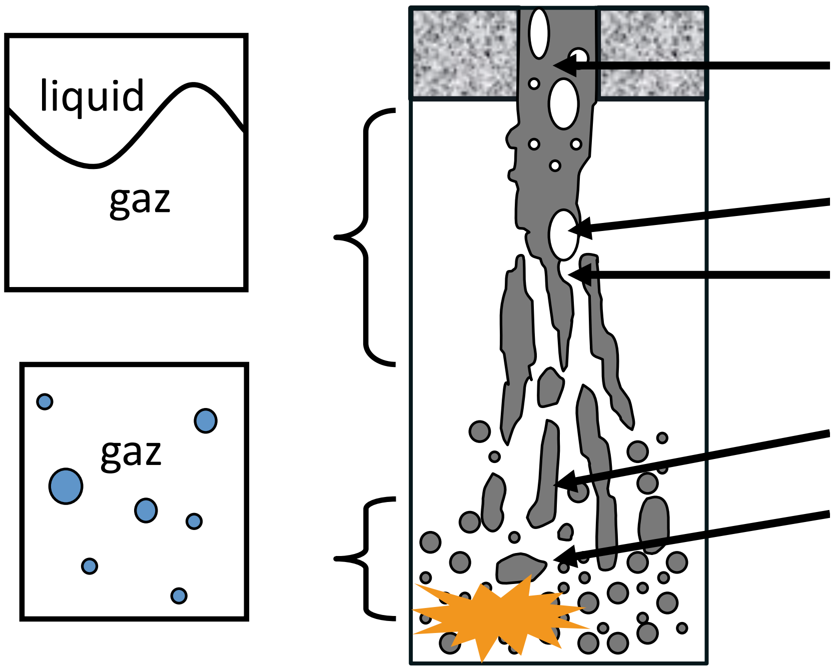
Describing a polydisperse evaporating spray with mesh movement for internal combustion engine applications

D. Kah, M. Massot, F. Laurent

O. Emre, Q.H. Tran, S. de Chaisemartin, S. Jay

General context:
Fuel Injection in engines

- Simulation of fuel injection in internal combustion engines
- Context: better understand engine cycles to reduce pollutants, increase efficiency



- Cavitation
- Primary atomization
- Turbulence in surrounding gas due to drag force exerted by the liquid
- Secondary atomization
- **Evaporation**, **drag**, heat exchange
- Collisions, coalescence

Better predict fuel fraction in gas before combustion
description of polydispersity

Disperse phase statistical modeling

- Statistical approach with Number Density Function (NDF) $f(t, \boldsymbol{x}, S, \boldsymbol{u})$

Simplified Williams-Boltzmann equation *(Williams, 58)*

$$\partial_t f + \underbrace{\nabla_{\boldsymbol{x}}(\boldsymbol{u} f)}_{\text{advection}} + \underbrace{\partial_S(K f)}_{\text{evaporation}} + \underbrace{\nabla_{\boldsymbol{u}}(\boldsymbol{D}_{\mathrm{r}} f)}_{\text{drag}} = 0$$

Eulerian framework: Resolution of f with Finite Volume method expensive:

Resolution of moments : $\mathcal{M}_{k,\boldsymbol{l}} = \int_{S_{min}}^{S_{max}} \int_{\mathbb{R}} S^k \boldsymbol{u}^{\boldsymbol{l}} f \, \mathrm{d}\boldsymbol{u} \mathrm{d}S$

Disperse phase statistical modeling

- Polydispersity → size moments: $m_k = \mathcal{M}_{k,\mathbf{0}}$

Sectional methods

- Multi-Fluid ***(Laurent & Massot, 2001, de Chaisemartin 2009))***
- One moment
- Several sections
- Costful

High order moment methods

- Presumed NDF ***(Mossa, 2005)***
- DQMOM ***(Fox et al., 2008)***
- Several moments
- One section
- Not generic (presumed NDF)
- Accuracy or stability issue for evaporating term

- **None of the methods are satisfactory for our purpose**

STANFORD MECHANICAL ENGINEERING

Disperse phase statistical modeling

EMSM (Eulerian Multi-Size Moment) model…

- Treat evaporation term stably and accurately
- Generic
- Much faster than Multi-Fluid model (10 sections) (4 times faster in 2D)
- One-way framework
- Cell-centered, steady, structured meshes
- Validated of academic test cases *(Massot et al., 2010) (Kah et al., 2012)*

… to be exported to an industrial software

- 2 way coupling
- ALE (Arbitrary Lagrangian Eulerian) :
- Staggered grid

Description of fuel injection
Moving mesh formalism
Implementation in industrial software

Outline

- EMSM: model and achievements
- Extension of EMSM to ALE formalism
- Validation in industrial software

Outline

- EMSM: model and achievements
- Extension of EMSM to ALE formalism
- Validation in industrial software

EMSM: one-way framework

Moment equation system

$$\partial_t m_0 + \nabla_{\boldsymbol{x}}(m_0 \boldsymbol{u}_p) = -Kn(t, \boldsymbol{x}, S = 0)$$

evaporating flux

$$\vdots$$

$$\partial_t m_N + \nabla_{\boldsymbol{x}}(m_N \boldsymbol{u}_p) = -KN m_{N-1}$$

$$\partial_t m_1 \boldsymbol{u}_p + \underbrace{\nabla_{\boldsymbol{x}}(m_1 \boldsymbol{u}_p \otimes \boldsymbol{u}_p)}_{\text{advection}} = \underbrace{-K m_0 \boldsymbol{u}_p}_{\text{evaporation}} - \nabla_{\boldsymbol{x}} P + \underbrace{\boldsymbol{D}}_{\text{drag}}$$

Closure issues in model

- $\boxed{f(t, \boldsymbol{x}, S, \boldsymbol{u}) = n(t, \boldsymbol{x}, S)\delta(\boldsymbol{u} - \boldsymbol{u}_p)}$ ➡ $P = 0$ (velocity dispersion)
- Closure of $n(t, \boldsymbol{x}, S = 0) = \Phi(m_0, ..., m_N)(t, \boldsymbol{x})$

Challenge: reconstruct, from the moments,

a pointwise value of the size NDF

Stability condition : **Realizability condition**

➡ Approximation of the size NDF by **Maximization of Entropy** *(Mead and Papanicoloaou, 84)*

$$\boxed{\boldsymbol{m}_N = (m_0, \ldots, m_N)^t \longrightarrow \tilde{n}_{ME}}$$

EMSM: one-way coupling framework

Numerical Strategy and issues

- Splitting: Successive resolution of evaporation, transport and drag
- Evaporation: System **cannot** be solved by ODE solvers: **Realizability Condition**
- Transport:
  - $P = 0$: Pressureless gas dynamics (**Singularities** and **Vacuum zones**)
  - **Realizability Condition**

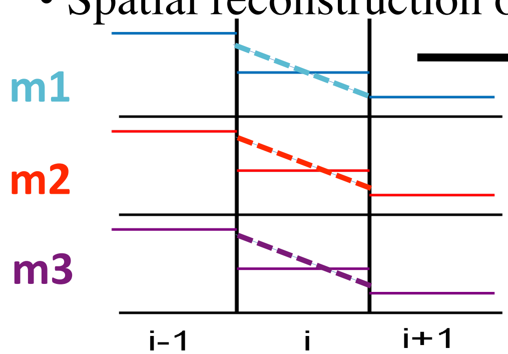
Solutions

- Flux computation : **Kinetic scheme**:

➔ Finite Volume method with exact computation of the fluxes from reconstructed profiles *(Bouchut et al, 2003)*

Evaporation *(Massot et al., 2010)*

- Spatial reconstruction of moments: **Canonical moments**



→ Realizability condition might not be satisfied in the whole cell *(Wright 07, McGraw 07)*

➔ Canonical moments

Transport *(Kah et al., JCP, 2012)*

STANFORD MECHANICAL ENGINEERING

EMSM: two-way framework

Moment equation system

Navier-Stokes equation system
+
Source terms

Solver for coupled system *(Emre et al., 2012)*

•Splitting sequence: transport / evaporation-drag
→ Fully coupled ODE system solved: gas and spray variables simultaneously vary

•Ability to solve for stiff problem with a time step not constrained by smallest time scales
→ Implicit Runge Kutta method

• Realizability condition satisfaction
→ Evaporation decoupled from drag

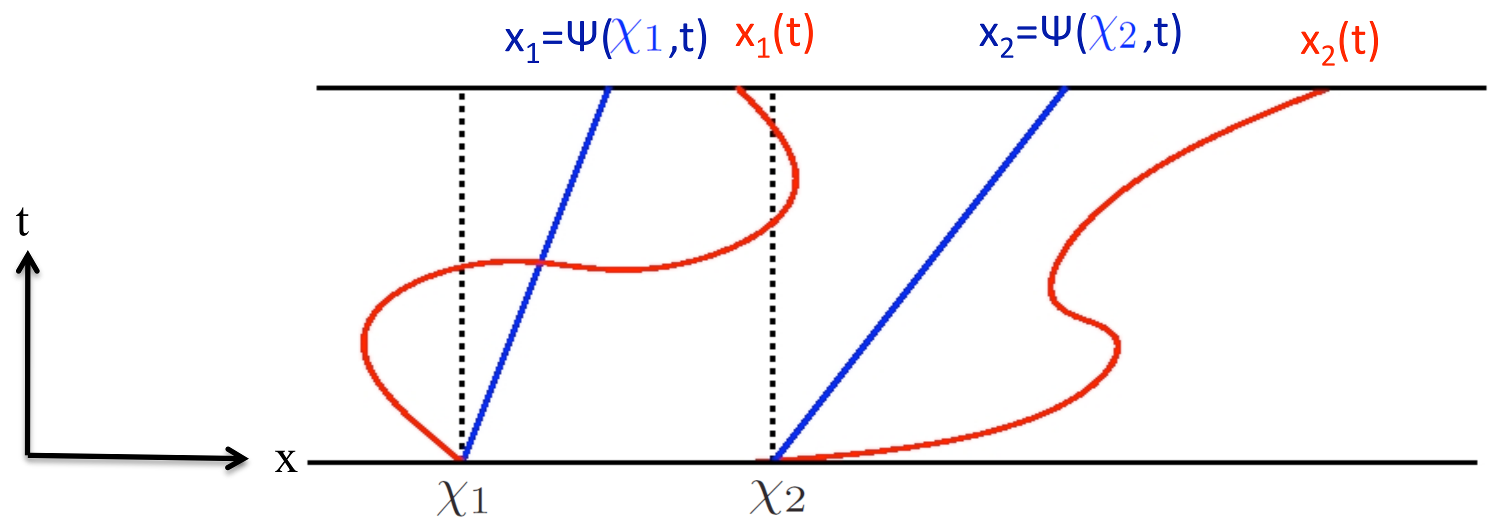
Outline

- EMSM: model and achievements
- Extension of EMSM to ALE formalism
- Validation in industrial software

Extension of EMSM to ALE: Principle of ALE

- IFP-C3D: moving boundary conditions (moving piston)
- Strategy adopted: ALE

Principle of ALE



- Resolution along the mesh characteristic (blue curves)

- Interest: Combination of *(Donea, 04)*
  - Accuracy of Lagrangian methods
  - Robustness of Eulerian methods

Extension of EMSM to ALE: Algorithm of IFP-C3D

- Operator splitting algorithm in IFP-C3D:
  - Phase A: source terms (evaporation, drag, …) Δt
  - Phase B: resolution of acoustic terms Δt
  - Phase C: advection terms / rezoning step Δt

Decouples acoustic waves from convective waves

Extension of EMSM to ALE: Achievements in a structured grid

- One-way coupling: high order transport scheme for moments in moving, staggered, structured grid (phaseB and C)

Moment transport

•Adaptation of kinetic scheme during rezoning step, with variable cell size (phase C)
• Realizability condition enforced and accuracy preserved

Momentum transport

• Nodal definition of velocity: dual mesh with variable cell size
• Computation of the momentum fluxes so that the two properties are enforced:
  • Conservation of momentum
  • Maximum principle on velocity

(Larrouturou 04)

High order in time and space on a moving structured grid *(Kah et al., IJMF,12)*

Extension of EMSM to ALE: Achievements in an unstructured grid

- Extension to two-way coupling: Source term resolution in phase A

Resolution method
• Local resolution: independent of mesh movement, same solver as in Eulerian grid • Nodal definition of velocity: dual mesh with variable cell size

Outline

- EMSM: model and achievements
- Extension of EMSM to ALE formalism
- Validation in industrial software

Validation in industrial software: Implementation in IFP-C3D

IFP-C3D *(Bohbot et al., 09)*

- A hexahedral unstructured solver devoted to internal CFD with spray and combustion modelling
- The conservation equations are solved on moving grids
- The equations are solved using a finite volume method extended with the ALE (Arbitrary Lagrangian Eulerian) method.
- The k-ε turbulence model is used (RANS)

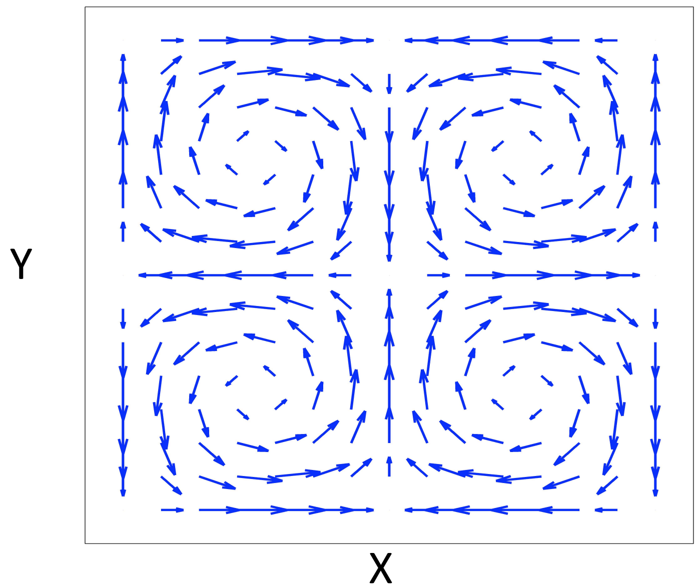
Implementation in IFP-C3D

- Validation on three test cases:
  - Moving piston : validates spray dynamics with mesh movement
  - **Interaction with Taylor-Green Vortices**
  - **Fuel injection in bomb-chamber**

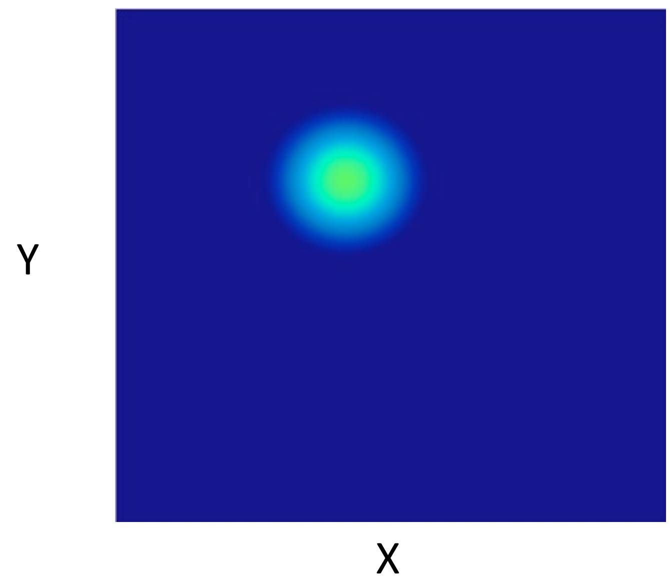
Validation in industrial software: Taylor-Green vortices

- 2D test with evaporation and drag (One-way coupling)

Taylor-Green vortices for gas flow

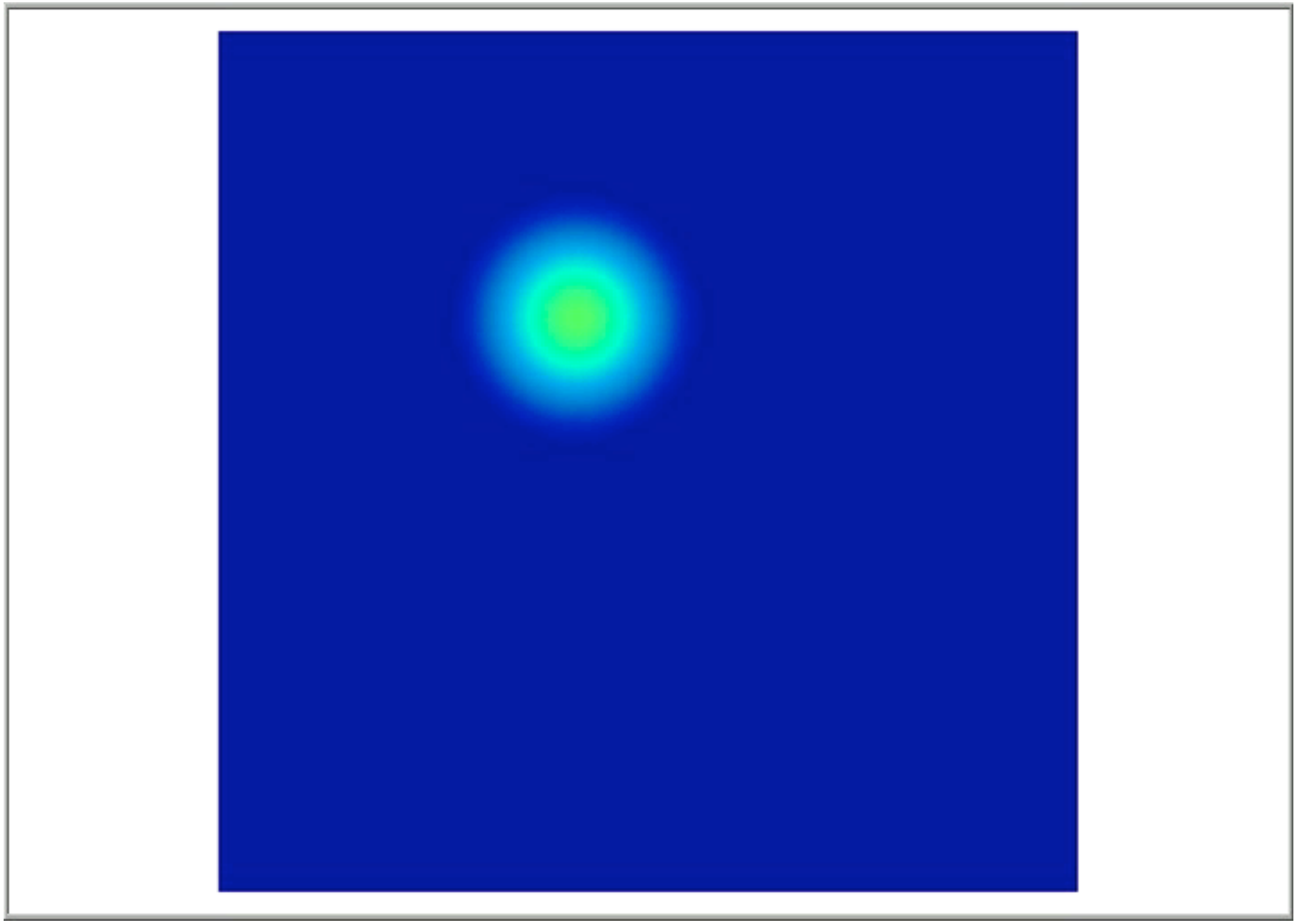


Initial condition for the spray



- Periodic Boundary conditions
- Drag: Maximum Stokes = 2.81
- Evaporation: K = 0.21
- Final time = 2 (one eddy turnover time)

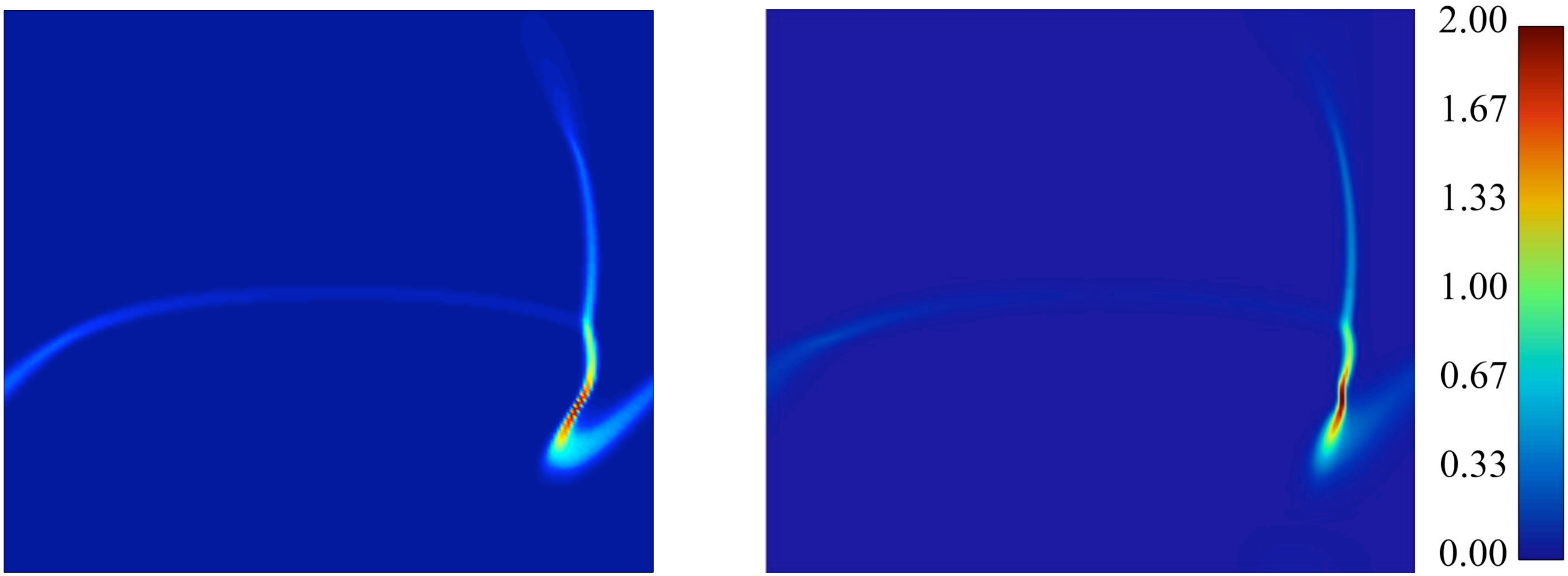
Validation in industrial software: Taylor-Green vortices



Validation in industrial software: Taylor-Green vortices

- Comparison with DNS code

- **Muses3D**
  - Structured
  - Eulerian
  - 2nd order
- C3D
  - Unstructured
  - ALE
  - 1st order



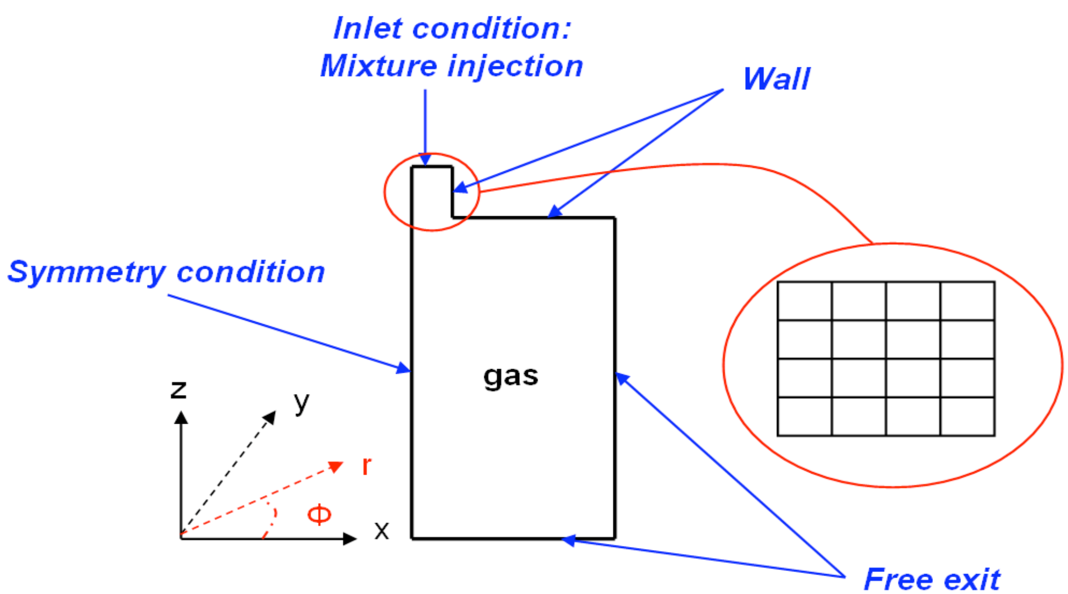
Very satisfactory level of comparison
Same robustness in IFP-C3D as in Muses3D

Validation in industrial software: Two-way coupling

- Fuel and gas injection in steady gas phase
- No turbulence model, coarse mesh, steady geometry

→ Test robustness of EMSM with two-way coupling in computation with ALE

- 2D axisymetrical test case:



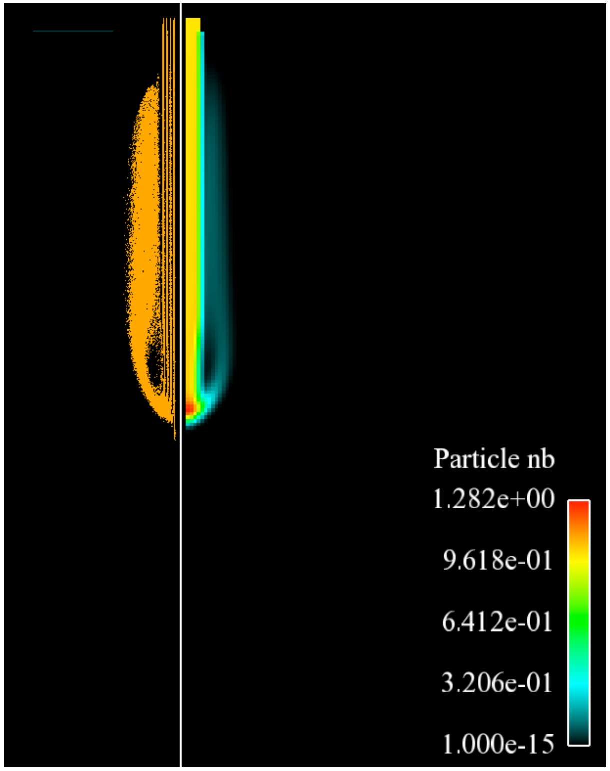
Physical parameters:

- Evaporation spray
- Drag: Average Stokes = 0.5
- Injection velocity : 18 m/s
- Rosin-Rammler distribution (smr =5 μm)

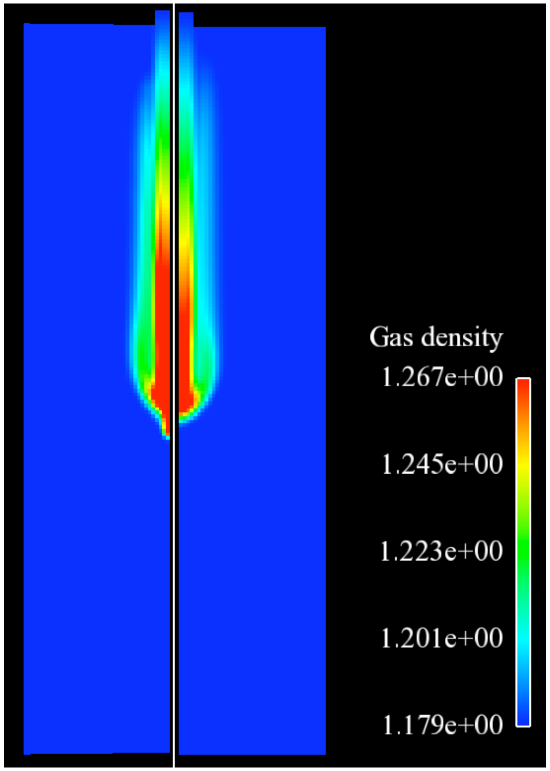
Validation in industrial software: Fuel Injection

- Comparison Lagrangian vs EMSM with two-way coupling framework:

Lagrangian / Eulerian
(Particle number)



Lagrangian / Eulerian
(Gas density)



Robustness of two-way coupling algorithm in ALE framework

Conclusions

- ✓ EMSM in ALE (one-way coupling framework)

  Extension of high order scheme transport for moments and momentum *(Kah et al., JCP, 12)* to ALE formalism, preserving **stability** and **accuracy** for moments *(Kah et al., IJMF, 12)*

- ✓ EMSM in a two-way coupling framework

  Solver for the two-way coupling, able to solve for **stiff** system while preserving the **realizability** of the moment vector; extension in **ALE** formalism *(Emre et al., ECCOMAS, 12)*

- ✓ Implementation in IFP-C3D and validation of numerical tools

  Scheme robustness assessed through mesh movement; implementation validation through comparison with DNS; Proof of robustness of two-way coupling algorithm in Ale formalism

Perspectives

- Modeling:

  Size-velocity correlation for EMSM *(Vie et al., JCP, 2011)*

- Turbulence modeling:

  Introduce fluctuation terms from RANS modeling

- Numerical Scheme :

  High order scheme in unstructured mesh

- Validation:

  Computation of a real injection case, with mesh movement, refined mesh, turbulence model, and comparison with experimental data