Simulation of Mixture Formation and Combustion for Gasoline Direct Injection Engine Using OpenFOAM

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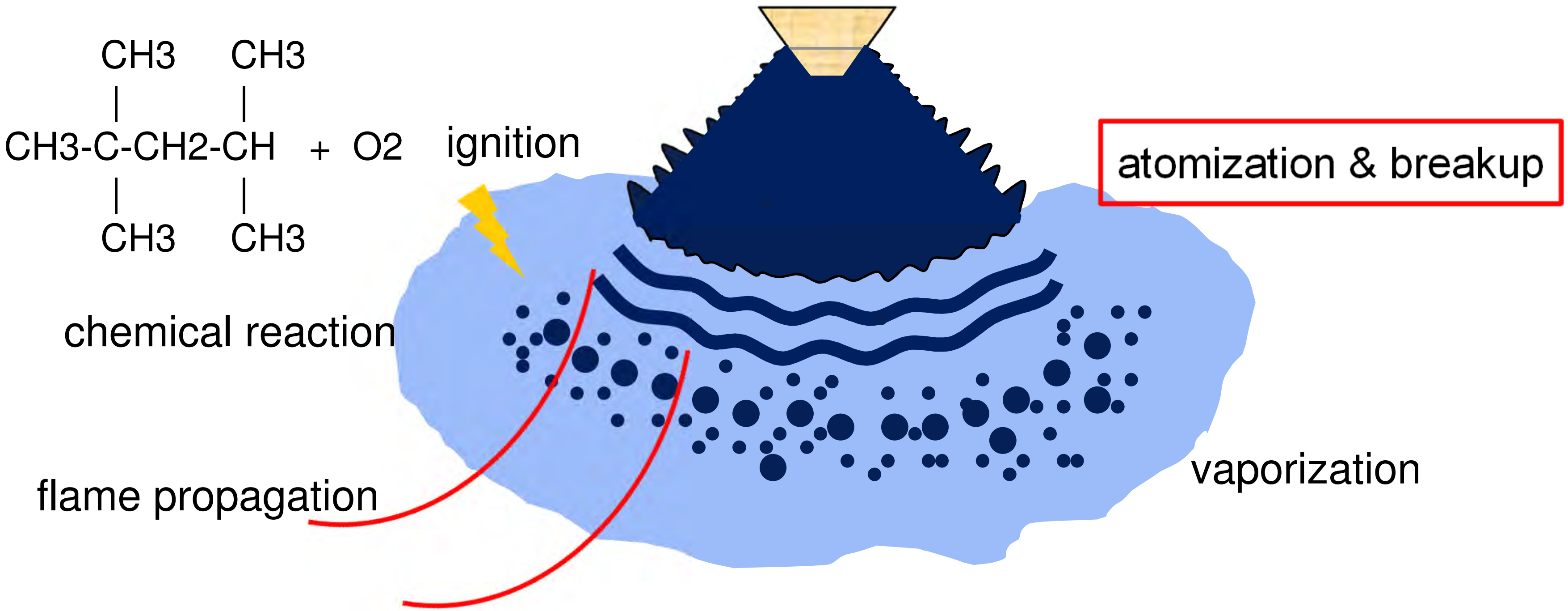
Outline

- Goals
- Simulation of gasoline-ethanol hollow-cone sprays
  - Modifications of spray sub-models
  - Validations
- On-going work: premixed turbulent combustion
- Conclusions

Goals



Main goal: *Assess* the potential of *OpenFOAM* and further develop it.

Another goal: *Assess* the applicability of *various spray models* to simulating sprays discharged by a *pintle*-type injector (***not develop new spray models***).

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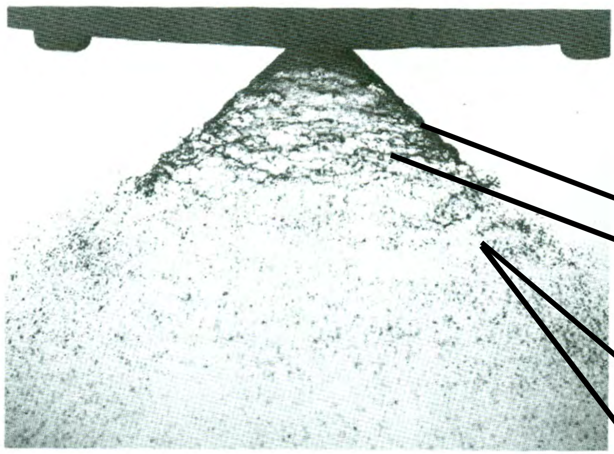
Illustration of modelling a hollow-cone spray using Lagragian approach



A fuel atomization jet*.

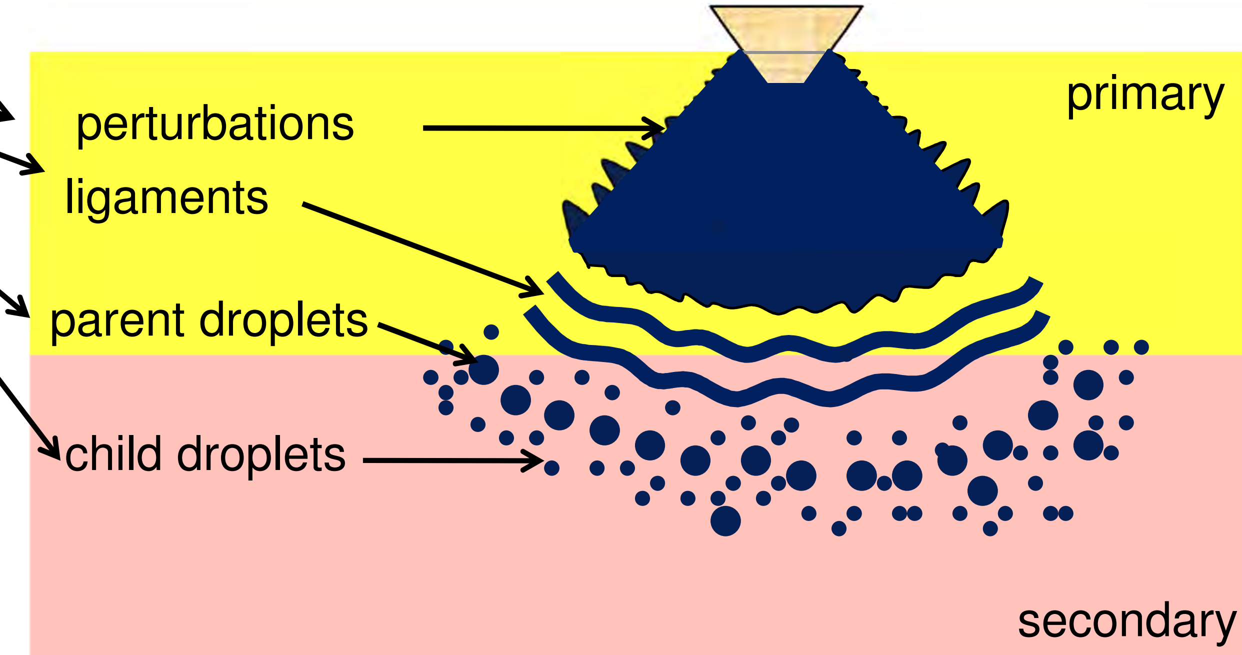


Illustration of how a hollow-cone spray is modeled numerically.

*Fantasy of flow: the world of fluid flow captured in photographs. By Kashika Jōhō Gakkai

Spray models in OpenFOAM

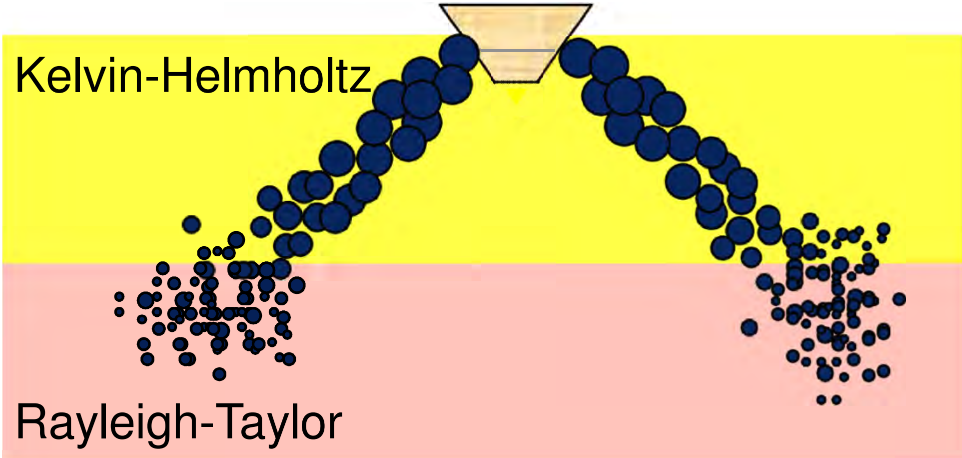
<table>
<tr><th>Function</th><th colspan="2">Name</th></tr>
<tr><td>Injector model</td><td>Unit</td><td>Pintle</td></tr>
<tr><td rowspan="2">Primary breakup model</td><td>Rosin-Rammler</td><td rowspan="4">KHRT</td></tr>
<tr><td>LISA</td></tr>
<tr><td rowspan="2">Secondary breakup model</td><td>TAB</td></tr>
<tr><td>Reitz-Diwakar</td></tr>
<tr><td rowspan="2">Collision model</td><td colspan="2">O’Rourke</td></tr>
<tr><td colspan="2">Trajectory</td></tr>
</table>

VSB2 spray model.

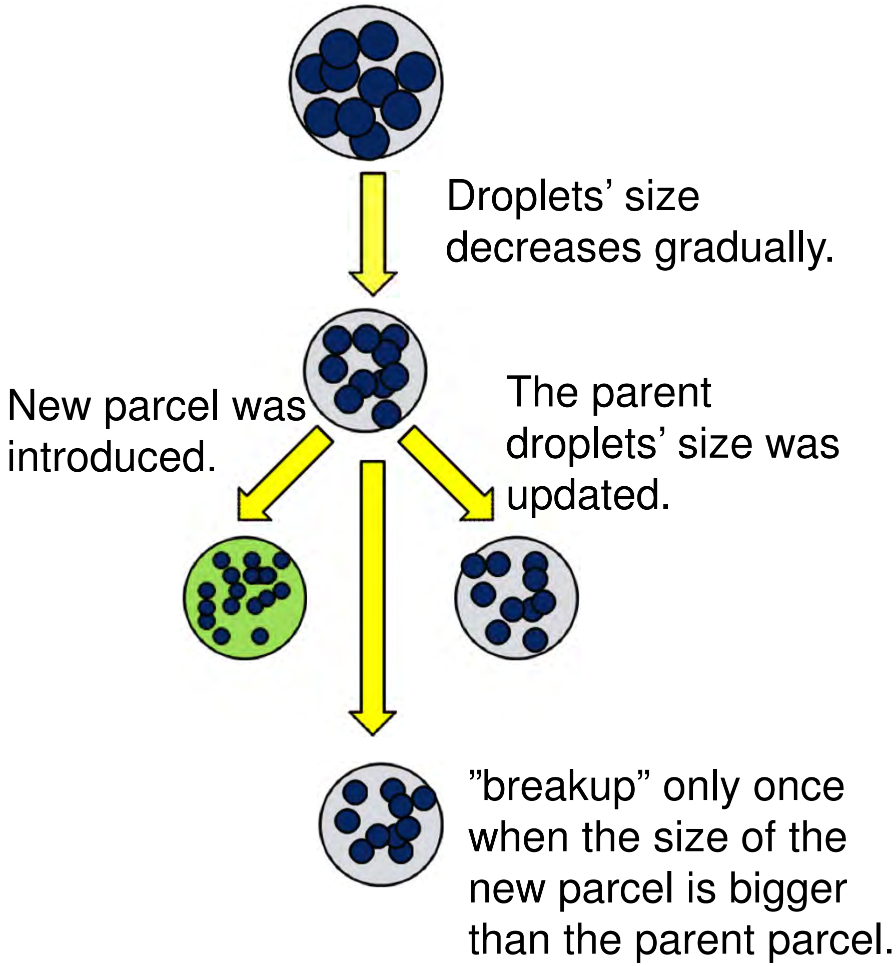
The physical properties of gasoline.*

*http://www.tfd.chalmers.se/~hani/kurser/OS_CFD_2009/ChenHuang/OFProject0122.pdf

The KHRT Model



RT instability grows and cause droplets breakup after a certain time.

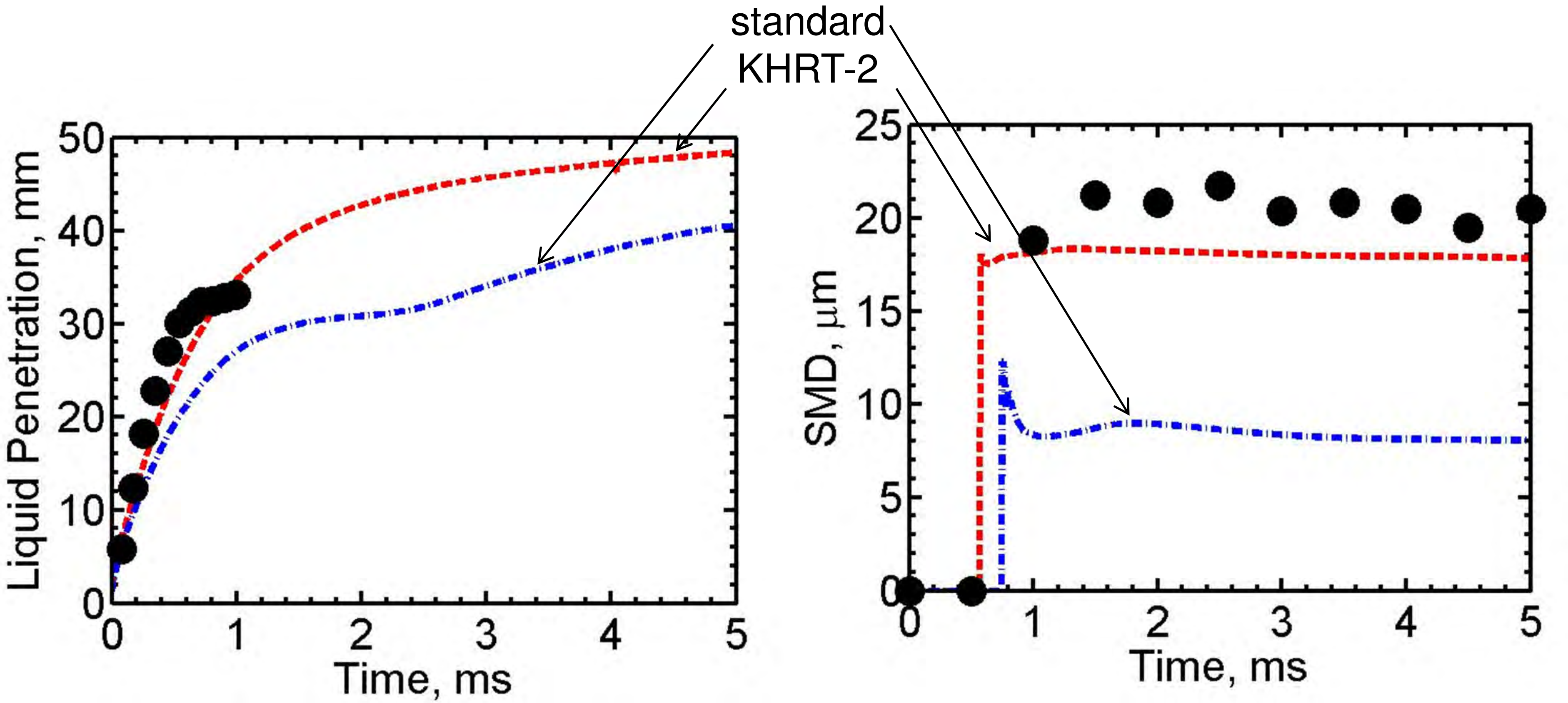


Modifications of KHRT model

	KHRT-2	Standard KHRT
The mass of the liquid stripped of the parent droplets	$4\pi N_0 \rho_f \left(r_0^3 - r^3\right)/3$	$\sum\left(4\pi N \rho_f r_{KH}^3 /3\right)$
The radius of parent droplets after breakup	$N r^2 \left(r - r_{\mathrm{KH}}\right) = N_0 r_b^2 \left(r_b - r_{\mathrm{KH}}\right)$	unchanged
The number of child droplets	$n = \dfrac{N r^3 - N r_b^3}{r_{\mathrm{KH}}^3}$	not calculated
Breakup criteria	$m_s = 0.03\overline{m_{inj}}, and\ \ n > N_0$	$m_s = 0.20\overline{m_{inj}}$

Correct version in OpenFOAM-2.0.0
src/lagrangian/spray/submodels/BreakupModel/ReitzKHRT

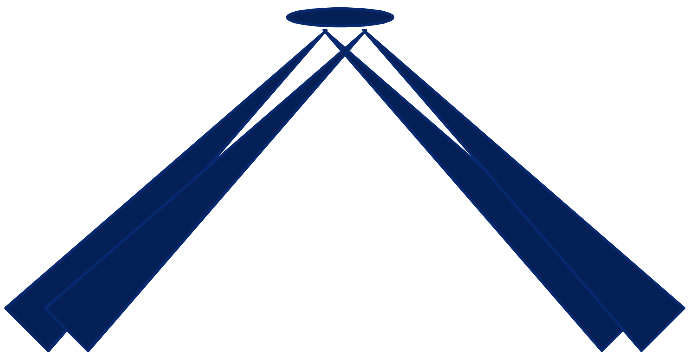
KHRT-2 vs. standard KHRT



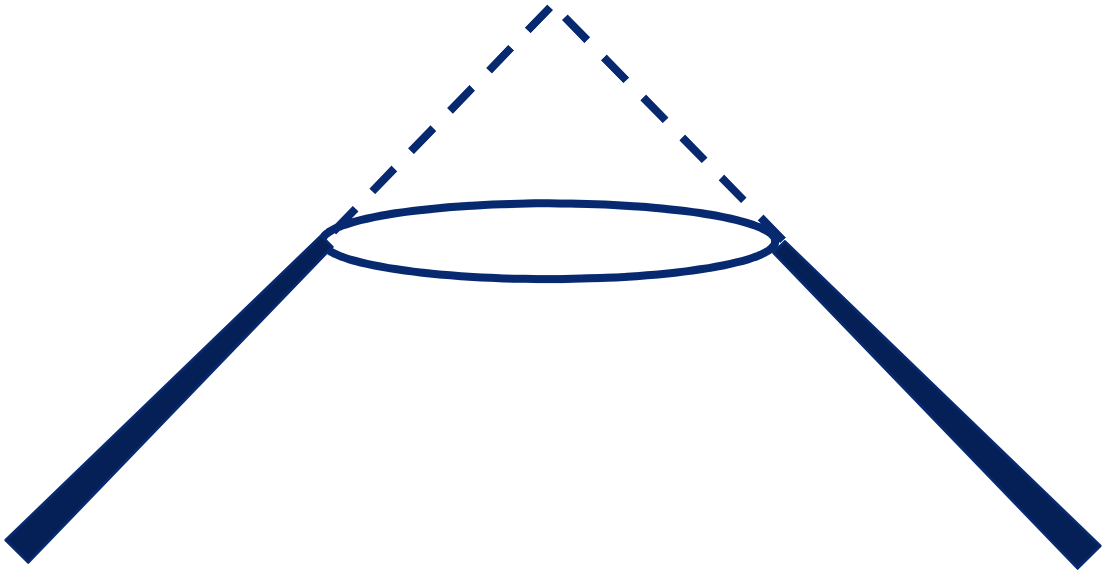
Comparison of measured (symbols) and calculated (lines) gasoline liquid penetration and SMD. T_a=350K, T_f=243K, p_a=6bar.

Injector Models

unit injector



pintle injector



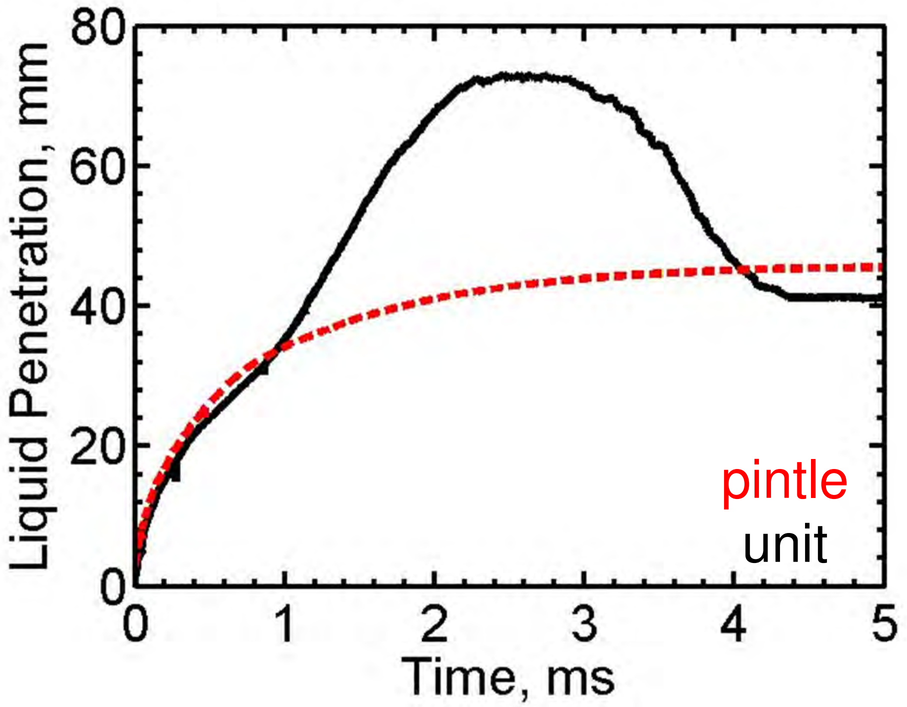
Injection direction: randomly distributed within inner cone angle and outer cone angle

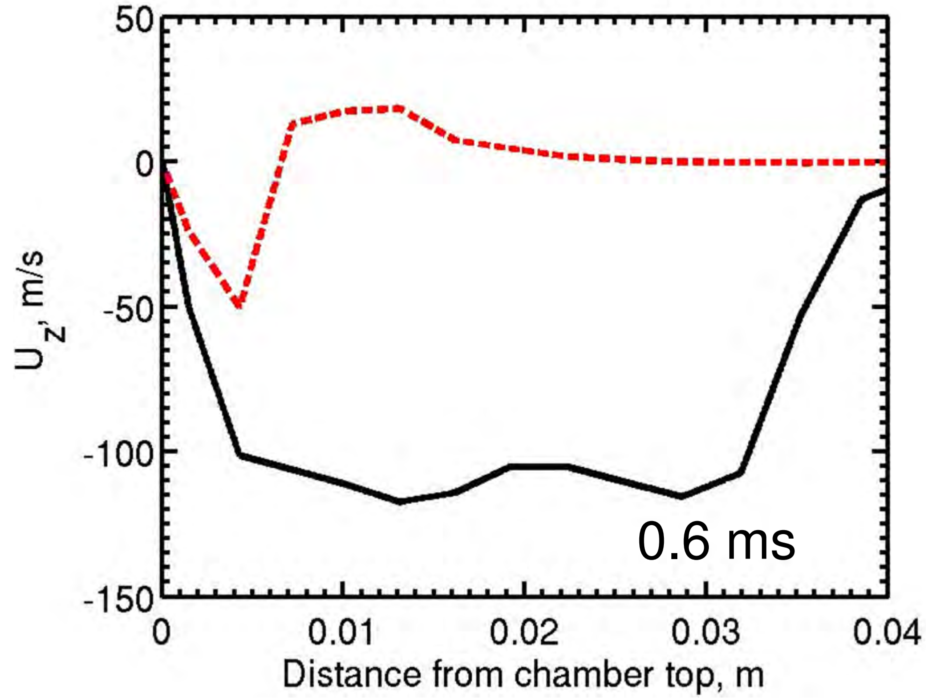
Injection position: randomly distributed over the circle

Injection direction: randomly distributed within inner cone angle and outer cone angle

Injection position: along the ring, depending on injection direction

Unit and Pintle Injector Models



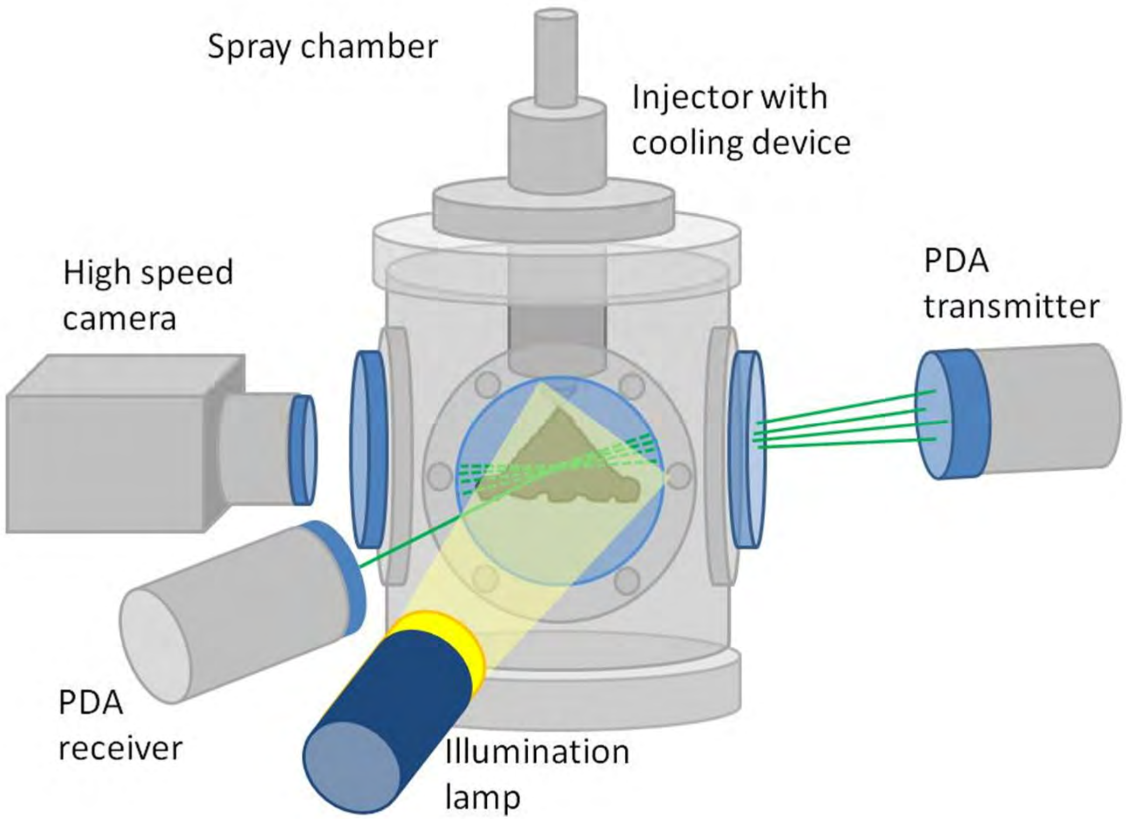


Comparison of liquid penetration and downstream velocity components U_z calculated using unit and pintle injector model along the central line of the spray.

OpenFOAM-2.0.0

src/lagrangian/intermediate/submodels/Kinematic/InjectionModel/ConeNozzleInjection/

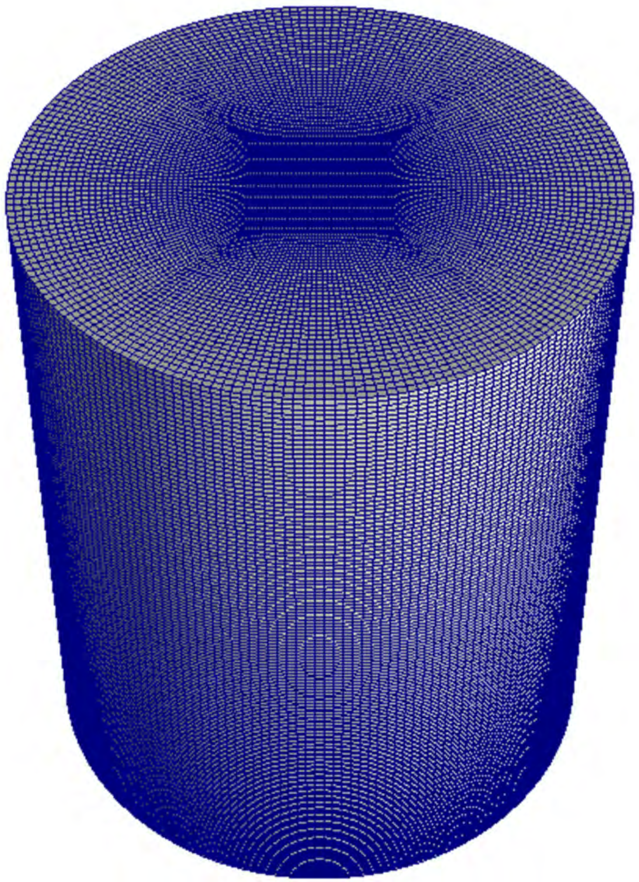
Experimental and Computational Setup



Experimental setup
(Hemdal et al. SAE 2009-01-1496)

high-speed camera: spray imaging PDA: droplet size

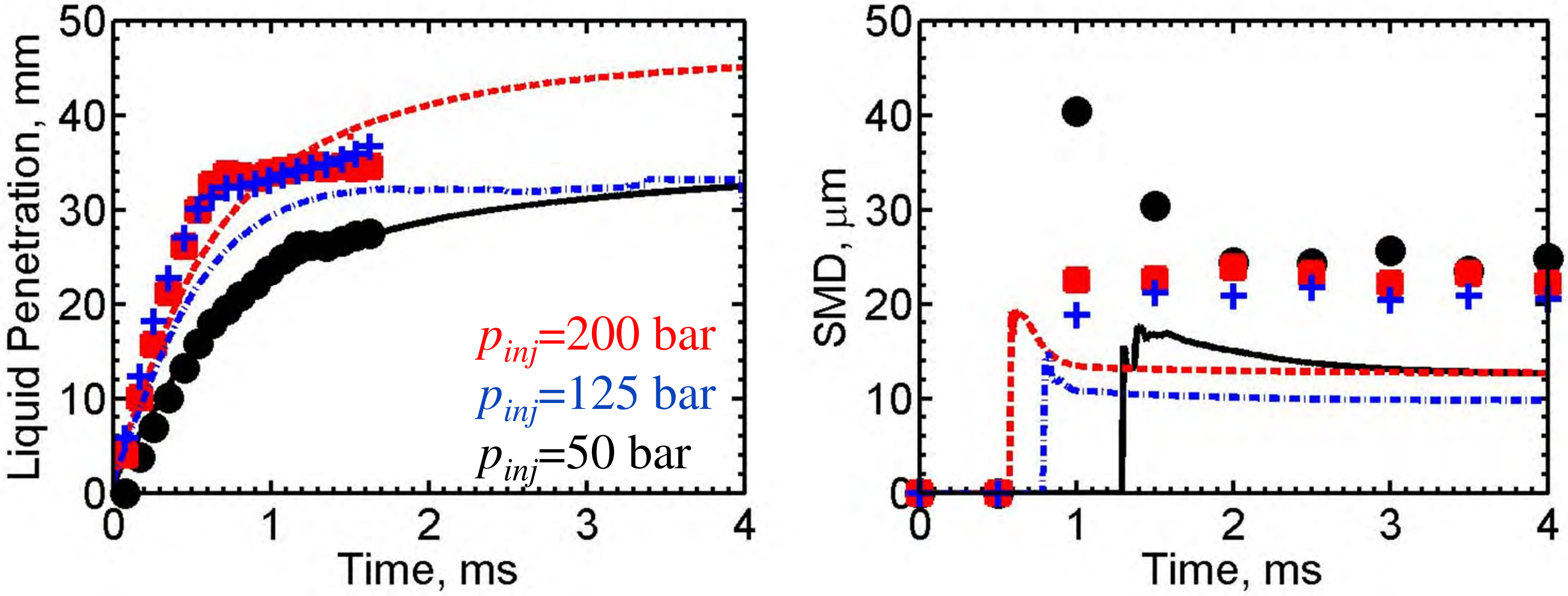
(T_{fuel}=243 K, T_{air}=350 K, p_{inj}=50, 125, 200 bar)



Computational mesh
1 754 400 cells
Size 0.78 x 0.78 x 0.85 mm (center)

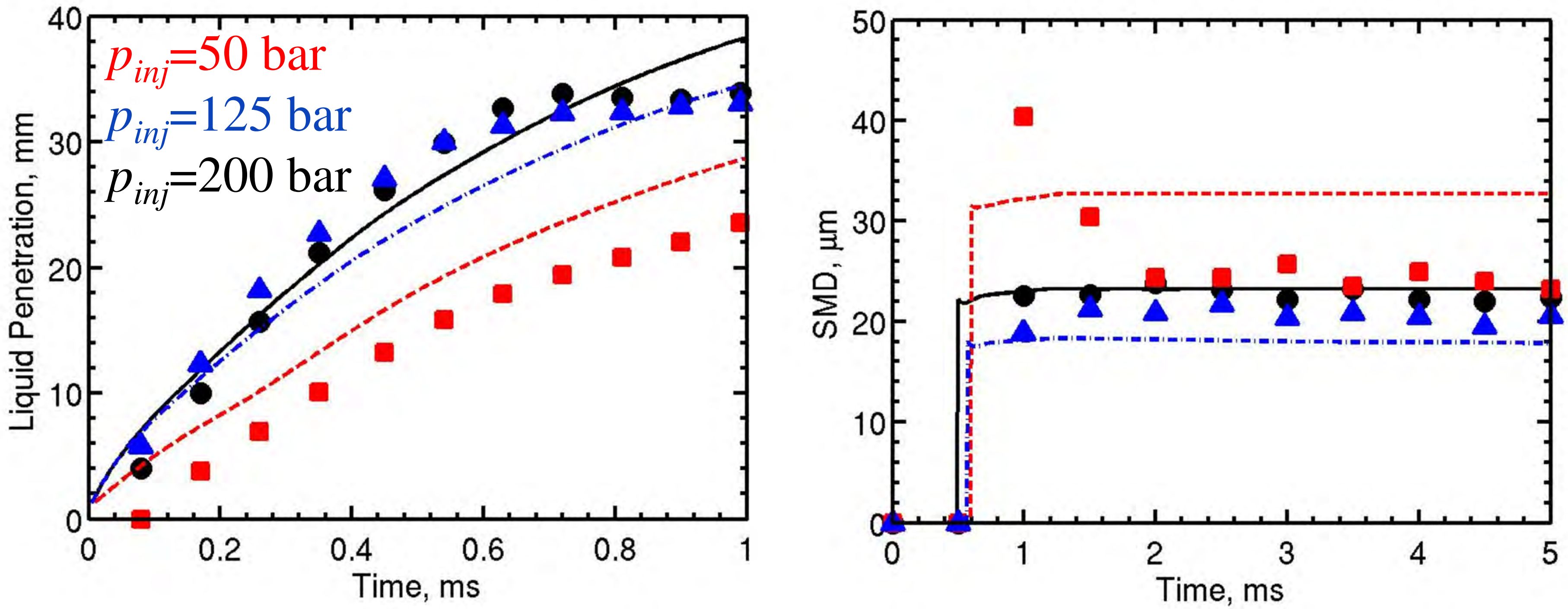
Validation, Rosin-Rammler + VSB2 model

effect of fuel and p_{inj}



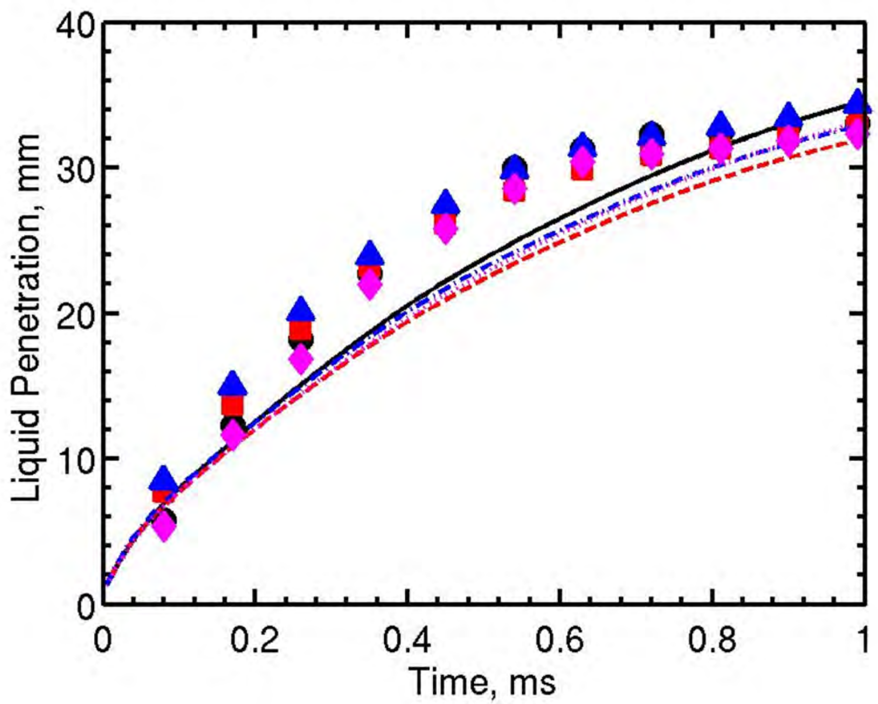
Comparison of measured (symbols) and calculated (lines) ethanol liquid penetration and SMD for different injection pressures. Rosin-Rammler distribution (r_m=7.5µm, q=3), VSB2 model. T_a=350K, T_f=243K.

Validation, Uniform droplet size + KHRT-2



Comparison of measured (filled symbols) and calculated (lines) liquid penetration and SMD of gasoline.

Validation, Uniform droplet size + KHRT-2



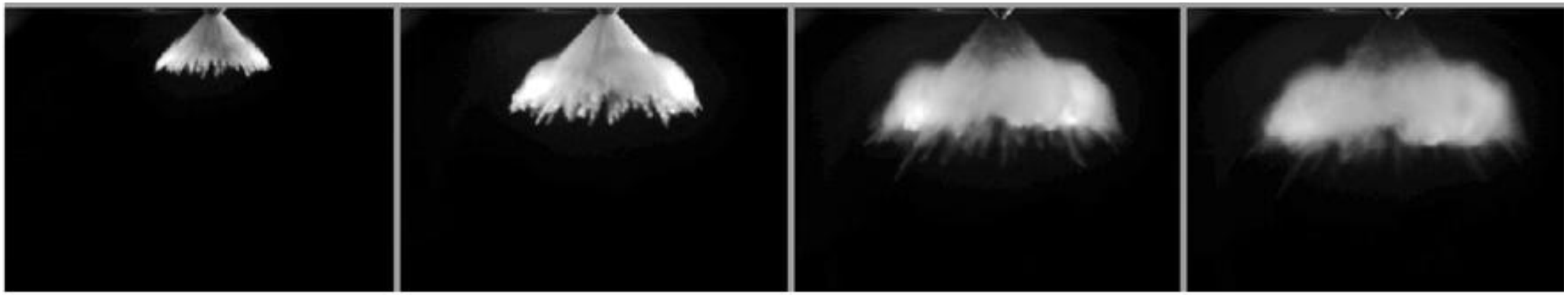
T_a=350 K, T_f=243 K
T_a=295 K, T_f=295 K
T_a=350 K, T_f=320 K
T_a=295 K, T_f=243 K

Comparison of measured (filled symbols) and calculated (lines) liquid penetration of gasoline for different ambient and fuel temperatures.

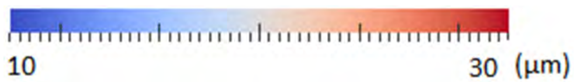
Comparison of spray shapes

Uniform droplet size + KHRT-2

0.18 ms 0.36 ms 0.64 ms 0.82 ms



Gasoline spray shapes measured (first row) and calculated using KHRT-2 model (second row) at different instances. T_{air}=350 K, T_{fuel}=243 K, p_{inj}=200 bar.



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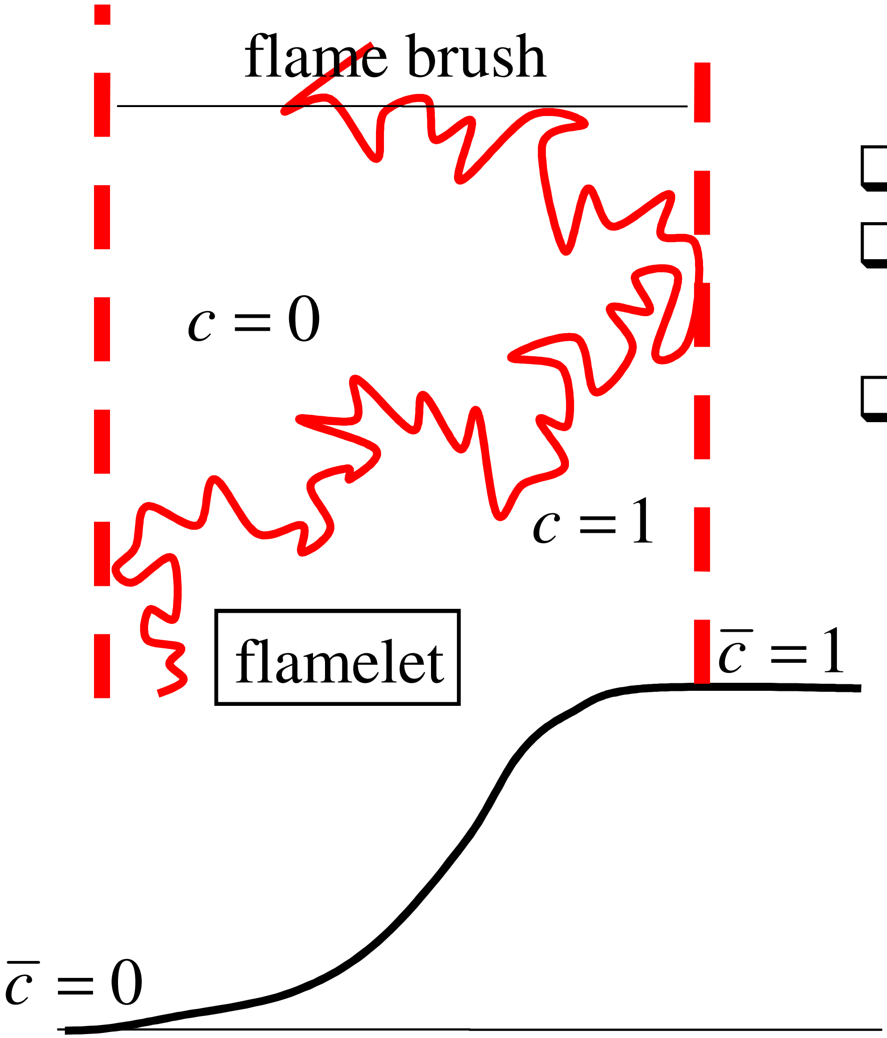
Basics on premixed turbulent combustion



- *c*: progress variable
- *b*: regress variable (*b=1-c*) used in OpenFOAM.
- Favre-averaging (equations become more compact)

$$\tilde{c} = \frac{\overline{\rho c}}{\bar{\rho}} \qquad \tilde{T} = \frac{\overline{\rho T}}{\bar{\rho}}$$

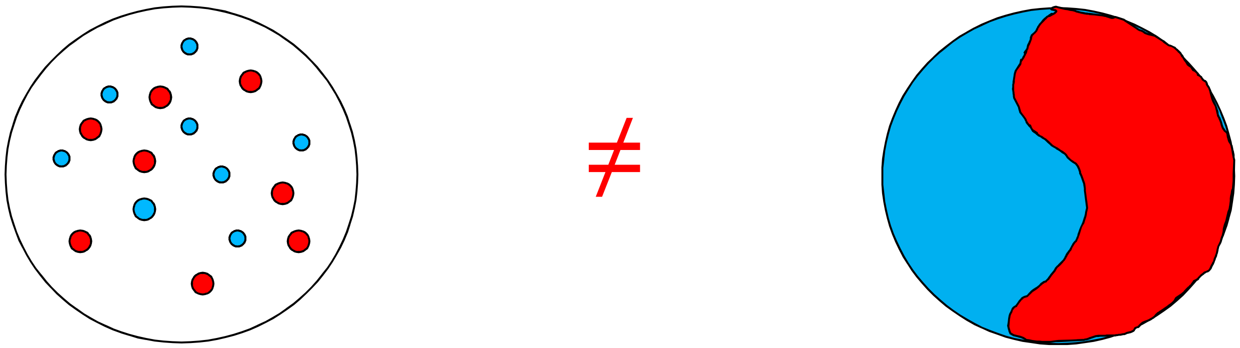
Which way is correct in calculating $\tilde{T}$?

Premixed turbulent combustion theory	Standard OpenFOAM
By BML concept	Solving the following eq. which seems like Janaf eq.
$\tilde{T} = T_u \tilde{b} + T_b (1 - \tilde{b})$	$\frac{\tilde{h} W_m}{R} = a_{1m} \tilde{T} + \frac{a_{2m}}{2} \tilde{T}^2 + \frac{a_{3m}}{3} \tilde{T}^3 + \frac{a_{4m}}{4} \tilde{T}^4 + \frac{a_{5m}}{5} \tilde{T}^5 + a_{6m}$

www.openfoamworkshop.org/6th_OpenFOAM_Workshop_2011/Program/Abstracts/ehsan_yasari_ab.pdf

Why is approach in OpenFOAM wrong?

- In OpenFOAM, unburned and burned gases are treated like a multi-component mixture.
  - But totally different phenomenon.



- Janaf eq. was averaged with error in OpenFOAM.

$$\tilde{T}^n \neq \widetilde{T^n}$$

Conclusions

- A number of modifications of the implementation of various spray models in OpenFOAM were done in order to follow the description of these models in the original papers.
- Pintle injector model was implemented in OpenFOAM to simulate sprays discharged by pintle injector.
- Among these modifications, the change of the implementation of the KHRT model had the most important effect on the computed penetration length and especially SMD at high injection pressures.
- Problem of calculating $\tilde{T}$ for premixed turbulent combustion in OpenFOAM was addressed.

Thank you for your attention!

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