

Research activities on compressible multiphase flows



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Outline of the presentation

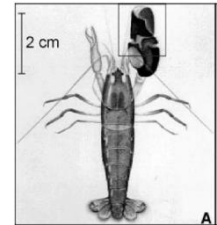
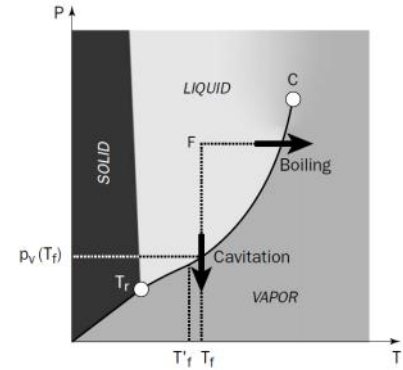
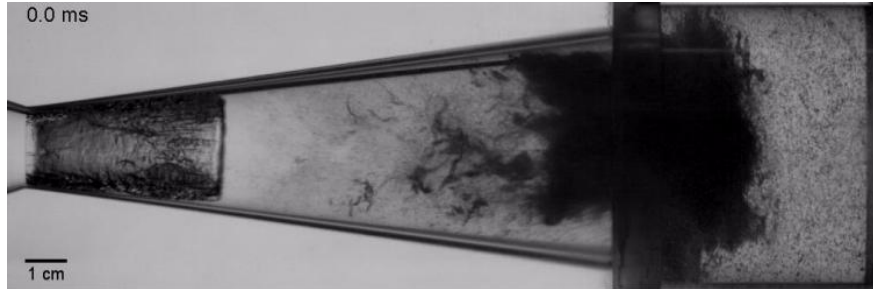
- Introduction/short overview
- Cavitation
Cavitation bubble collapse mechanisms and effects
- Fuel sprays and Fuel Injection Equipment (FIE)
Thermodynamic effects, cavitation and link to erosion, sprays
- Future directions

Introduction/motivation

- Multiphase flows have relevance in many fields, incl. industry, biomedical
- Multiple spatial/temporal scales, often difficult to experimentally investigate.
- Additional complexities in the case of property disparity along the involved phases (e.g. liquid/gas), large velocities/pressure ratios or the presence of phase change.

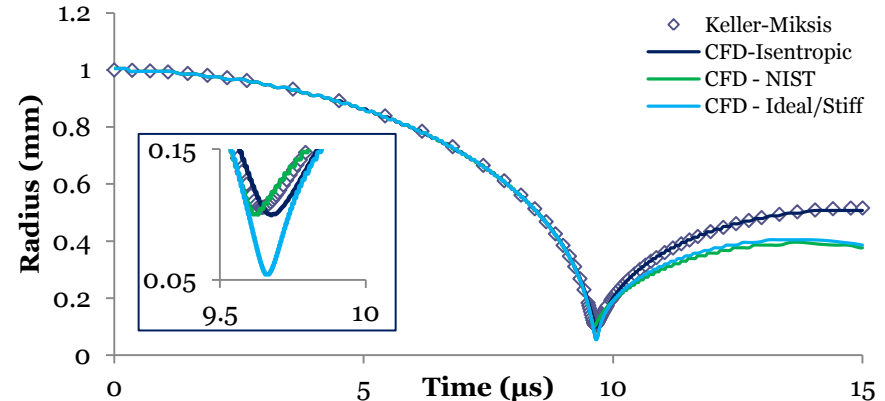
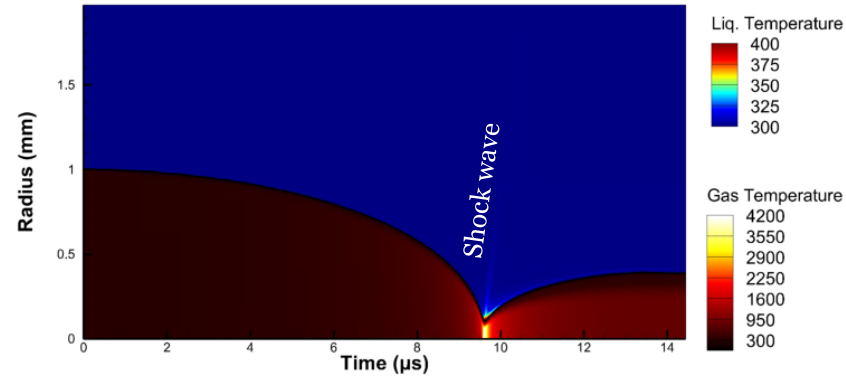
Cavitation - introduction

- Formation of vaporous cavities within the bulk of a liquid
- Relevance to hydraulic machinery and biological systems
- Extends to a vast range of scales (nuclei: nanoscale/microscale, cavitation sheets: meters)



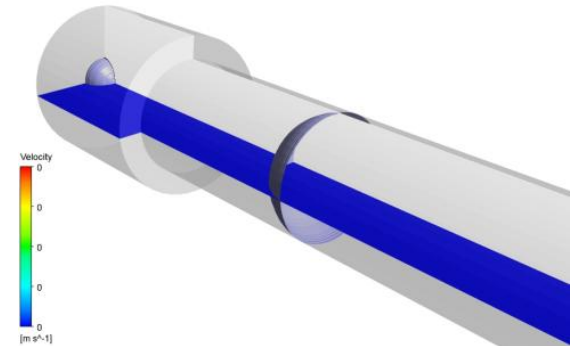
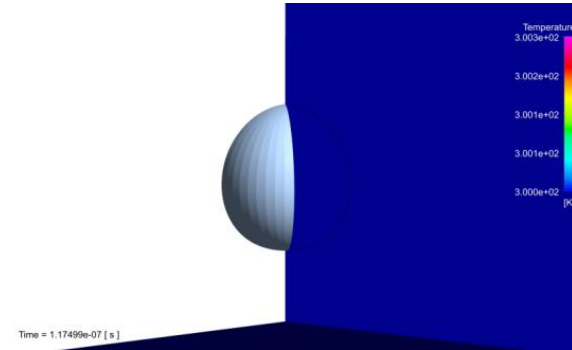
Cavitation - fundamental bubble dynamics

- Cavitation is highly energetic; localised pressures can reach in the order of several GPa.
- Suitable thermodynamic closure is required, to avoid shortcomings from simplified closures.



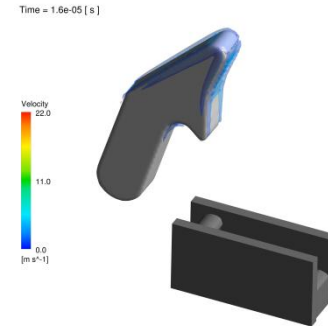
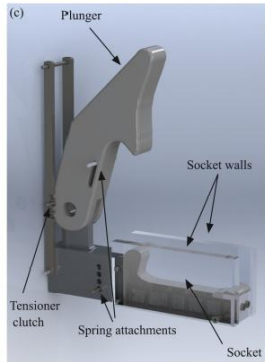
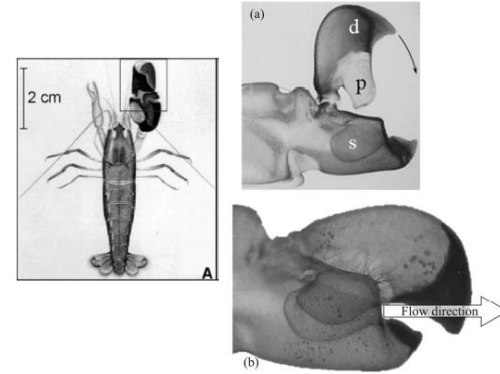
Cavitation - biomedical applications

- Pressure gradients can be caused by shock waves (e.g. shock wave lithotripsy)
- Example, 353bar shock wave, $4\mu\text{s}$ duration (Dornier HM3), bubble radius $50\mu\text{m}$.
- Exploitation of jetting as a mechanism for drug delivery
- In the extreme limit can be used as a means of needleless injection (example 650mJ bubble, 0.5mm diameter tube)



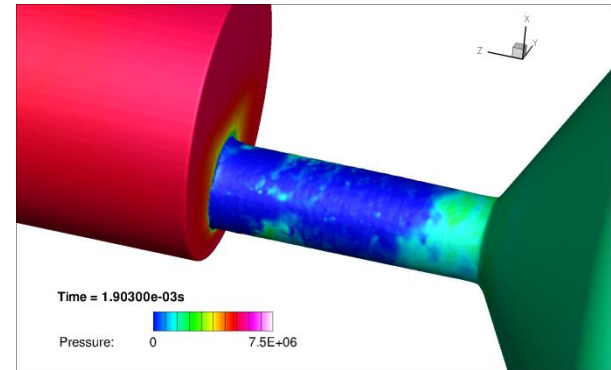
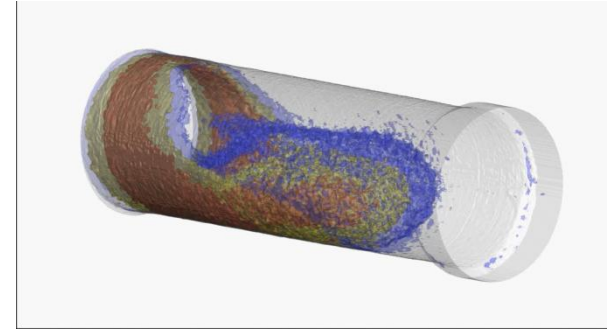
Other - Bio-inspired flows

- Pistol shrimp can generate cavitation with its fast moving claw.
- Claw model at enlarged scale (70x of actual size) was examined with PIV, to validate computational model.



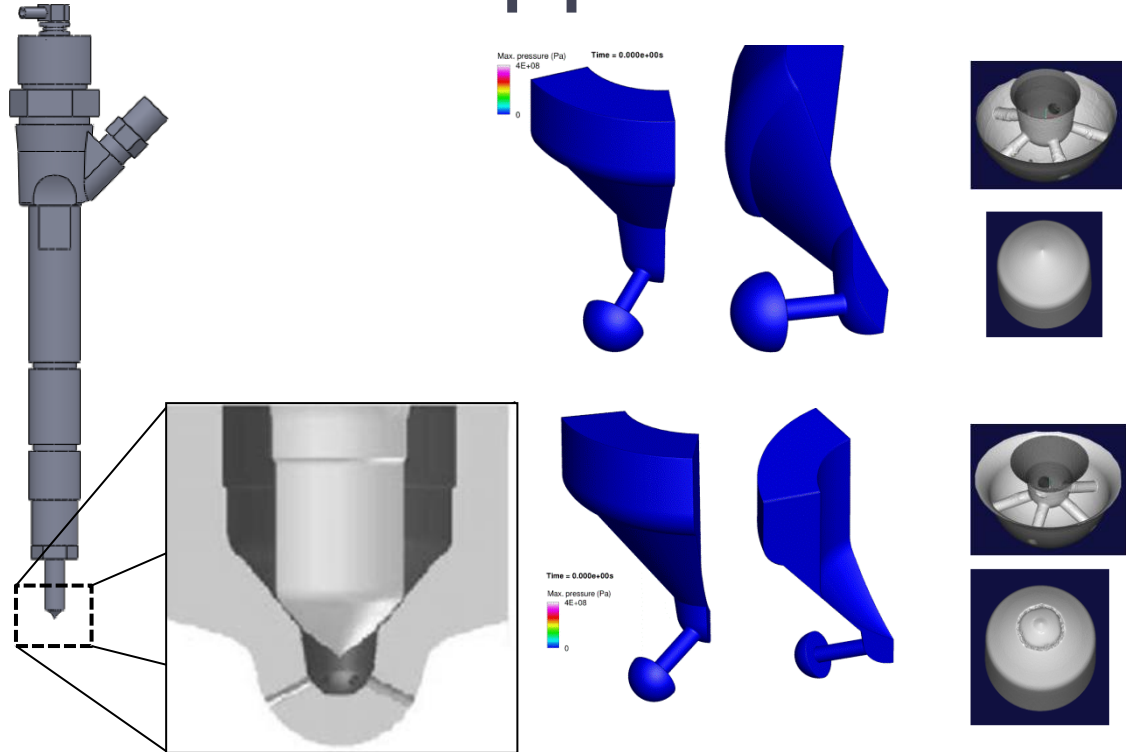
Cavitation – industrial applications

- Cavitation erosion can be assessed through the collapse of vaporous structures, under a homogeneous equilibrium assumption.
- Accurate prediction of time averaged volumetric cavitation distribution in an orifice
- Comparison with X-ray CT scans (both for assessing fluid density and material erosion).



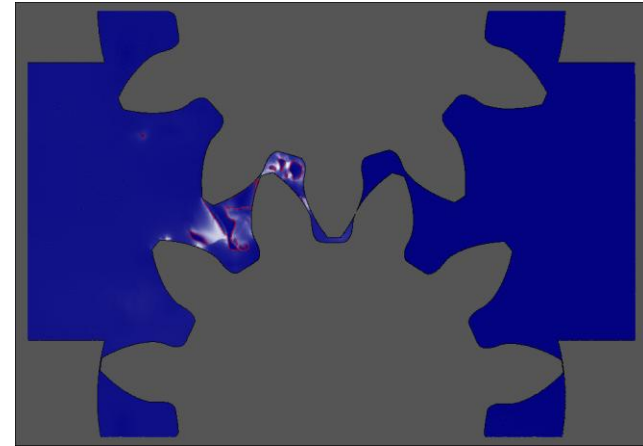
Cavitation – industrial applications

- Diesel fuel injectors operate at extreme conditions
- Upstream pressure 2-3·10³bar, downstream ~50bar
- Velocities up to 700m/s



Cavitation – industrial applications

- Air propulsion fuel delivery systems (gear pumps) also suffer from cavitation.
- Additional complexities emerge from:
 - (1) pseudocavitation (aeration), due to pressure reduction (high altitude operation).
 - (2) gear contacts (moving geometry handling) which renders mesh deformation/remeshing complex – here performed with Immersed Boundaries.



Fuel sprays

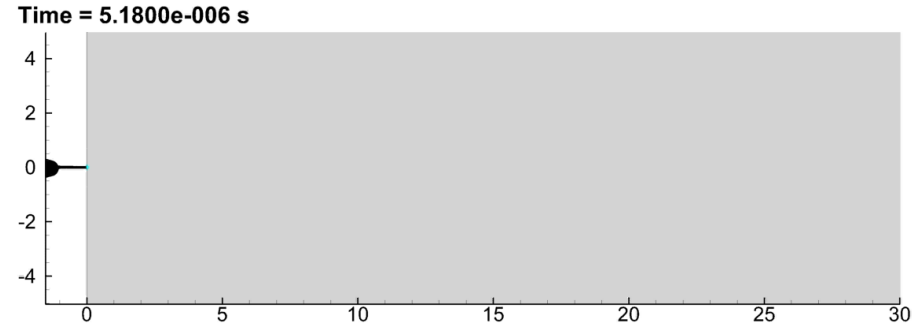
- Downstream conditions 20-60bar
- Temperatures in the order of 500-900K
- Fuel sprays in modern ICE depart from classical atomization
- Example C_{12} planar jet at 363K, 100 μ m width, 600m/s, in N_2 110bar, 975K.
- Fuel mixing resembles turbulent diffusive mixing.



yC12: 0 1
Time = 0.0000e+000s

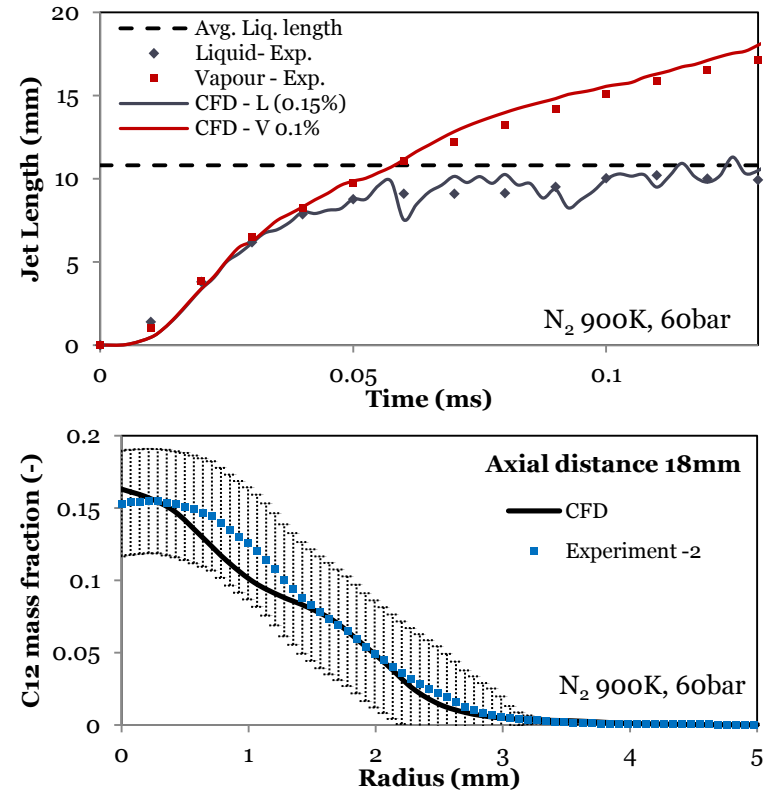
Fuel sprays

- Thermodynamic closure needs to take into account mixing
- Identification of critical point of the mixture is not trivial..
- C_{12} critical point is 18bar, 658K
 N_2 critical point 34bar and 126K
- Example, ECN Spray-A conditions & injector (C_{12} injection, 363K, 600m/s, 90 μ m diameter, to N_2 at 60bar, 900K)



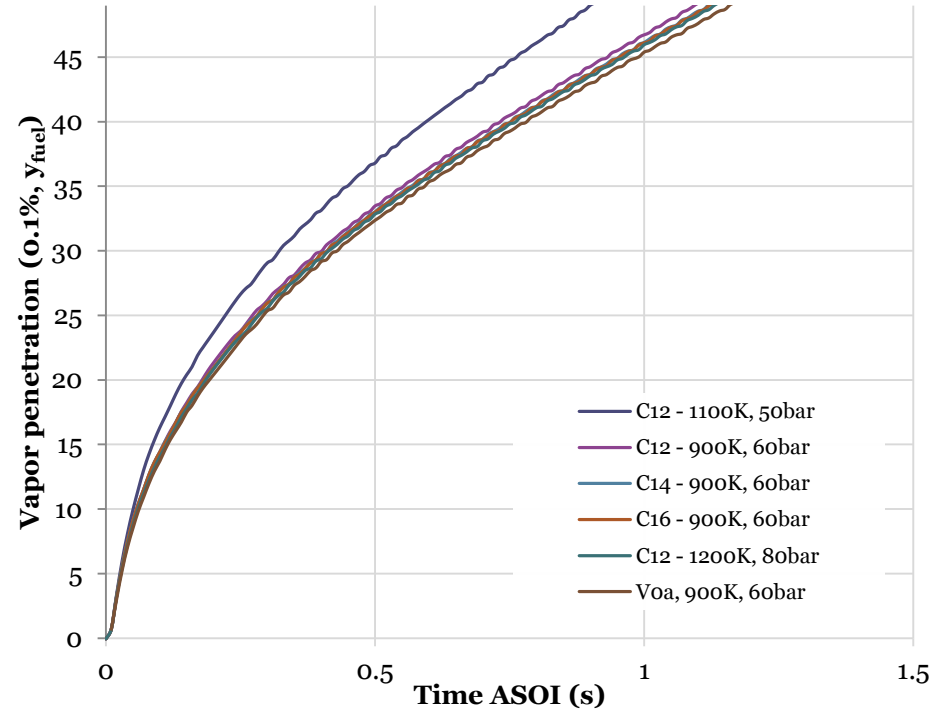
Fuel sprays

- A good agreement is obtained against experimental measurements:
- In terms of spray length (liquid and vapor penetration)
- And radial distribution of fuel (here C_{12}) mass fraction



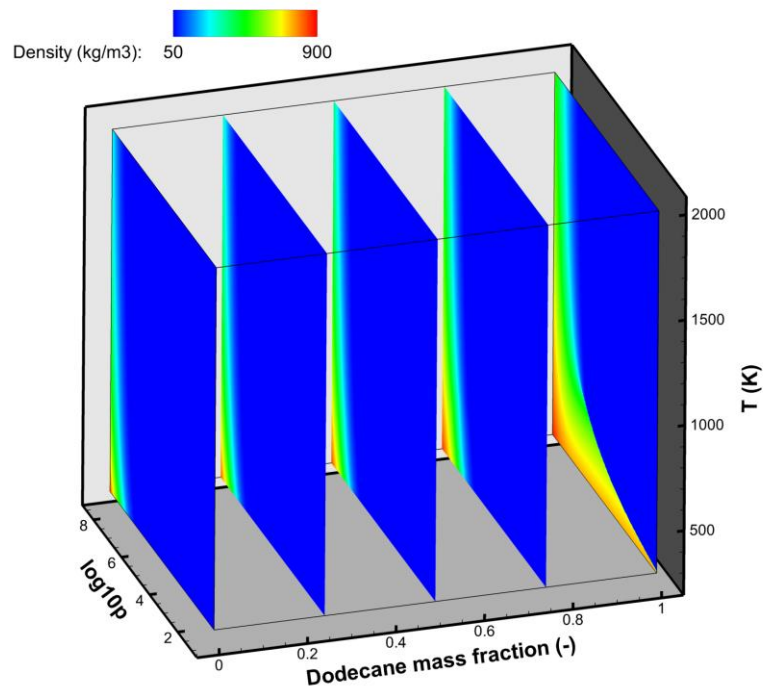
Fuel sprays

- Effect of different fuels can be explored
- Example, different diesel surrogates, such as:
- single component (C12, C14, C16) and
- multi-component (Voa, also V1 – not shown here)



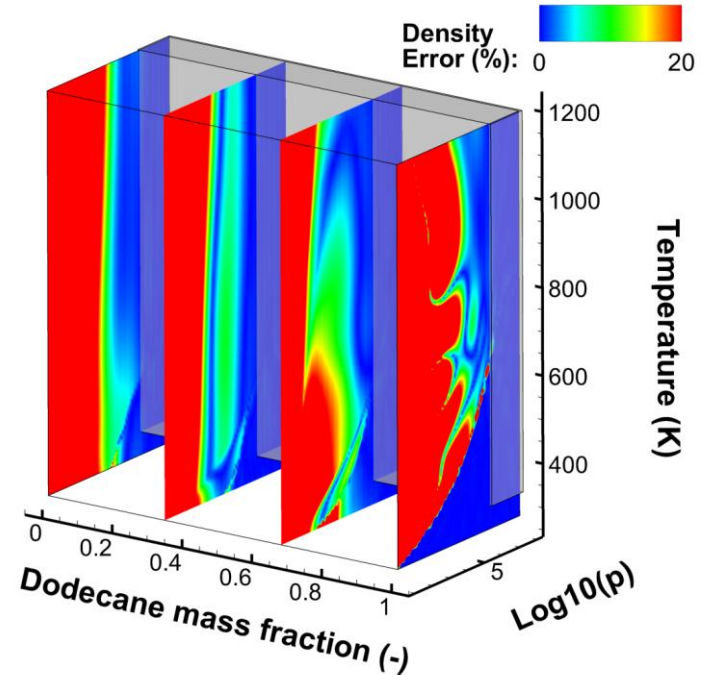
Fuel sprays

- Thermodynamic model is quite costly to evaluate (strongly non-linear)
- Much faster to evaluate it once, tabulate data and then interpolate from table.
- Advantage: simple evaluation of properties (esp. structured table)
- Disadvantage: very large table size, cumbersome for multi-species.



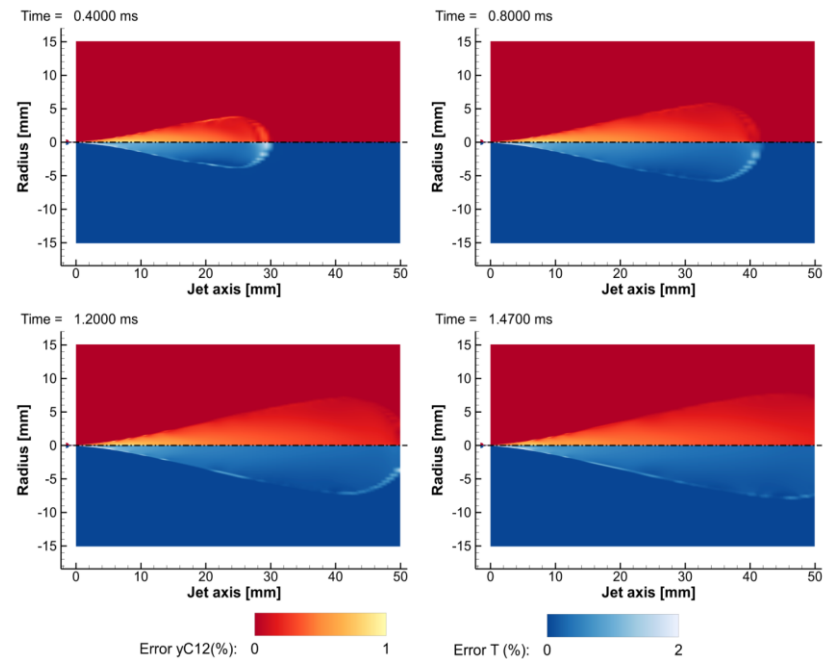
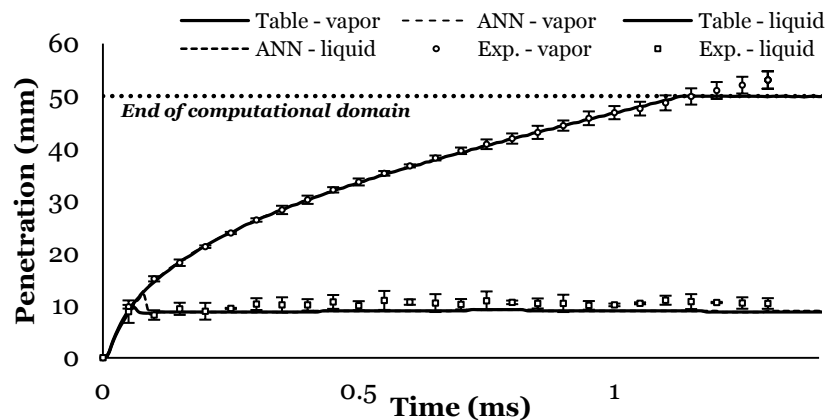
Fuel sprays & ML

- Machine learning can potentially be used as a surrogate thermodynamic model
- Example: C_{12}/N_2 mixture, Shallow NN – 4 layers, Bayesian back propagation.
- A trained Neural Network is much more compact than a table
- Can be generalized to take into account different fuels
- Attention is needed in sharp changes of properties (density)

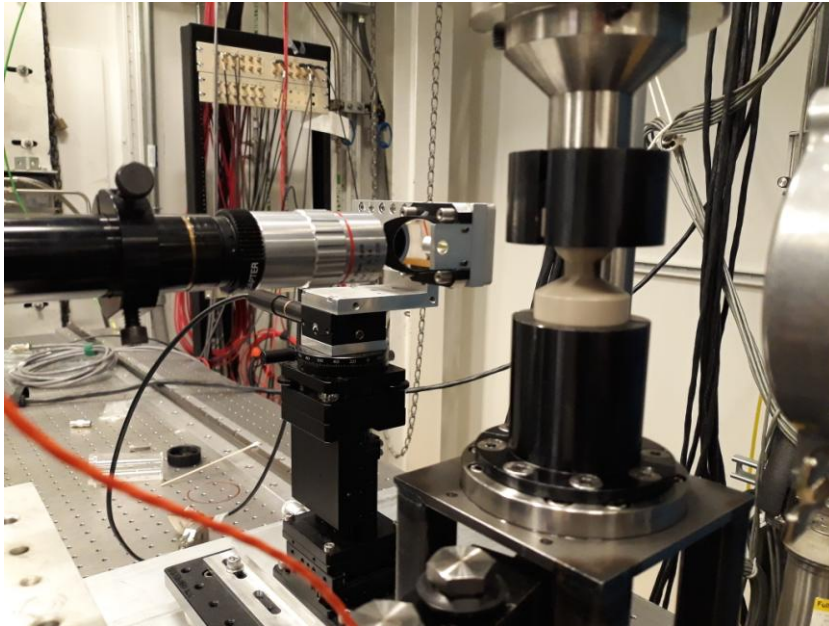


Fuel sprays & ML

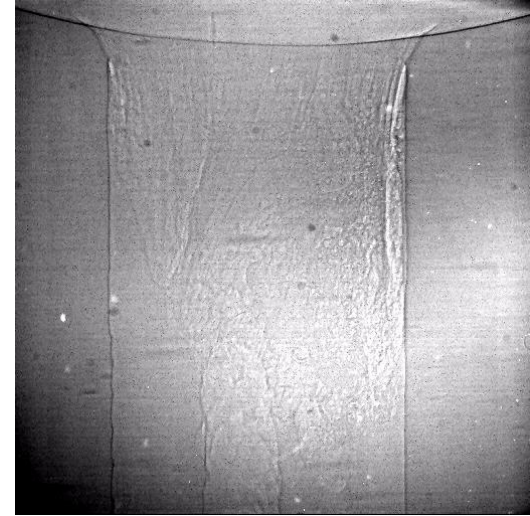
- Effectively same results as tabulated thermodynamic model
- Very little computational overhead (excluding training)



Time resolved X-ray diagnostics



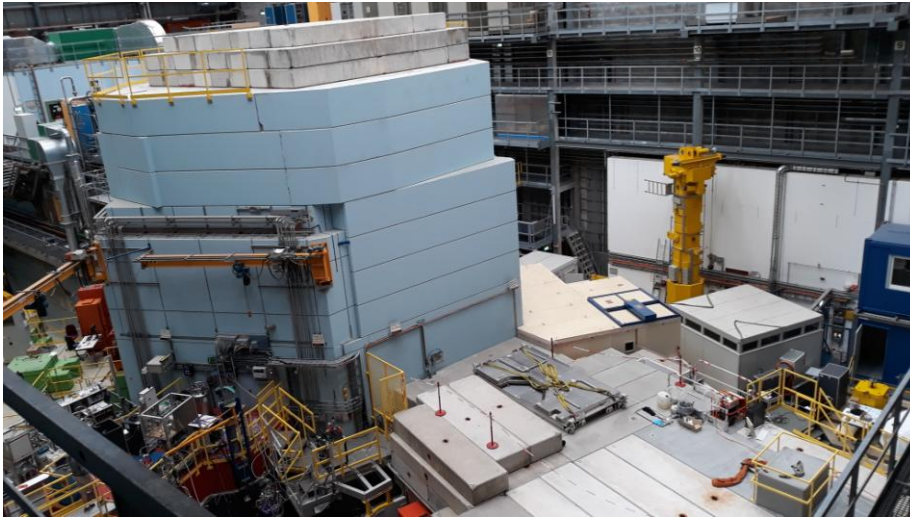
Close-up of PEEK orifice for cavitation investigations



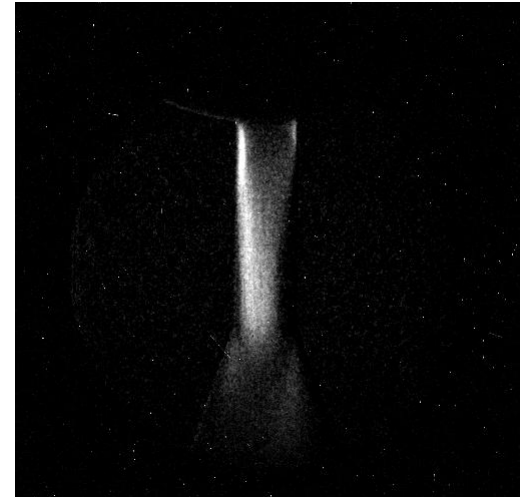
*High speed imaging of cavitation
(70,000fps) within the orifice*

Neutron Imaging

- ICON – cold neutron imaging facility



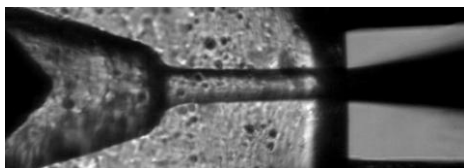
Neutron source and ICON test cell



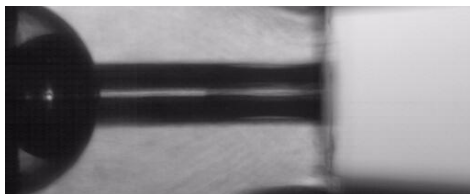
Time averaged (~60s) view of cavitation

Spray diagnostics

- In-nozzle diagnostics

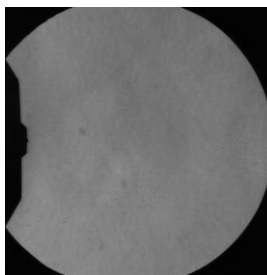


Schlieren

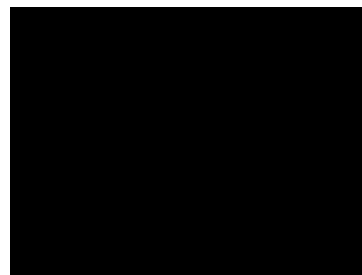


Diffuse Back Illumination

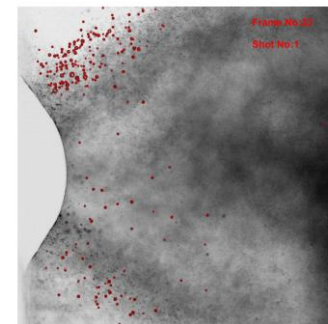
- Spray diagnostics



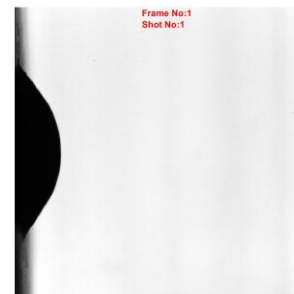
Schlieren



Tomography of LVF



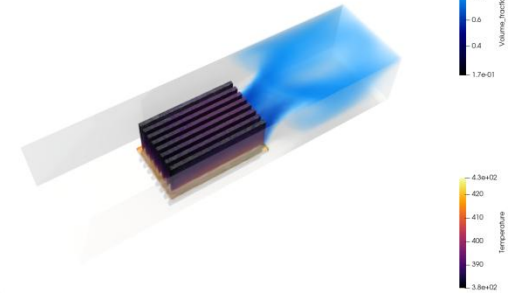
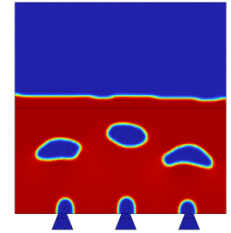
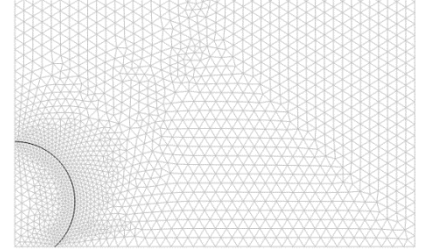
Droplet characterization



Spray angle characterization

Future directions

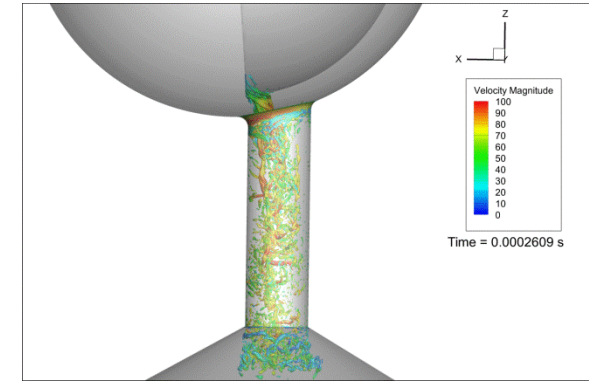
- Multiphase flows for electrification
- Potential of applying two-phase heat transfer for tackling the increasing heat generation density of power electronics/ICs/batteries
- Low-boiling fluids, vapor chambers, heat-pipes etc.
- Interface tracking/capturing + thermodynamic aspects of phase change.



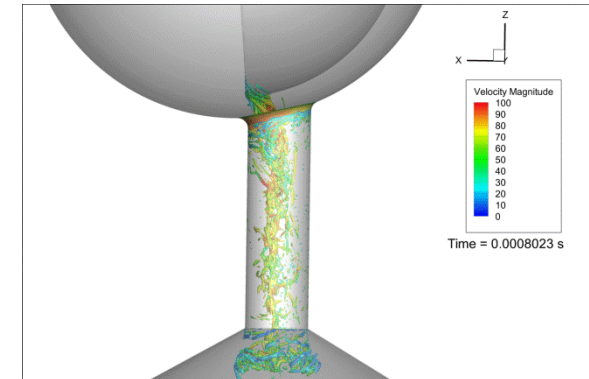
Future directions

- Multiphase flows & non-Newtonian effects
- Viscoelastic fluids have demonstrated the effect to suppress vortical structures (incl. cavitation as well)
- Interest concerning viscoelastic fluids, both subject to cavitation (e.g. biofluids) and as means of controlling turbulence/cavitation/heat transfer.. (additives)

Karathanassis, I.K., Trickett, K., Koukouvini, P. et al. Illustrating the effect of viscoelastic additives on cavitation and turbulence with X-ray imaging. *Sci Rep* **8**, 14968 (2018). <https://doi.org/10.1038/s41598-018-32996-w>



Newtonian – Q crit.



Viscoelastic – Q crit.

Conclusions

- Multiphase flows in the microscale are relevant to industrial, biomedical and fundamental research.
- Challenging topic due to large variations of scales, p/T conditions and properties

Thank you for your attention!

Questions?

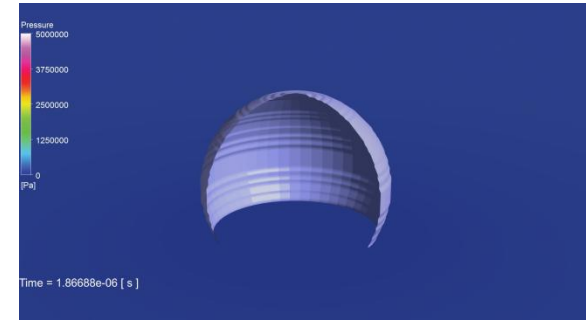
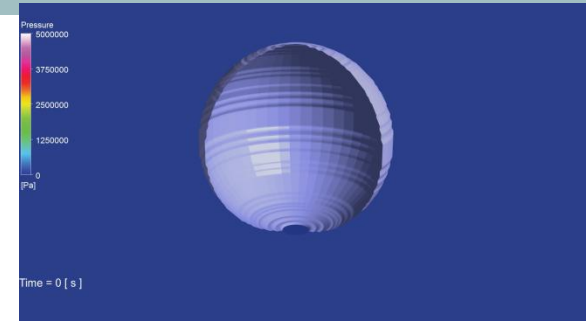
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Colleagues : I. Karathanassis, J. Hwang, N. Kyriazis, A. Papoutsakis, C. Rodriguez, A. Vidal, E. Stavropoulos-Vasilakis, S. Bidi., M.-G. Mithun, N. Mitroglou, M. Gavaises, L. Pickett

Cavitation

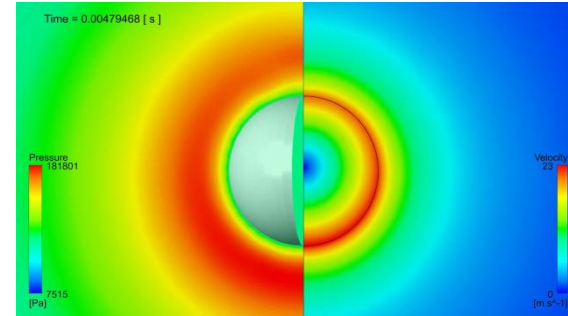
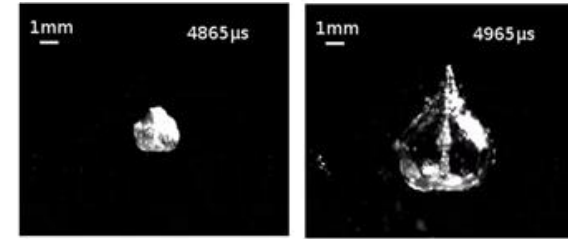
- Cavitation bubbles are very sensitive to pressure gradients
- Asymmetric collapse and formation of jetting (jet velocities in the order of 100s m/s)
- Examples: presence of rigid boundary
- $p_{\infty}=1\text{bar}$, $p_{g,0} = p_{\infty}/8$, $R_0=1\text{mm}$, different contact angles (0, 60°, 120°).

Nikolaos Kyriazis, Phoevos Koukouvini, Manolis Gavaises, Numerical investigation of bubble dynamics using tabulated data, International Journal of Multiphase Flow, Volume 93, 2017, Pages 158-177, ISSN 0301-9322,



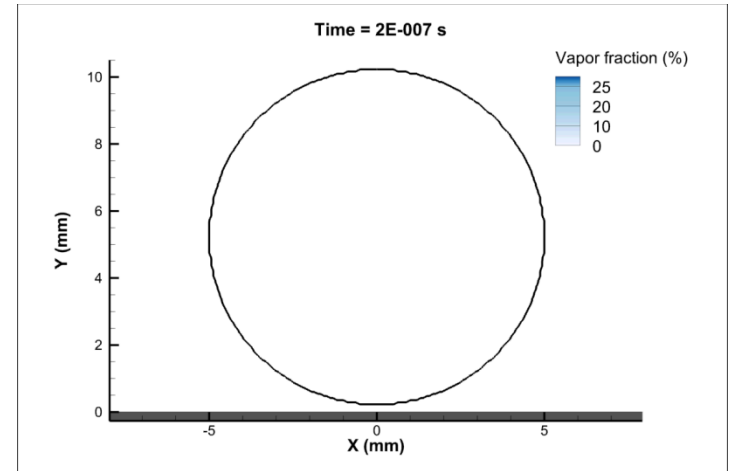
Cavitation

- Other examples of inducing pressure gradients can be material interfaces (free surfaces), or even gravity.
- In the case of material interfaces there is reflection of shock waves as rarefaction waves (and vice versa), giving rise to secondary cavitation



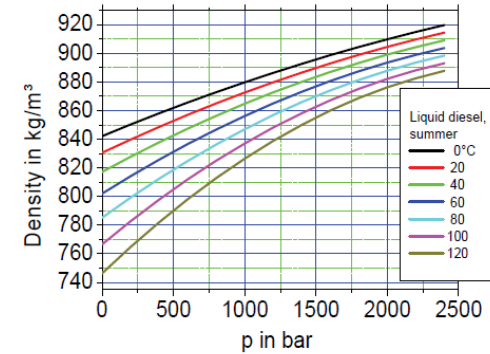
Cavitation

- Cavitation can be also initiated as shockwave reflection at material interfaces, e.g. from strong impacts (percussion)
- Example, cylindrical droplet ($D=10\text{mm}$) impact on wall, at 110m/s
- Relevance to both biomedical (effect of shockwave on tissues) and industrial fields (condensate droplet impact on steam turbine blades)

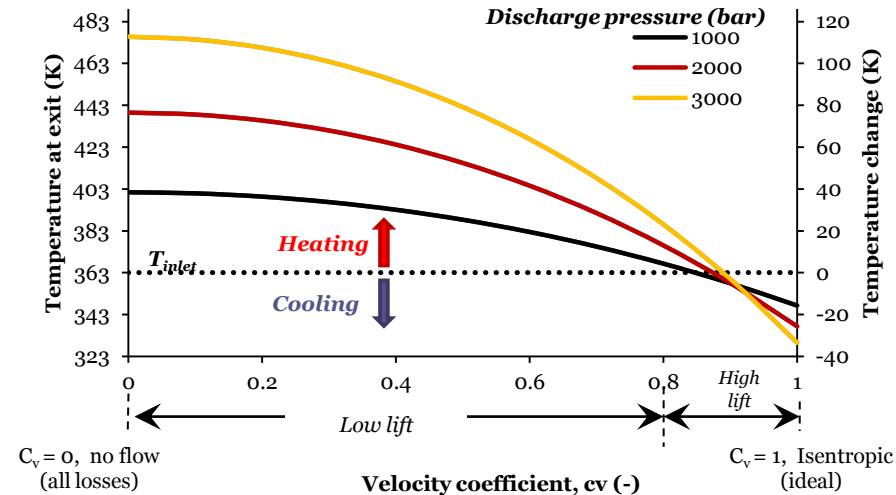


FIE

- Thermodynamics of fuel play an important role in the flow characteristics
- The fuel experiences friction heating, due to viscosity, and cooling, due to expansion.
- At high needle lift (high C_v) -> cooling
- At low needle lift (low C_v) -> heating



Temperature variation for C12 injection, 363K inlet temperature, 1bar outlet pressure



FIE

- Highly transient flow field at start-up and closure / importance in fuel injection strategies
- Relatively steady flow field during high-lift operation
- Influence of initial conditions

Time = 0.0000e+000 s

