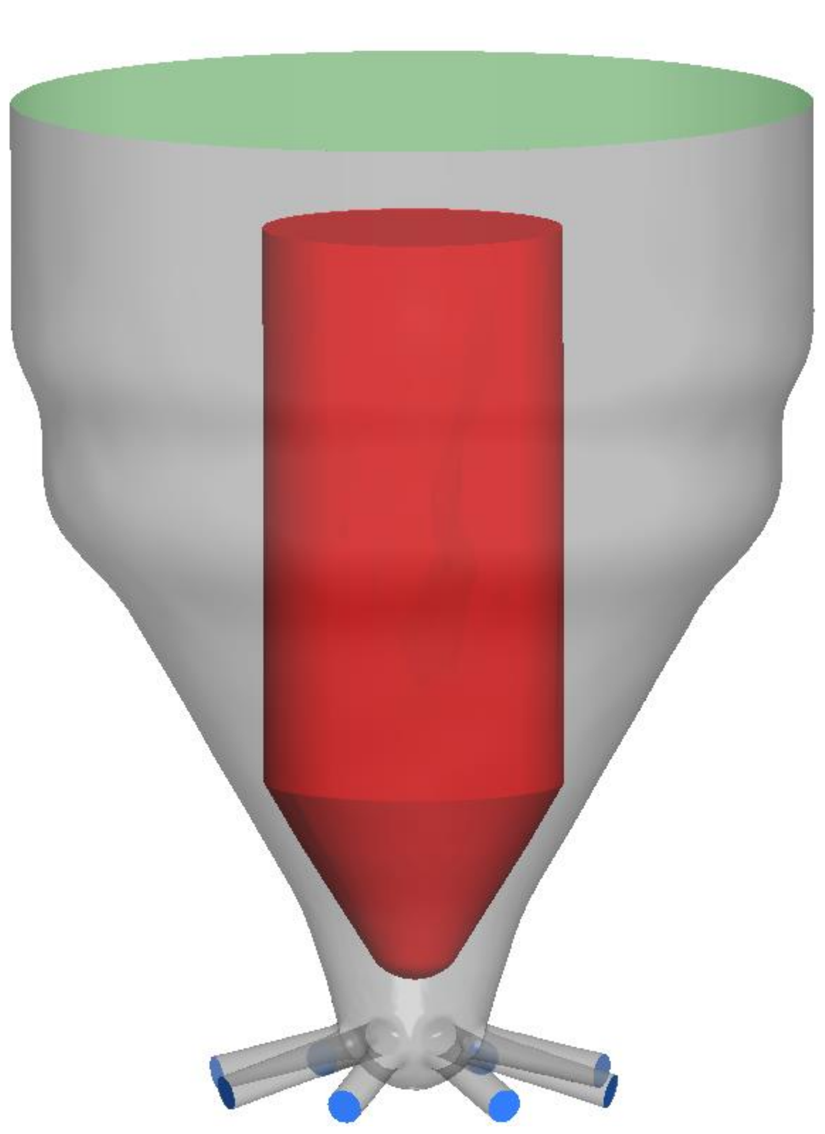

Figure 2. Needle and the sac including 8-hole at highest lift position

Methodology

The flow is examined with unsteady Reynolds Averaged Navier Stokes simulation. Assuming a homogeneous mixture, cavitation is modelled via the mass transfer approach. Hence, the Zwart-Gerber-Belamri cavitation model is used with altered model coefficients. Second order numerical discretization schemes are applied for spatial terms, while time is discretized first order as the used CFD solver Ansys FLUENT does not provide higher order time integration schemes here.

For cavitation erosion assessment, results are presented only with maximum squared material derivative of pressure, $(Dp/Dt)^2$, evaluated throughout the simulated time of 2000 µs.

Needle lift and off-axis grid motion profiles (Figure 1) are implemented using the overset mesh technique. At the beginning of the simulation, the needle is seated with 25 µm distance to the sac to achieve simulation times with reasonable level.

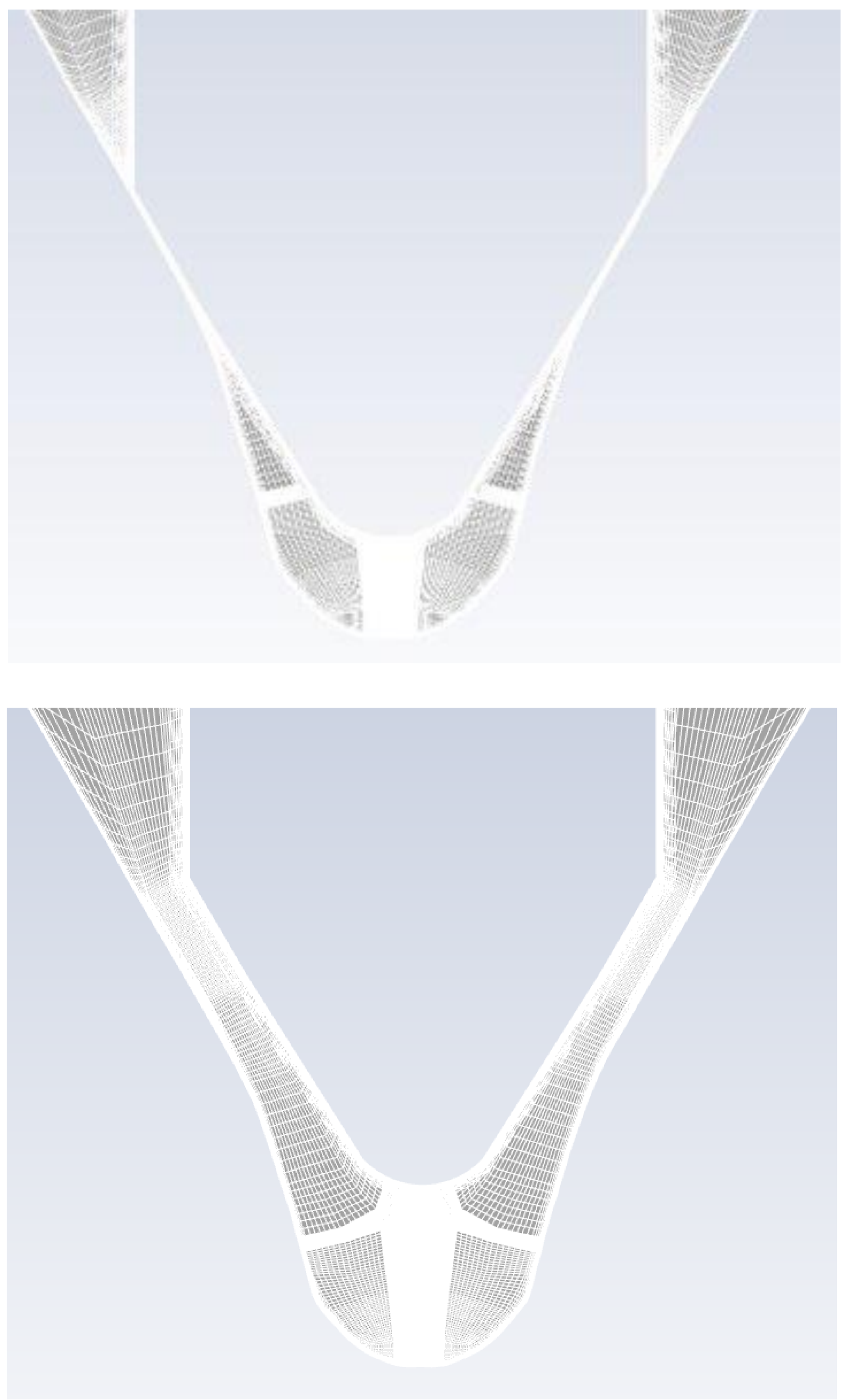

Figure 3. Cut plane of the overset mesh: (Top) Start and end of the simulation - 25 µm, (Bottom) Highest lift position - ~ 500 µm

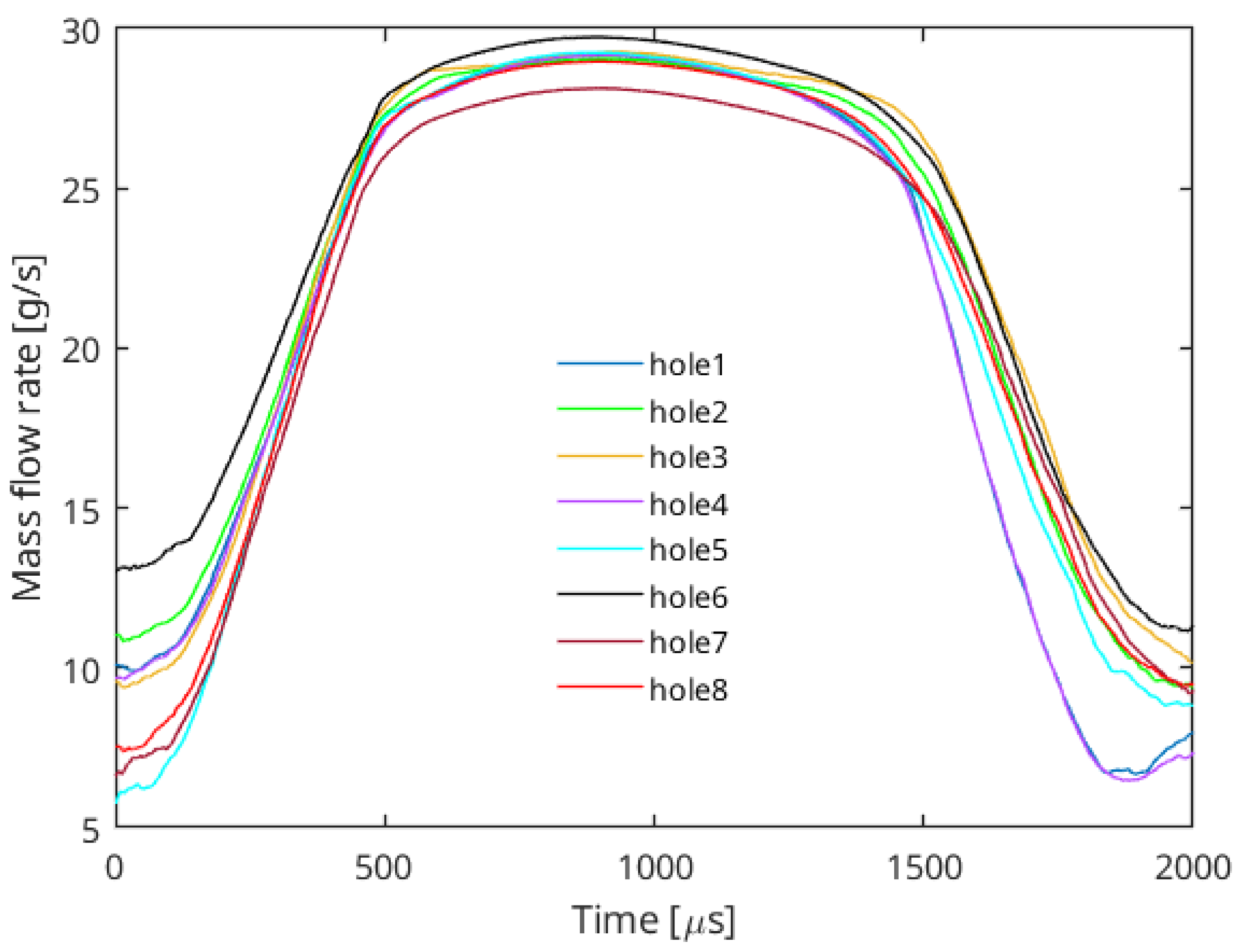

Figure 4. Mass flow rate (smoothed) change each hole's outlet with time

Results

- Wobbling needle motion was numerically investigated with the overset mesh technique. The impact of cavitation erosion was examined through the $(Dp/Dt)^2$ post-processing erosion indicator.
- Change of mass flow rate of each hole over time is plotted in Figure 4. It is clear from the graph the off-axis motion affect the flow dynamics within each hole. This would significantly affect the injector performance.
- Figure 5 presents computational results at highest and lowest lift position, corresponding to the mid and final time of the simulation. On the left side of the figures, vapor formation is visualized with iso-surfaces. On the right side, needle and sac surfaces are colored based on the maximum $(Dp/Dt)^2$ value up to the respective time. The red-colored areas indicate potential zones for cavitation erosion. Additionally, experiments in static lift positions 20 µm and 450 µm are also presented in Figure 6.
- Typical time scales for cavitation erosion in experiments is in the order of hours, while numerical simulations and cavitation erosion assessment are typically conducted over periods several orders of magnitude lower, here: 0.002 ms. Although a direct comparison is challenging, the simulated areas prone to erosion over the sac and needle agree reasonably well with the experiments, particularly for the low lift needle position - even considering just one lift cycle.

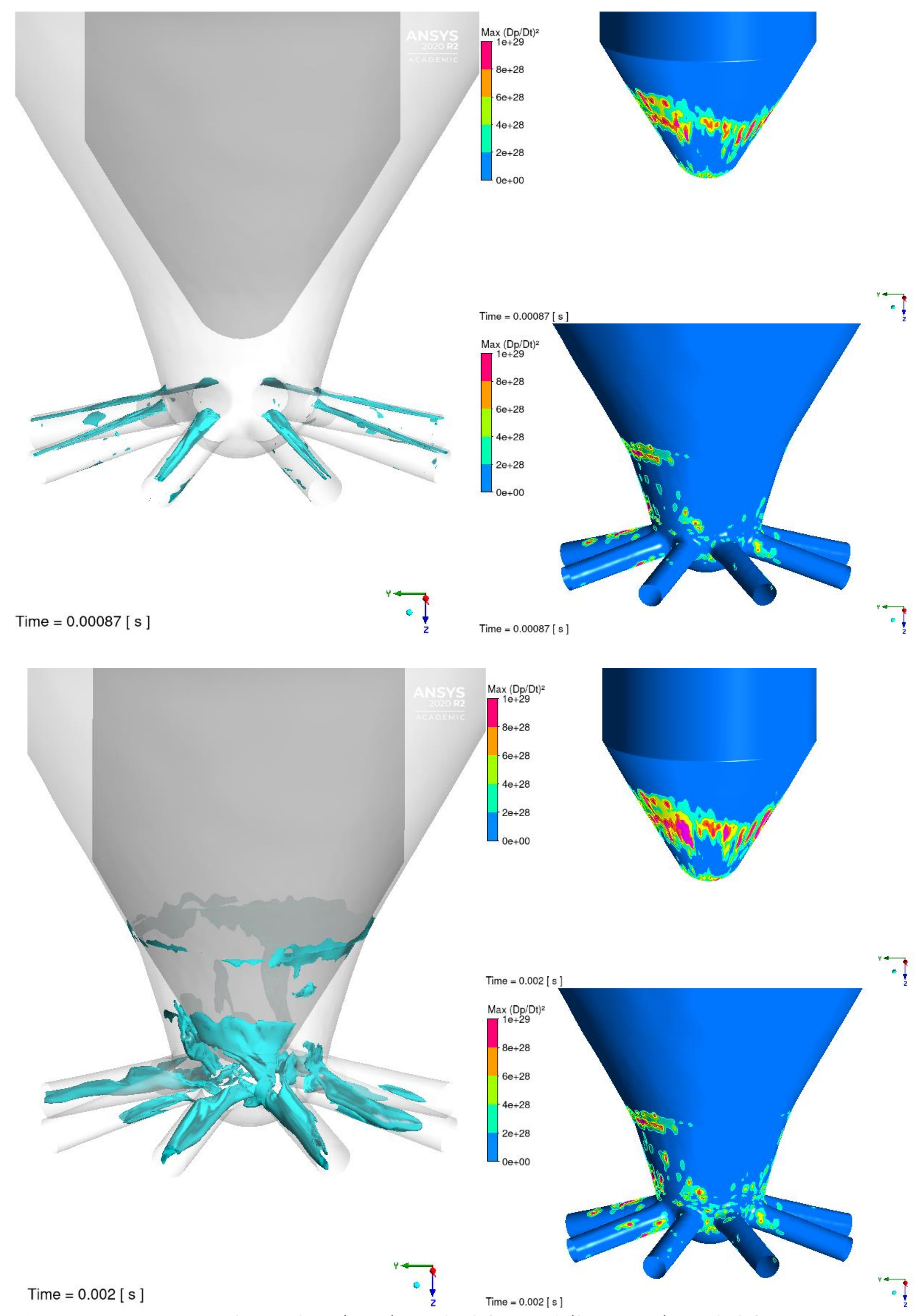

Figure 5. Numerical results: (Top) High lift and (bottom) High lift

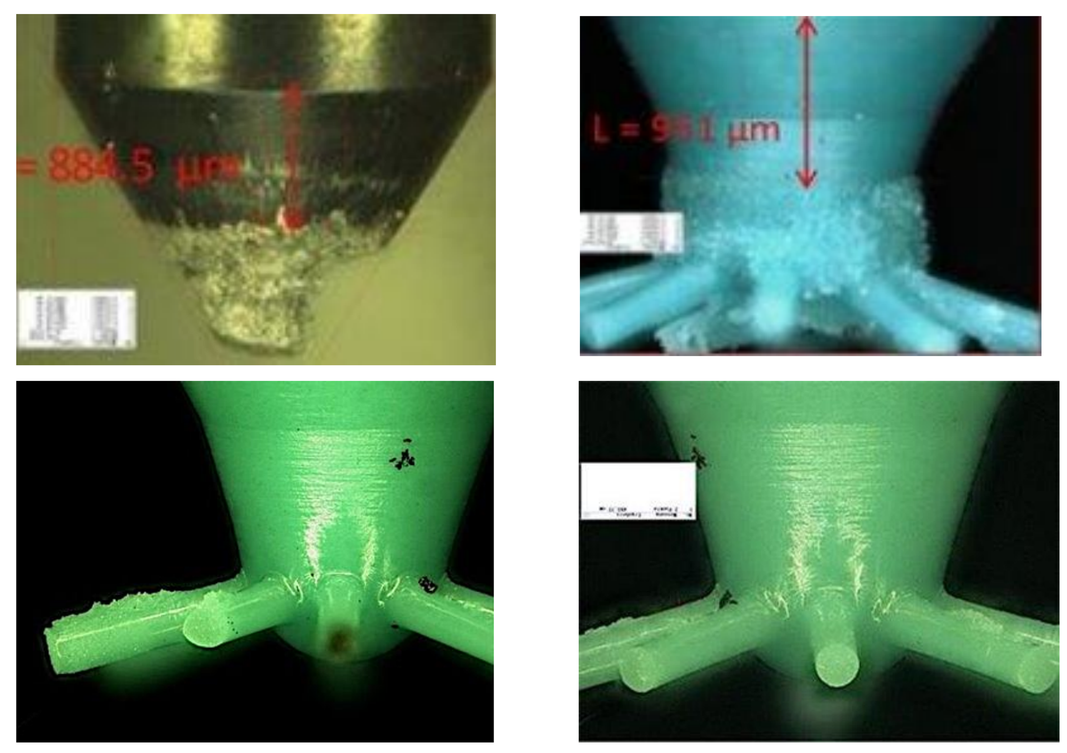

Figure 6. Experiments: (Top) Low lift - 20µm and (bottom) High lift 450 µm

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References

[1] Osman, A. 2006. "Failure of a Diesel Engine Injector Nozzle by Cavitation Damage." Engineering Failure Analysis 6: 1126-33
[2] Xue, Q., Som, S., Battistoni, M., Longman, D. E., Zhao, H., Senecal, P. K., & Pomraning, E. (2013). Three-Dimensional Simulations of the Transient Internal Flow in a Diesel Injector: Effects of Needle Movement. ILASS Americas, May.
[3] Gomez Santos, E., Shi, J., Venkatasubramanian, R., Hoffmann, G., Gavaises, M., & Bauer, W. (2021). Modelling and prediction of cavitation erosion in GDi injectors operated with E100 fuel. Fuel, 289, 119923.
[4] Kolovos, K., Kyriazis, N., Koukouvinis, P., Vidal, A., Gavaises, M., & McDavid, R. M. (2021). Simulation of transient effects in a fuel injector nozzle using real-fluid thermodynamic closure. Applications in Energy and Combustion Science, 7, 100037.
[5] Mouvanal, S., Chatterjee, D., Bakshi, S., Burkhardt, A., & Mohr, V. (2018). Numerical prediction of potential cavitation erosion in fuel injectors. International Journal of Multiphase Flow, 104, 113–124.
[6] Brunhart, M. (2020). Cavitation and the application of methods for erosion prediction in high pressure fuel injection systems.