An improved sub-grid scale flow model for transient fuel sprays

Federico Perini, Rolf D. Reitz

Funding Sponsor – Sandia National Laboratories

Motivation

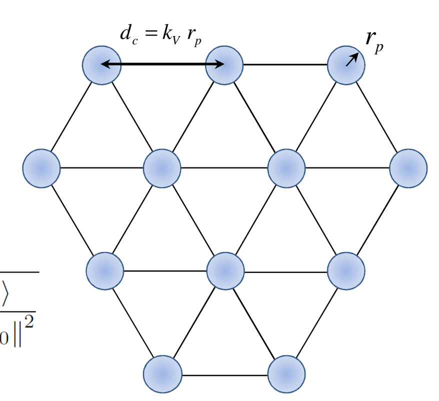
- Combustion efficiency and noise control in engines require multiple injection strategies
- Transients become a relevant part of the injection, affecting spray jet properties
- Computational efficiency of the model is crucial to extend its operation to realistic engine geometries & multiple nozzles

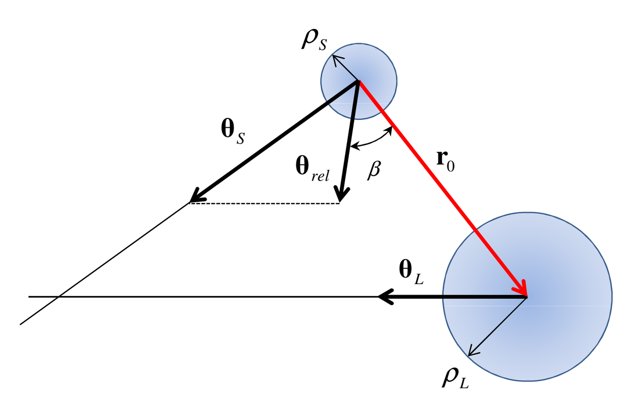
Efficient collision modeling with extended outcomes

- Estimate Radius-of-Influence (ROI) based on a tetrahedralization of the drops inside the computational parcel

$$ROI = r_p \sqrt[3]{\left(\frac{k_V^3}{6\sqrt{2}} - \frac{4}{9}\pi\right) N_p}$$

$$b = \sin\beta = \sqrt{1 - \frac{\langle \theta_{S0} - \theta_{L0}, x_{L0} - x_{S0} \rangle}{\|\theta_{S0} - \theta_{L0}\|^2 \|x_{S0} - x_{L0}\|^2}}$$



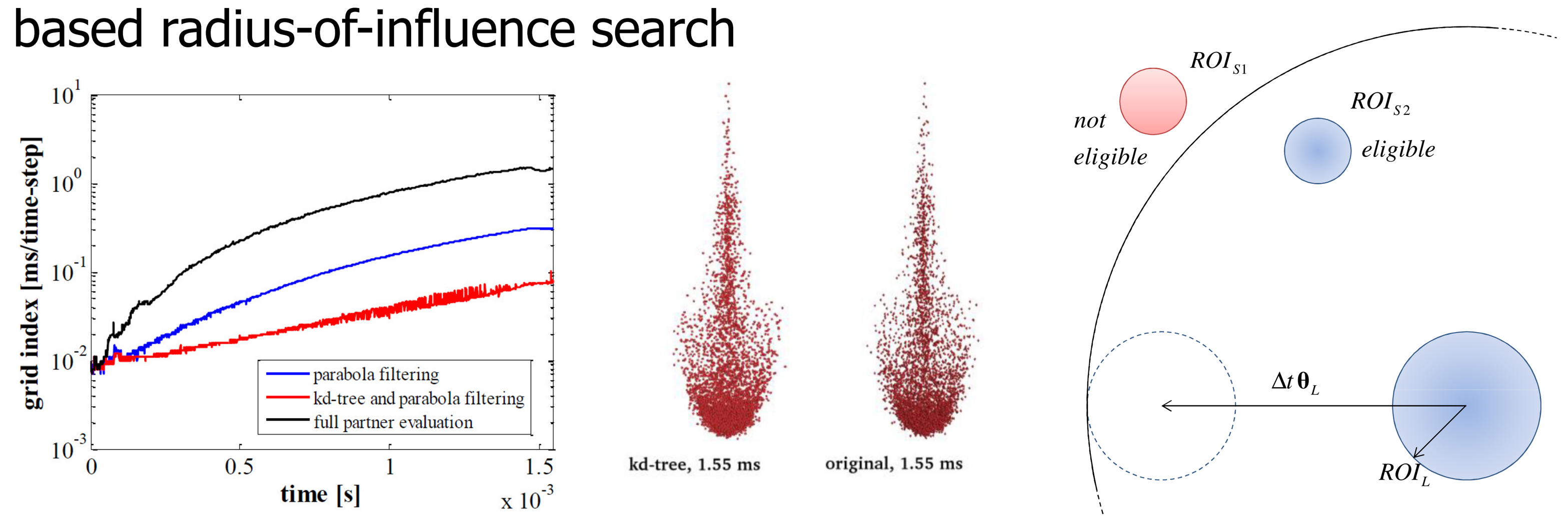


- ROI-based collision estimation is O(n²), *n* number of particles → filter impossible collisions based on squared distance function between two droplets within the timestep

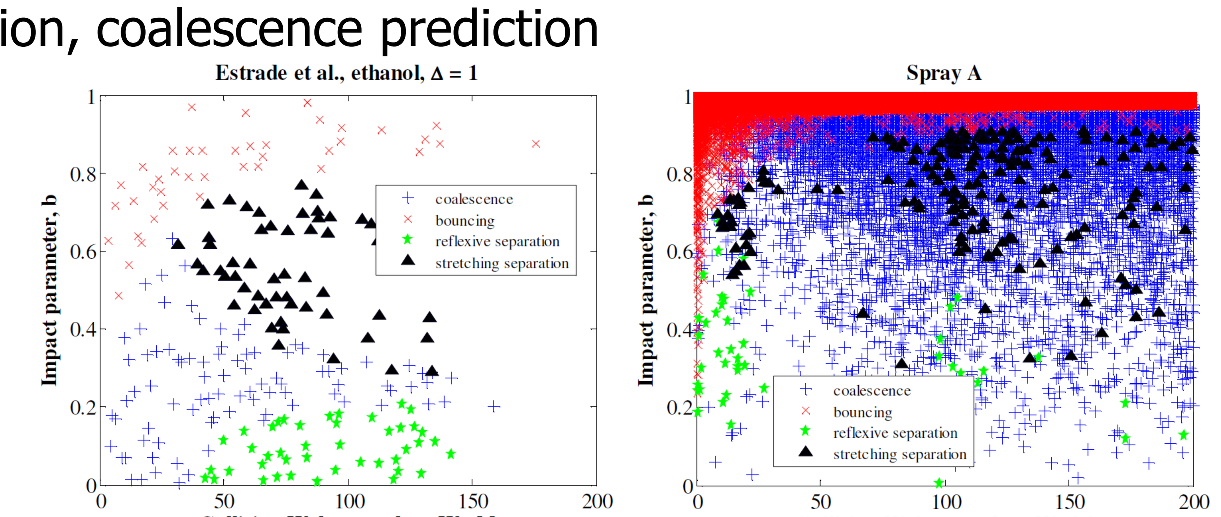
$$f(t) = d^2(\mathbf{x}_1(t), \mathbf{x}_2(t)) = \|\boldsymbol{\theta}_{rel}\|^2 t^2 + 2\langle \mathbf{x}_{1,0} - \mathbf{x}_{2,0}, \boldsymbol{\theta}_{rel} \rangle t + \|\mathbf{x}_{1,0} - \mathbf{x}_{2,0}\|^2 = at^2 + bt + c$$

$$t_{min} = -b/(2a) \rightarrow collision\ possible\ if\ t_{min} > 0\ \&\ t_{min} \leq \Delta t\ \&\ d(t_{min}) \leq ROI$$

- Pre-processing filter of eligible parcel couples by running a kd-tree based radius-of-influence search



- Deterministic bouncing, stretching separation ('grazing'), reflexive separation, coalescence prediction



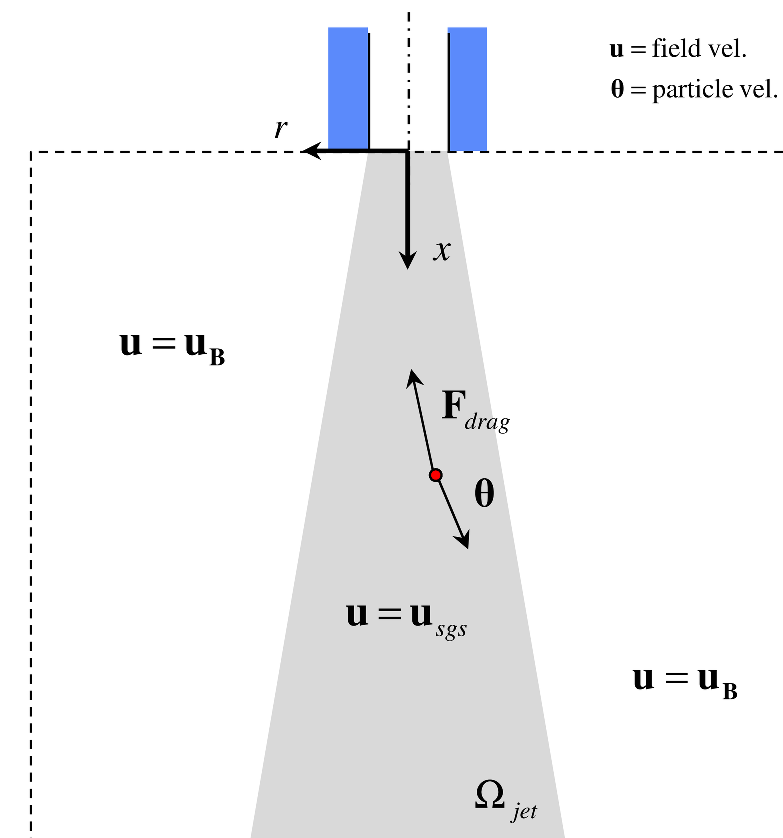
Sub-grid scale near-nozzle flow modeling

- A sub-grid scale, transient flow prediction ($\mathbf{u}_{sgs}$) is used for the spray calculation instead than under-resolved momentum cell values

$$\begin{cases} \boldsymbol{\theta}_B = \dfrac{\boldsymbol{\theta}'_n + \Delta t\, d_{p,sgs}(\boldsymbol{\theta}_t + \mathbf{u}_{sgs})}{1 + \Delta t\, d_{p,sgs}} \\ (m_B + S_{uvw})\mathbf{u}_B - m_n \mathbf{u}_n = \mathbf{E} - \mathbf{r}_u \end{cases}$$

$$S_{uvw} = \sum_{p \in i4} \begin{cases} \frac{4}{3}\pi\rho_p N_p r_B^3 \dfrac{\Delta t\, d_p}{1 + \Delta t\, d_p}, & p \notin \Omega_{jet} \\ 0, & p \in \Omega_{jet} \end{cases}$$

$$\mathbf{r}_u = \sum_{p \in i4} \begin{cases} \frac{4}{3}\pi\rho_p N_p \left(r_B^3 \dfrac{\boldsymbol{\theta}'_n + \Delta t\, d_p \boldsymbol{\theta}_t}{1 + \Delta t\, d_p} - r_n^3 \boldsymbol{\theta}'_n \right), & p \notin \Omega_{jet} \\ \frac{4}{3}\pi\rho_p N_p \left(r_B^3 \dfrac{\boldsymbol{\theta}'_n + \Delta t\, d_p (\boldsymbol{\theta}_t + \mathbf{u}_{sgs})}{1 + \Delta t\, d_p} - r_n^3 \boldsymbol{\theta}'_n \right), & p \in \Omega_{jet} \end{cases}$$



- Implicit coupled solution with SIMPLE solver iteration maintained
- Transient turbulent gas-jet model used to represent the sub-grid scale flow field using the effective gas jet assumption:

$$\frac{f_v x}{u} = Strouhal \approx Stokes = \frac{\tau_l}{\tau_p}$$

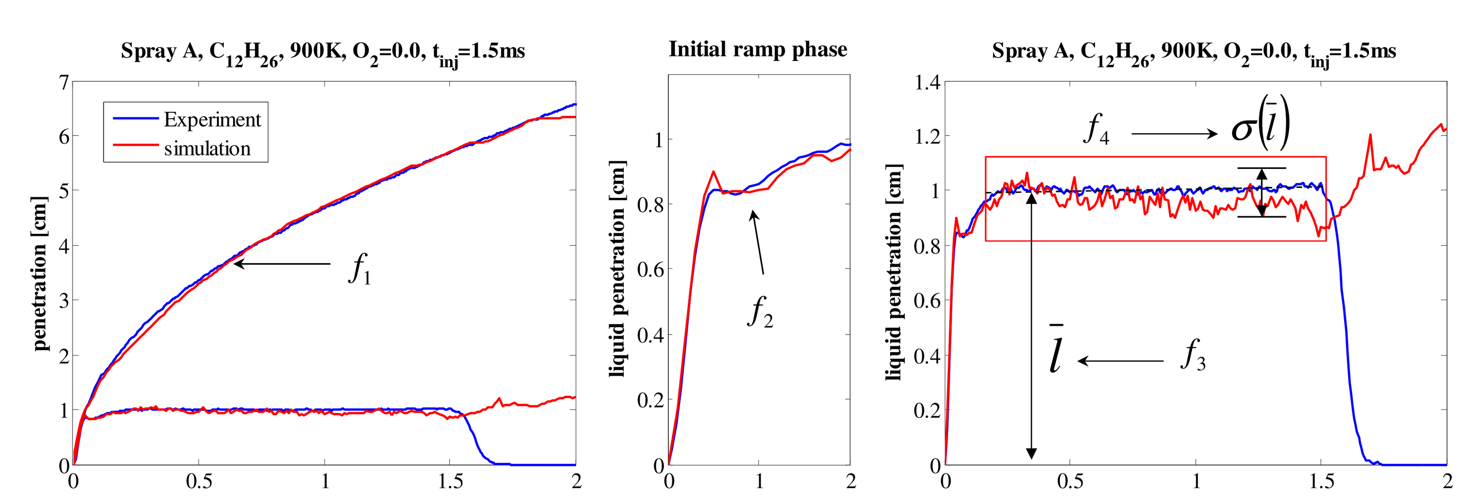
$$\mathbf{u}_{axis}(x,t) = \mathbf{u}_{inj}(t_0) + \int_{t_0}^{t} \left[1 - \exp\left(-\frac{\tau - t_0}{St\,(x - x_{inj})} \|\mathbf{u}_{inj}(\tau)\|\right)\right] \frac{\partial \mathbf{u}_{inj}(\tau)}{\partial \tau} d\tau,$$

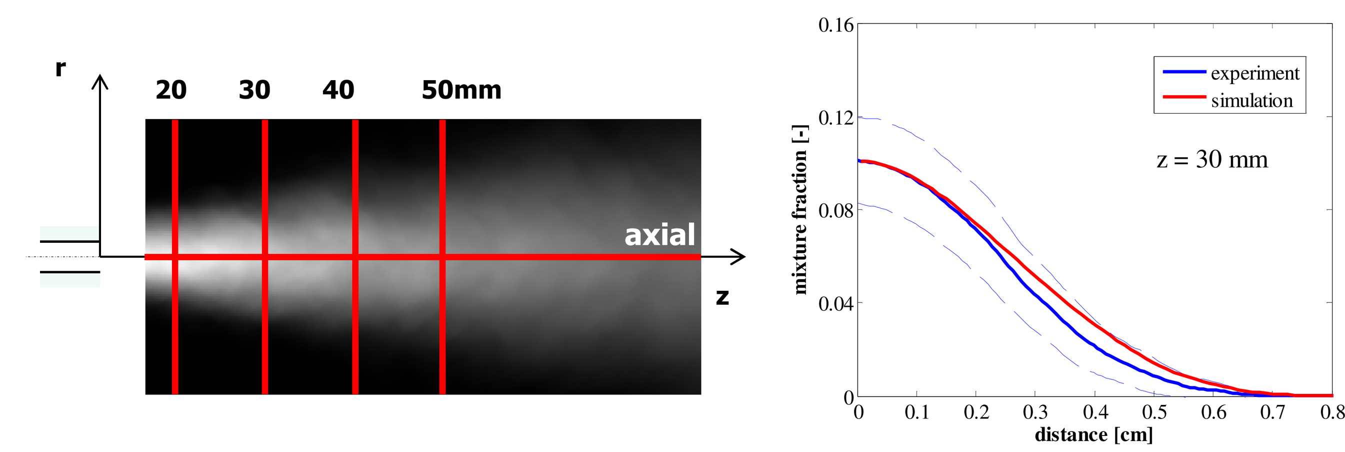
$$\mathbf{u}_{sgs}(x,r,t) = \frac{f_{entr}(x)\mathbf{u}_{axis}(x,t)}{\left(1 + \dfrac{12 r^2}{x^2 K_{entr}^2}\right)^2}$$

- Stokes number and turbulent entrainment function f_{entr} are model constants

GA-based study of spray model constants

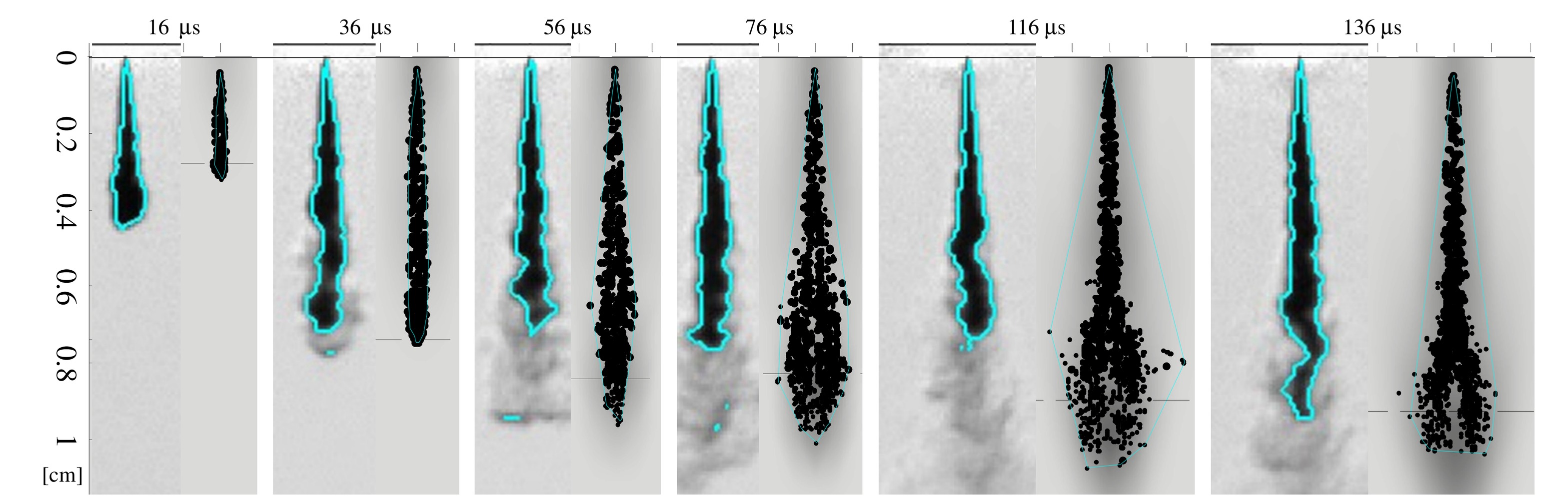
- 5 objective functions: vapor penetration, liquid transient, steady state liquid penetration and standard deviation, mixture fraction distribution
- 6 optimized model variable: C_{RT}, $C_{\Lambda RT}$, B_1, St, K_{entr}, γ_{max}

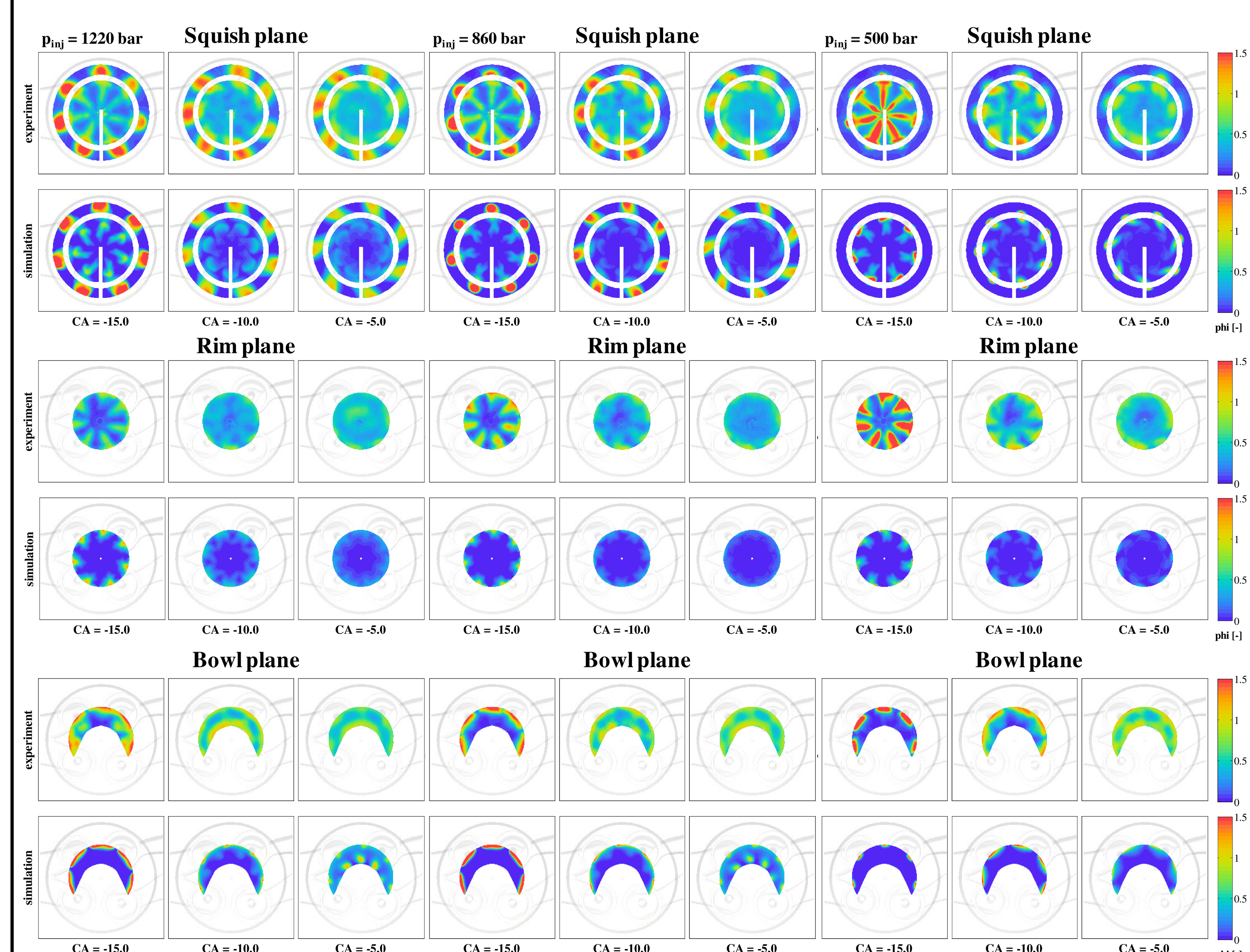




Validation

- Sandia Spray A and mixture preparation in a light duty optical diesel engine





References

[1] Perini F and Reitz RD, "An effieient atomization, collision and sub-grid scale momentum coupling model for transient vaporizing engine sprays", Int J Multiphase Flow, submitted, 2015