Hydrogen Spray Simulation with a Hollow-Cone Injector

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Outline

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- Experimental and Computational Setups
- Computational Validations
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    - H_2 Jet Area and Penetration Length
    - Impact of Needle Lift
    - Shock Wave Prediction
    - Mass Flow Rate
- Conclusions

Background

Hydrogen is a promising green fuel for future transportation. The **direct-injection** hydrogen-fueled internal combustion engine (DI-H_2 ICE) has been viewed as one of the efficient transportation solutions, especially for heavy-duty applications.

Advantages of DI-H_2 in ICEs

- High volumetric efficiency and power density.
- No backfire and pre-ignition.
- High engine combustion efficiency.

Challenges

- High-pressure supersonic injection.
- Rapid fuel-air mixing in a confined chamber.
- Few usable measured data for high-fidelity modeling.

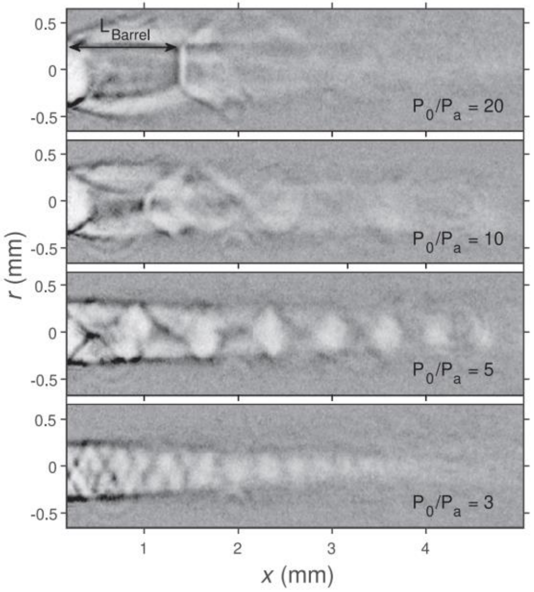

Fig. Near-field H_2 jet behavior at different reservoir pressure ratios[1].

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[1]Int. J. Hydrogen Energy 45 (2020) 32562-32578.

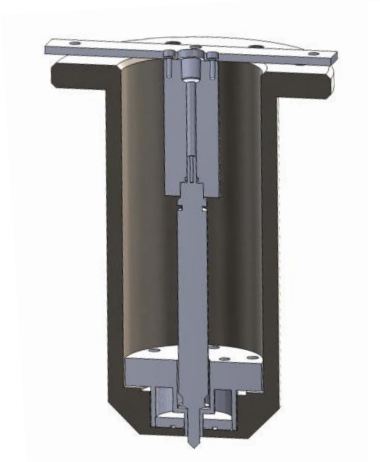
Research Objective

Work in Progress

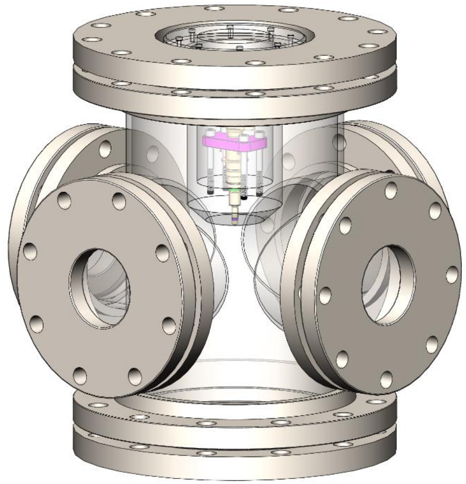
1. Configure numerical models to adequately predict the H_2 jet behavior at different pressures (subcritical and supercritical).
2. Resolve the real injector geometry with a proper mesh to effectively and efficiently perform simulations.
3. Analyze the H_2 jet dynamics and identify the optimum solution to obtain the expected fuel-air mixing distribution.
4. Investigate the effects of nozzle geometry variation, inlet and ambient boundary conditions, and jet/wall interaction on the jet evolution process.

Constant Volume Chamber in KAUST

High-Pressure CVC



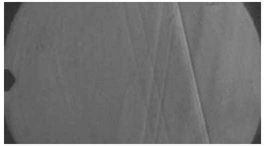
HDEV4 fixture



Test matrix

Parameters	Value
Hydrogen purity	> 99.98%
Hydrogen temperature [K]	298
Injection pressure [bar]	10, 20, 30, 40, and 50
Ambient pressure [bar]	1, 5, and 10
Ambient density [kg/m^3]	1.13, 5.65, and 11.32
Ambient temperature [K]	298
Injection duration [ms]	1 – 5

Z-type schlieren;
Pulsed LED;
30 and 100 K fps



Ambient content: N_2 at 2bar
Injected fuel: H_2 at 11bar

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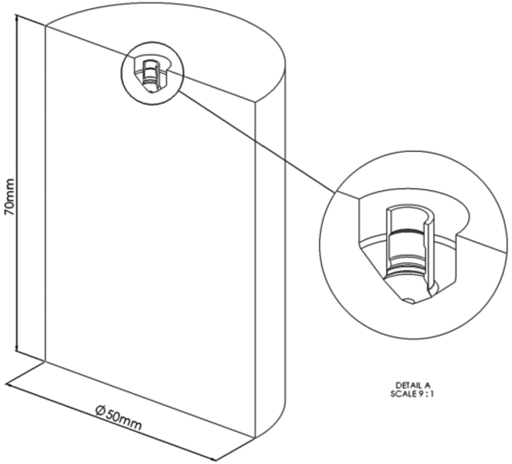
Bosch Hollow-Cone Injector

BOSCH
Invented for life

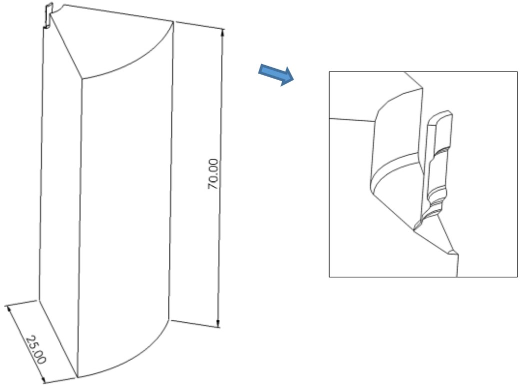
Technical features	
Needle actuation	Direct
Spray angle	85° ± 5°
Shot-to-shot scatter	± 1°
Back-pressure dependence	< 4%
Resistance to carbon buildup	< 3°
Droplet size SMD (Sauter Mean Diameter)	10–15 µm
Penetration	< 30 mm
System pressure	20 MPa
Needle lift	≤ 35 µm
Dynamic flow range q_{dyn}	34.5 mg/lift @ t_i = 1 ms
Partial-lift capability	≥ 10–35 µm
Injection time	70–5,000 µs
Multiple injection	≤ 5 injections/cycle
Interval time	≥ 50 µs
Metering range	0.5–150 mg/injection

1 µm resolution

Half domain



60° sector



X-Ray tomography from Prof. Lubineau and Hassan Al-kady (PhD student).
PSE Divion, Mechanics of Composites for Energy and Mobility Laboratory

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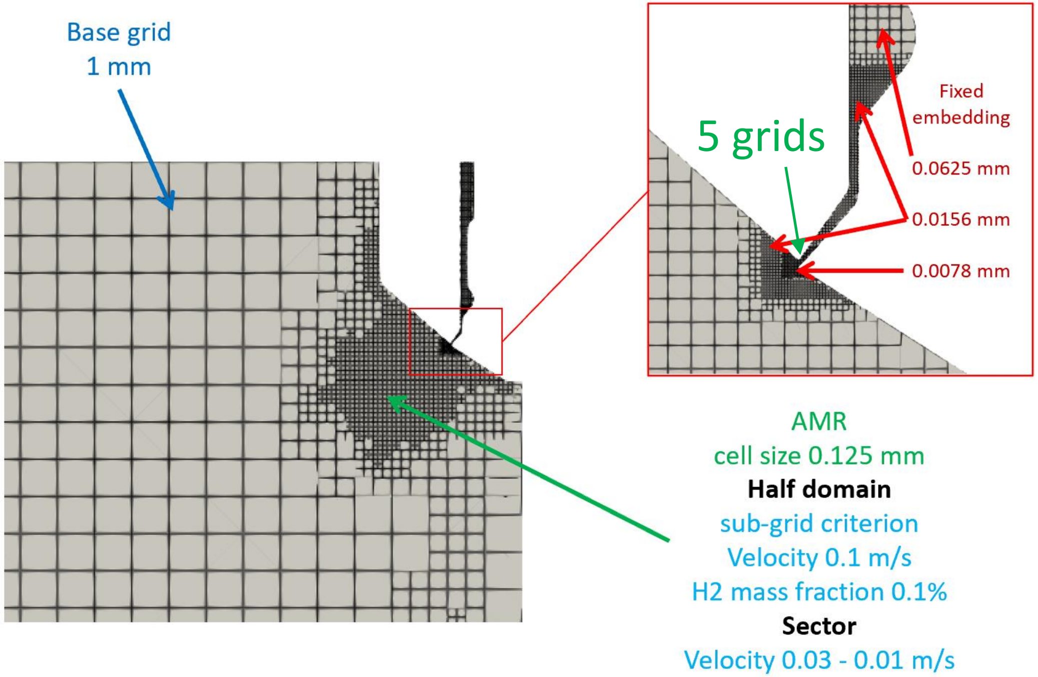
Mesh Details and Boundary Conditions



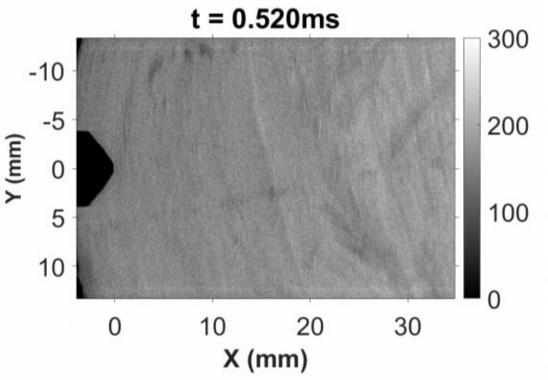
Fuel	H_2
Ambient gas	N_2
Injection pressure (bar)	11, 21, 51
Ambient pressure (bar)	2
Injection and ambient temperature (K)	298.15
Equation of state	Redlich-Kwong
Injector type	Hollow cone
Simulation type	Eulerian
Simulation duration (ms)	2

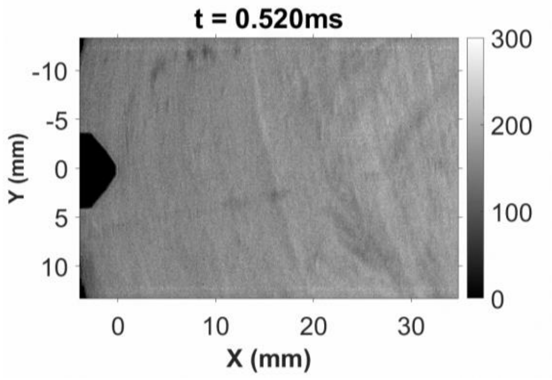
- CONVERGE 3.1 for CFD modeling.
- Turbulence model: RNG k-ε.

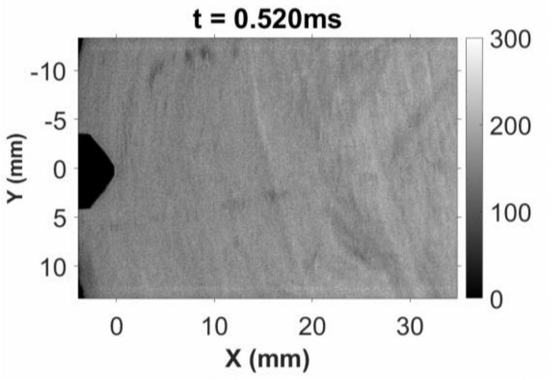
Qualitative Comparison – Jet Evolution

P_{inj} = 11 bar | P_{inj} = 21 bar | P_{inj} = 51 bar

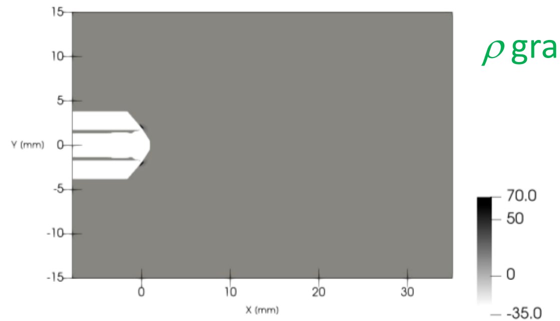
Experiment
Z-type schlieren



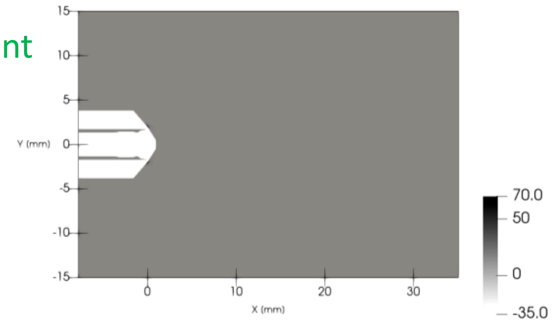


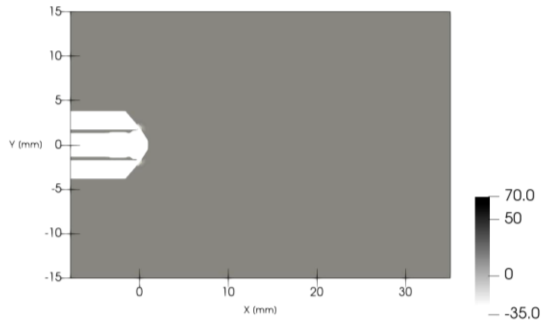


Simulation
Plane schlieren



ρ gradient





- Jet initiation delay due to hydraulic delay and starting video
- The predicted fields are overall reasonable.

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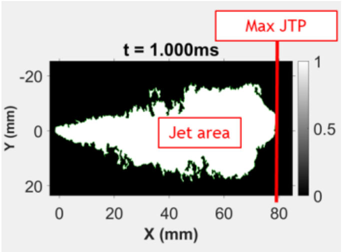
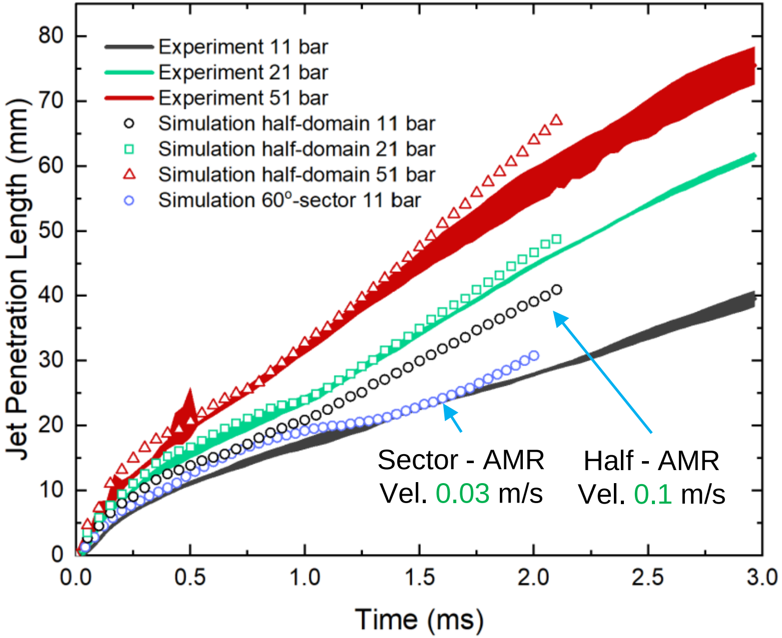
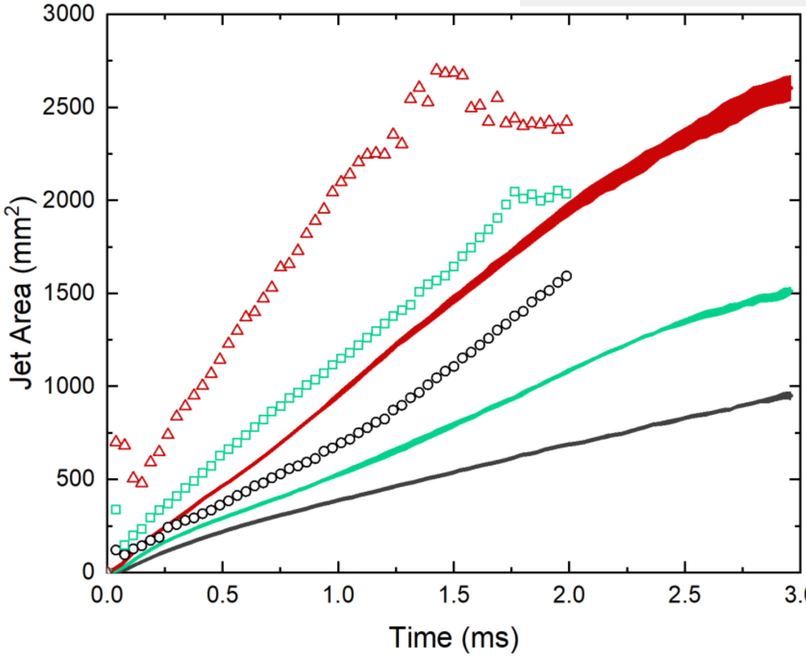
Jet Penetration and Area







- Jet penetrations could be reasonably reproduced with a very fine AMR velocity sub-grid criterion.
- Jet area still existed a large discrepancy that should resolved.

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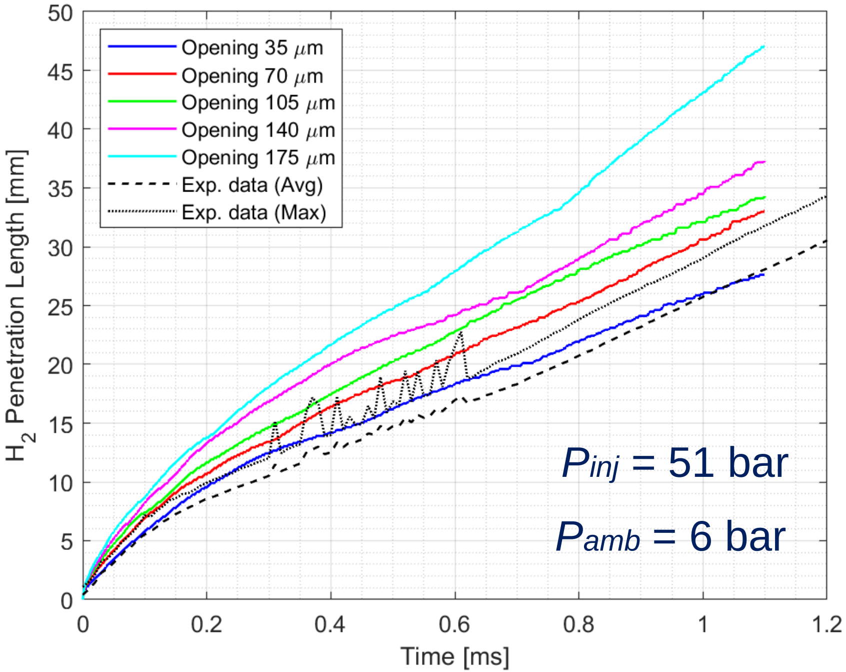
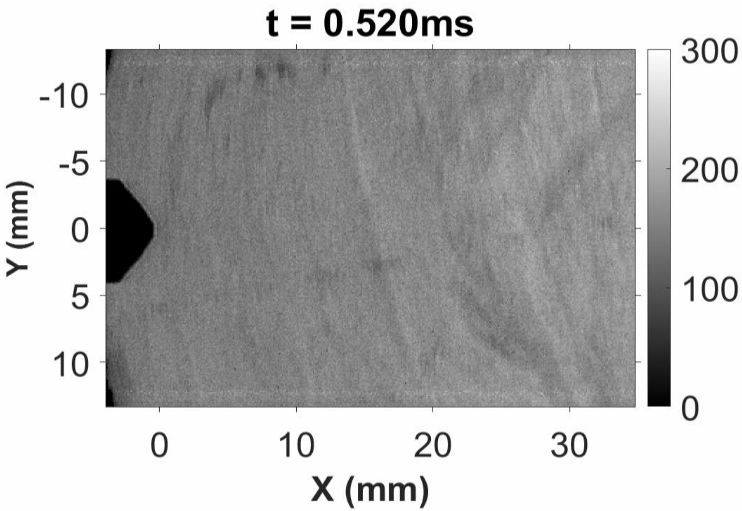
Impact of Needle Lift



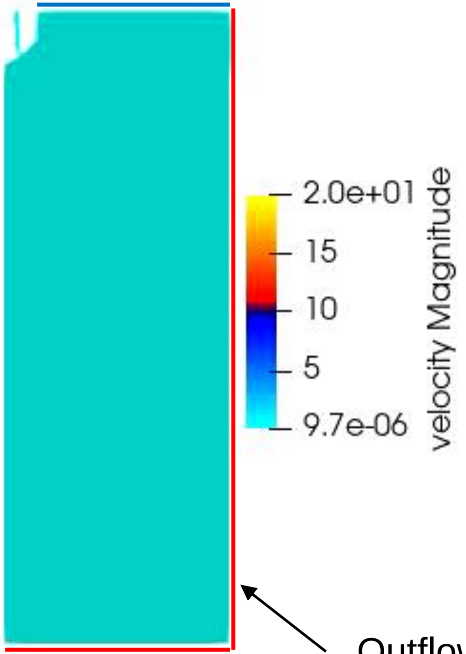


- Penetration increases with a higher needle lift.

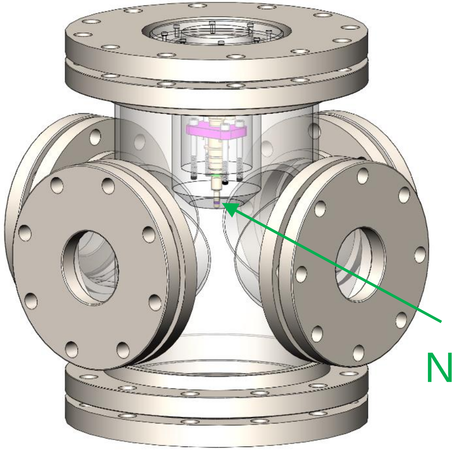
Shock Wave Observation

Experiment

Plane of 60° sector simulation



CVC test kit



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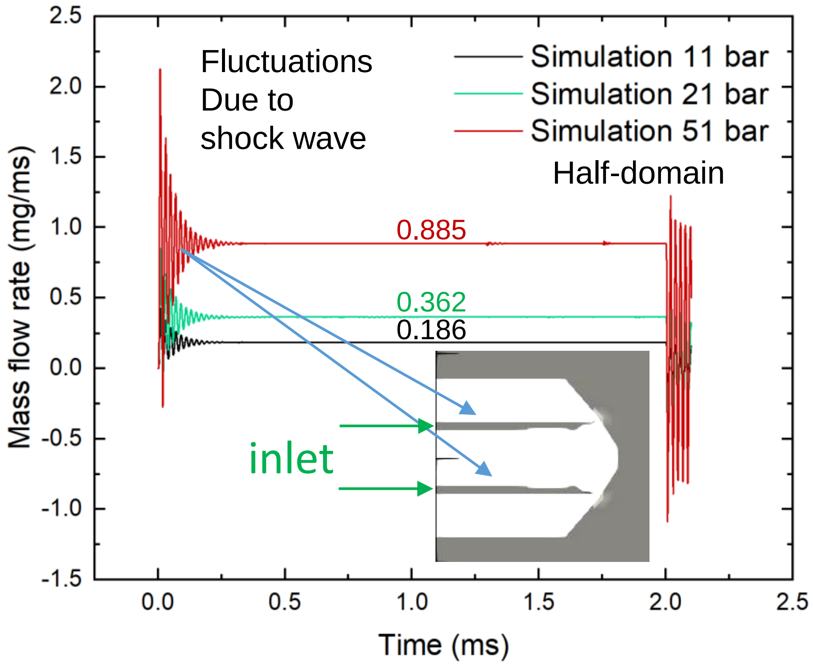
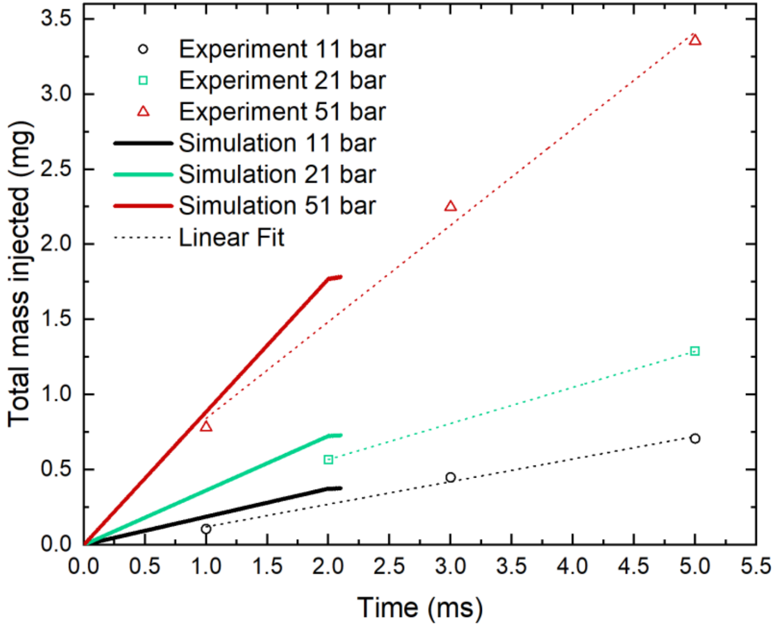
- Wave reflection issue in outflow possibly due to boundary setup.

Mass Flow Rate and Fuel Consumption



Integrated



- Initial pressure difference between two regions led to shock, which induced pressure fluctuation on the inlet boundary.
- Maybe more data from experiment needed to ensure more accurate slope.

Conclusions

1. For H_2 jet simulation using a hollow-cone injector, a precisely-measured nozzle geometry is significant in reproducing the measured jet metrics.
2. The predicted jet penetration is very sensitive to the mesh setup, especially near the nozzle exit region. A finer AMR sub-grid criterion resulted in the better agreement with measured data.
3. Injection pressure, needle lift, and start of injection timing are three of the most significant parameters that affect the prediction of jet penetration.
4. The outflow boundary with a fixed pressure condition yielded shock wave reflection, which should be resolved by properly setting up the outlet or wall boundary condition.

شكراً

THANK YOU!

Question?

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