Modeling of Direct Gas Injection in Internal Combustion Engines

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- License of compressible LES solver CHRIS was provided by Cascade Technologies Inc.

- Simulations were performed with computing resources granted by RWTH Aachen University under project thes0382 and JARA0117.
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Motivation:
Spark-Ignited Direct Injection Engine with CNG as Fuel

• Emissions
  – CNG composition\(^1\): \(70\text{-}95\% \text{CH}_4\)
  – High H/C ratio leads to lower \(\text{CO}_2\) emissions (upto \(25\%\) reduction\(^3\))
  – Lower particulate emissions\(^2\)

• Potentially higher thermal efficiency
  – High resistance to knock => High compression ratio

• Direct Injection vs Port Injection
  – Higher volumetric efficiency

➢ Design and optimization of DI CNG engines using numerical simulations (URANS)

However, this is challenging

\(^2\) INGAS- Integrated GAS Powertrain, Project Final Report.
Challenges in DI CNG Simulations

• Direct gas injector: Poppet-type valves
  – Small and complex gas passages (order of micrometer)
    • Small mesh size (10-20 µm) required to resolve flow in the gaps

• Compressible flow in gas passages
  – High pressure ratios: Supersonic velocities (~1000 m/s)
    • Under/Over-expanded configuration leading to expansion waves or compression shocks
    • Small time-step of order of 10 nanoseconds on coarse mesh
  – Typical duration of injection in an engine: 3-6 ms
    - Simulation time for a full engine cycle including injection: 3-4 weeks

➢ First focus on injection process
Simulation Setup

- Axi-symmetric cylindrical domain
  - Diameter: 75 mm, Length 82.5 mm
- Injected fluid: **Helium**
- Fluid in cylinder: **Air** (77% N\(_2\), 23% O\(_2\) by mass)
- Boundary conditions:
  - Inlet total pressure: **15 bar**
  - Inlet temperature: **298 K**
  - Injector walls: **Adiabatic**
- Initial conditions:
  - Pressure: **1.01325 bar**
  - Temperature: **298 K**
- Duration of Injection: **0.8 ms**
• Base size: 2 mm
• Fixed Embedding as shown in Figure
• No adaptive mesh refinement (AMR)
Nozzle Flow Model

• Scale separation
  • Separate nozzle flow from the full simulation: Develop a fast and accurate model
  • 3D simulation of the downstream region

➤ Model the poppet-type valve as a duct with varying area of cross section

![Diagram of nozzle flow model with poppet-type valve and duct with varying area of cross section.](image)
Solve one-dimensional (1D) system of inviscid Euler equations for the duct with varying area

\[ \frac{\partial \rho A}{\partial t} + \frac{\partial \rho u A}{\partial s} = 0 \]
\[ \frac{\partial \rho u A}{\partial t} + \frac{\partial (\rho u^2 + P)A}{\partial s} = -P \frac{\partial A}{\partial s} \]
\[ \frac{\partial \rho E A}{\partial t} + \frac{\partial (\rho E + P)u A}{\partial s} = -P \frac{\partial A}{\partial s} \]
\[ A = A(s, t) \]
\[ \frac{\partial A}{\partial t} = 0, \text{for fixed needle lift} \]
\[ \frac{\partial A}{\partial t} \neq 0, \text{for moving needle} \]

- Solved using MUSCL scheme (upto 2nd order spatial accuracy) and forward Euler time integration scheme
- CFL: 0.3
1D Code Validation: Comparison with 3D LES* of Nozzle at Steady State

- Helium at nozzle pressure ratio of 15
- Reasonable prediction of the nozzle internal flow using 1D code

* LES was performed using CHRIS solver developed by Cascade Technologies Inc.
Coupling of 1D code to CONVERGE using mass, momentum, and energy sources
## Simulation Cases

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• **CONVERGE Setup:**
  - URANS with **RNG k-epsilon** turbulence model
  - Second order numerical scheme with fully implicit time integration

• **Experimental data using Schlieren imaging provided by Delphi**
  - Injection into open ambient conditions
  - Injection pressure: 16 bar
Results: Fixed Needle

3D Valve Geometry

1D Valve Model

t = 800.021 µs
t = 800.064 µs
Quantitative Parameters

- Axial Penetration Length (APL)
- Maximum Width (MW)

- Area of Jet (AJ)
- Volume of Jet (VJ)
Quantitative Comparison
Fixed Needle

- Reasonable agreement between Full 3D nozzle and 1D nozzle flow model
Needle Opening Effects using 1D Code

Needle Lift Vs. Time

Needle Lift [μm] vs. Time [μs]

Normalized Area [-]

Mach Number [-]

Pressure [bar]

Needle Lift Vs. Time

Normalized Area [-]

Mach Number [-]

Pressure [bar]
Results: Needle Lift Profile

3D Valve Geometry

1D Valve Model

t = 805.005 μs

t = 800.143 μs
Quantitative Comparison Moving Needle

- Initial non-linear behavior captured well with 3D valve geometry, but later deviates from experiments

This is still a work in progress
Reduction in Computational Cost

Time-step relative to minimum time-step in 3D

![Graph showing Time-step relative to minimum time-step in 3D with different cases: 3D-FN, 1D-FN, 3D-MN, 1D-MN.]

- Computational cost reduced by a factor of 5-6
A one dimensional nozzle flow model was developed for a poppet-type gas injector.

The 1D code is coupled to CONVERGE and the results with fixed needle lift agree with full 3D case and reasonably with experiments.

Computational time reduced by a factor of 5-6 by increasing the simulation time-step using the nozzle flow model.

Next

Further investigation of effect of needle opening on gas jet evolution

Application to full engine simulations
Thank you for your attention

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