Modeling of Diesel Fuel Spray Formation in OpenFOAM

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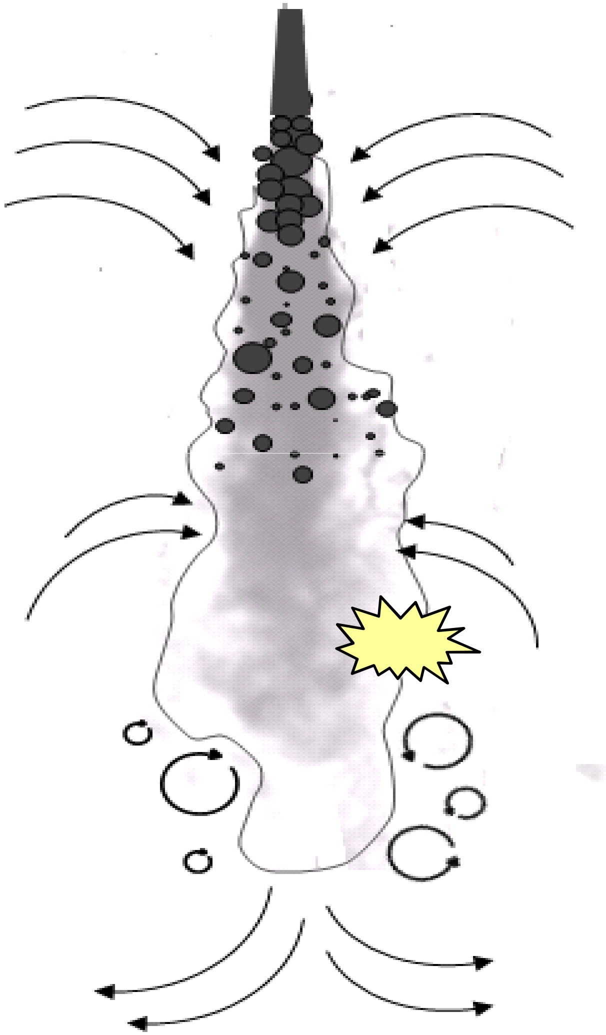
Combustion Engine Research Center

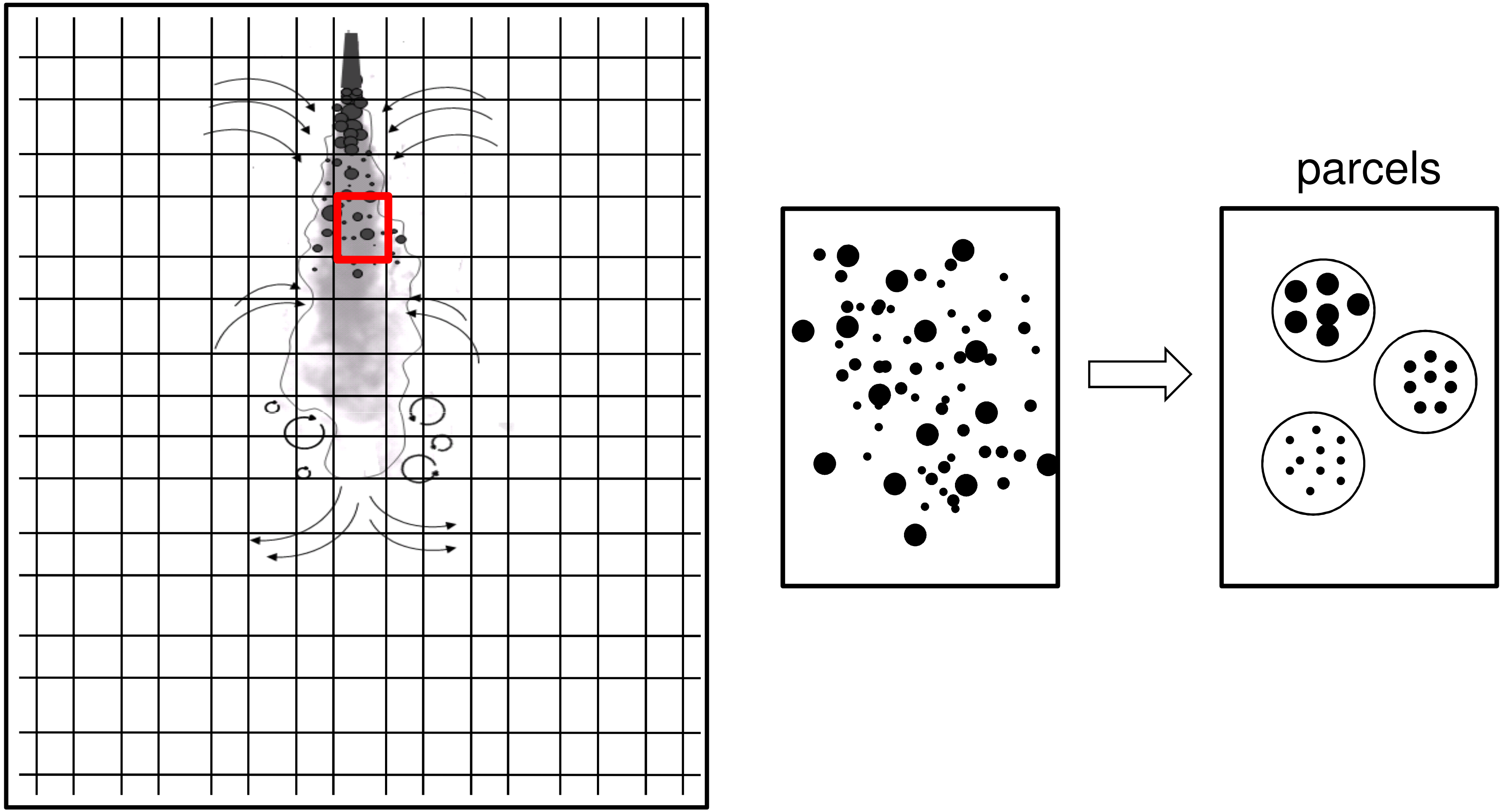
Motivation

- Sprays are involved in many applications
  (internal combustion engines, exhaust aftertreatment, gas turbines…)
- CFD is an increasingly used tool in the development of these applications
- Spray and combustion models include many sub models
- Numerical unrobustness & many tuning parameters is an issue

Spray phenomena



- breakup
- evaporation and heat transfer
- droplet drag
- spray induced turbulence
- combustion


parcels

Spray Modeling - Shortcomings

McKinley & Primus*

“cell widths are large and […] inadequate for capturing the strong gradients in velocity, temperature and fuel vapor concentration. This [leads] to under prediction of gas velocities and over prediction of gas temperatures within the spray”

- **Grid dependence**
- **Time step dependence**
- **Robustness**
- **Tuning parameters** (sub models)

*McKinley, T.L. & Primus, R.J., “Three dimensional calculations of air motion, sprays and combustion in a quiescent Direct-Injection Diesel engine.” *ASME paper 90-ICE-2,* 1990.

Work that has been done

McKinley, T.L. & Primus, R.J., *ASME paper 90-ICE-2*

Abraham, J., *SAE technical paper 970051*

Wan, Y.P. & Peters, N., *SAE technical paper 972866*

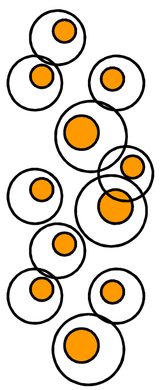
Abraham, J. & Magi, V., *SAE technical paper 1999-01-0911*

Durand, P et. al, *SAE technical paper 960632*
SAE technical paper 980134

Béard et. al, *SAE 2000-01-1893*

(CLE: "Couplage Lagrangien-Eulérien)

- Gaseous drop



Abani et. al, *SAE 2008-01-0970*

- Gas jet theory used for gas velocity

$$V_x = V_{gas} = min\left[U_{inj}, \frac{3U_{inj}^2 d_{eq}^2}{\left[32\nu_t x\left(1+\frac{3U_{inj}^2 d_{eq}^2 r^2}{256\nu_t^2 x^2}\right)^2\right]}\right]$$

VSB2 Spray Model

Vsb2 stochastic Blob and Bubble model

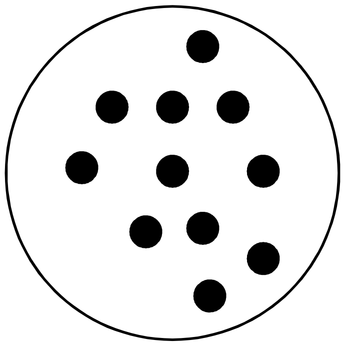
- Unconditional robust
- Minimal number of parameters
- Adaptable to any CFD code feat. particle tracking

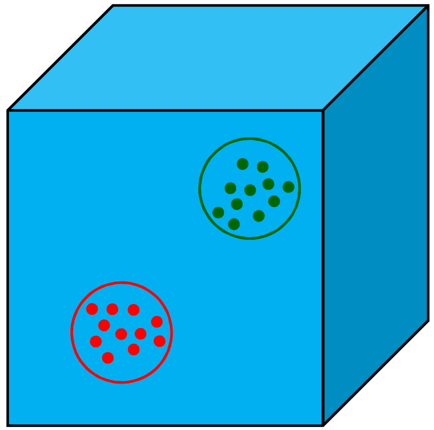
*developed by **Karlsson, A. (Volvo Tech. Corp.)**

results using *OpenFOAM* code are published in: **Kösters, A. and Karlsson, A., SAE 2011- 01- 0842**
results using *STAR-CD* code are published in**:** **Husberg, T., Denbratt, I. and Karlsson, A., SAE 2008- 01-1328** **Eismark, J. et al., presented at Thiesel 2010, Valencia**

Standard spray model

parcel
collection of equal droplets





Computational cell

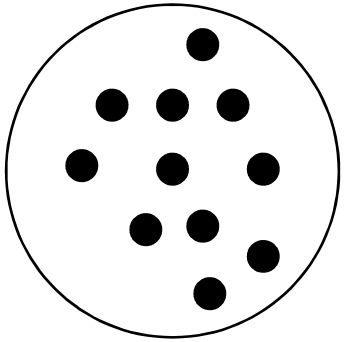
E.g. consider the energy balance of the parcel:

$$m_d \frac{dh_d}{dt} = \pi D_d k\left(T_g - T_d\right) f(z) Nu + h_v \frac{dm_d}{dt}$$

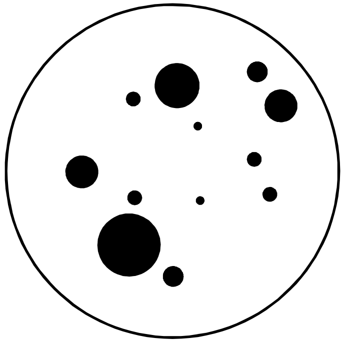
Problem: How can ***Tg*** be estimated if there are more than one parcel within the cell and/or there is a high evaporation rate?

VSB2 spray model – blob

parcel
collection of equal droplets



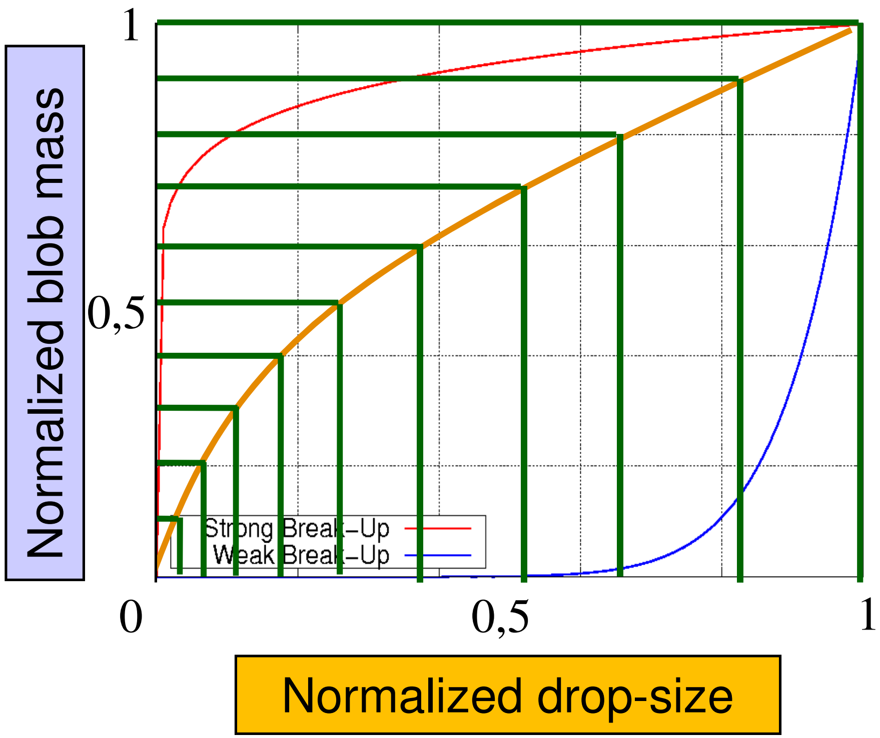
blob
droplet size distribution (based on local instantaneous We and Oh), using break-up rate correlations by Pilch&Erdman*

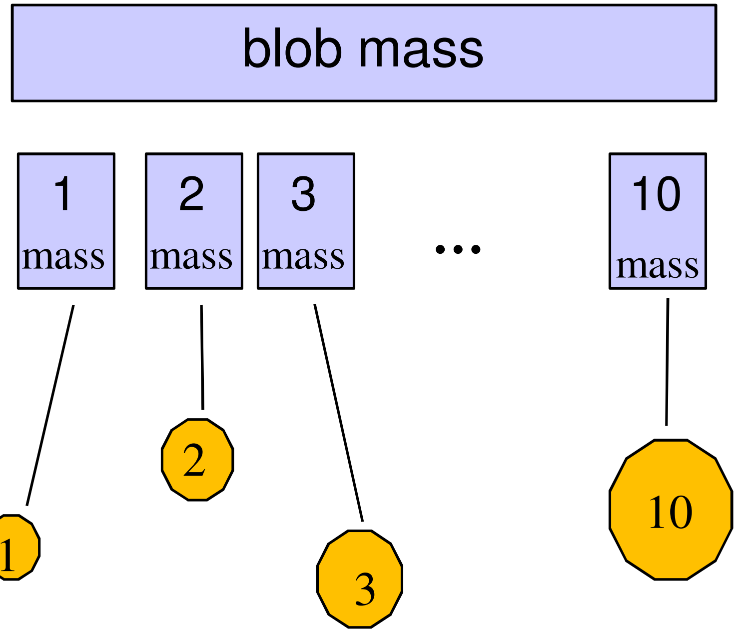


*Pilch, M. and Erdman, C.A., *Int. J. Multiphase Flow* **13(6)**:741-757, 1987

VSB2 spray model – blob

accumulated droplet size distribution





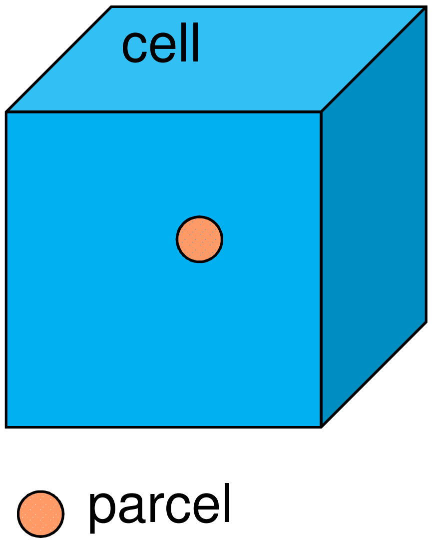
E.g. gas phase enthalpy source

$$m_b \Delta h_b = \sum_{i=1}^{10} m_{b,i} \Delta h_{b,i}$$

VSB2 spray model – bubble

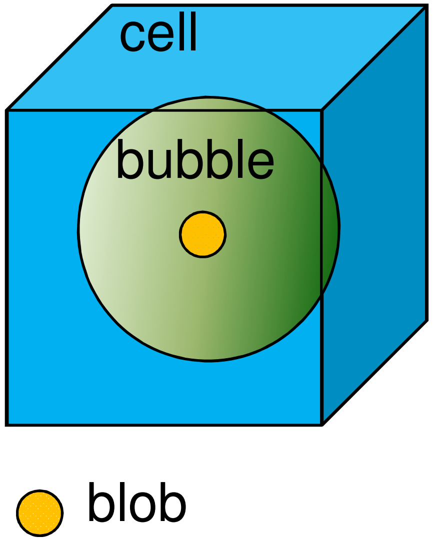
Common spray model

Gas phase in one **cell** used to calculate the interaction with the parcel



VSB2 spray model

Gas phase in a **bubble** used to calculate the interaction with the blob



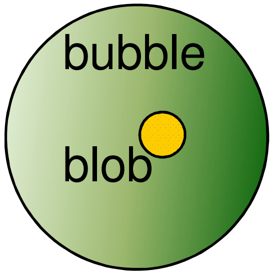
$$V_{bub} = N_D \frac{\pi}{6}\left[(D_B + l_t)^3 - D_B^3\right]$$

$$l_t = min\left[C\frac{k^{3/2}}{\varepsilon}, V_{cell}^{1/3}\right]$$

VSB2 spray model – robustness

	relaxation equations (based on equilibrium)	relaxation times
momentum	$\frac{dU_{j,b,i}}{dt} = \frac{U_{eq} - U_{j,b,i}}{\tau_U}$	$\tau_U = \frac{4\rho_b D_b}{3\rho C_D U_R}$
mass	$\frac{dm_{b,i}}{dt} = \frac{m_{eq} - m_{b,i}}{\tau_m}$	$\tau_m = \frac{\rho_b D_b^2 R T_m}{6D\ Sh\ p}$
energy	$\frac{dT_{b,i}}{dt} = \frac{T_{eq} - T_{b,i}}{\tau_T}$	$\tau_T = \frac{\rho_b D_b^2 C_{p,b}}{6k\ f(z)\ Nu}$

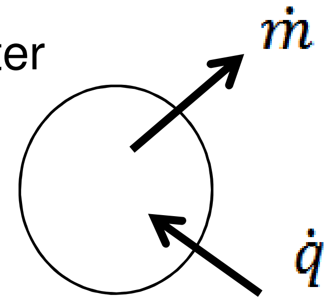
VSB2 spray model – equilibrium



Momentum: $$U_{j,eq} = \frac{(\rho V_{bub} U_{j,bub} + m_b U_{j,b})}{(\rho V_{bub} + m_b)}$$

Mass & energy:

1. **Mass**: evaporation → saturation (incl. heat of vaporization) → m_{eq} is remaining blob mass
2. **Heat**: T_{eq} calculated after evaporation



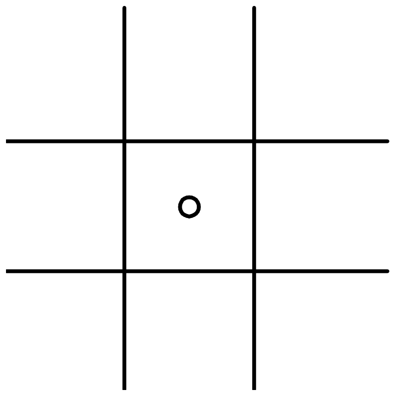
Modifications in the ***dieselSpray*** library:

parcel	**rewritten**
spraySubModels atomizationModel heatTransferModel breakupModel injectorModel collisionModel wallModel dispersionModel dragModel evaporationModel	atomizationModel heatTransferModel breakupModel dragModel evaporationModel

Numerical Set-up

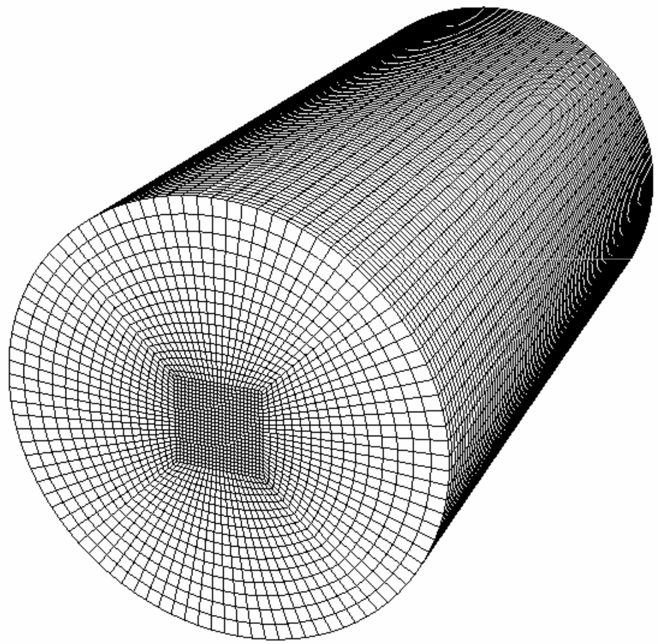
- fuel: n-hexadecane
- tuned k-ε model (C_1 & σ_ε)

Injector position:



Default grid in all simulations:

0.5x0.5x1.0 mm
232 320 cells



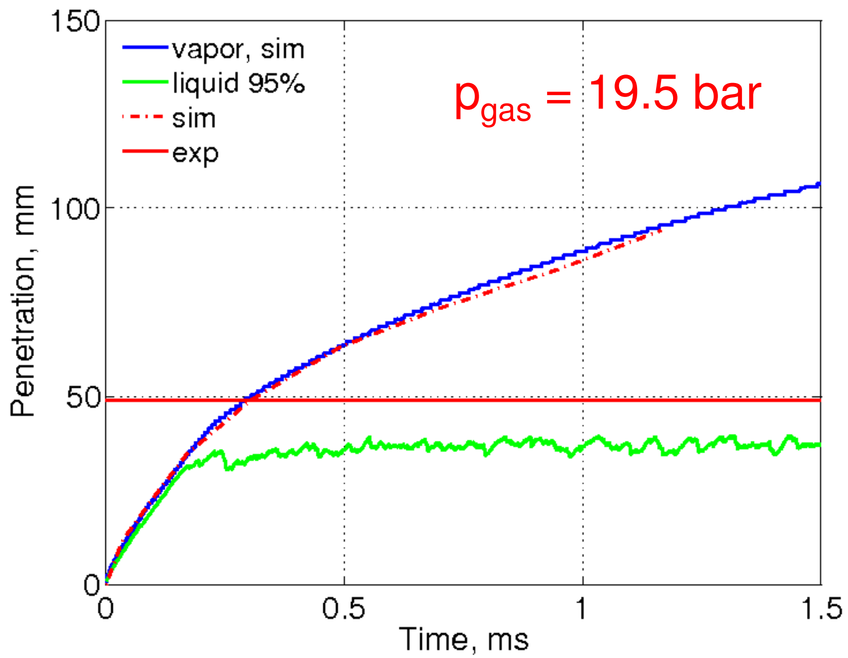
Results

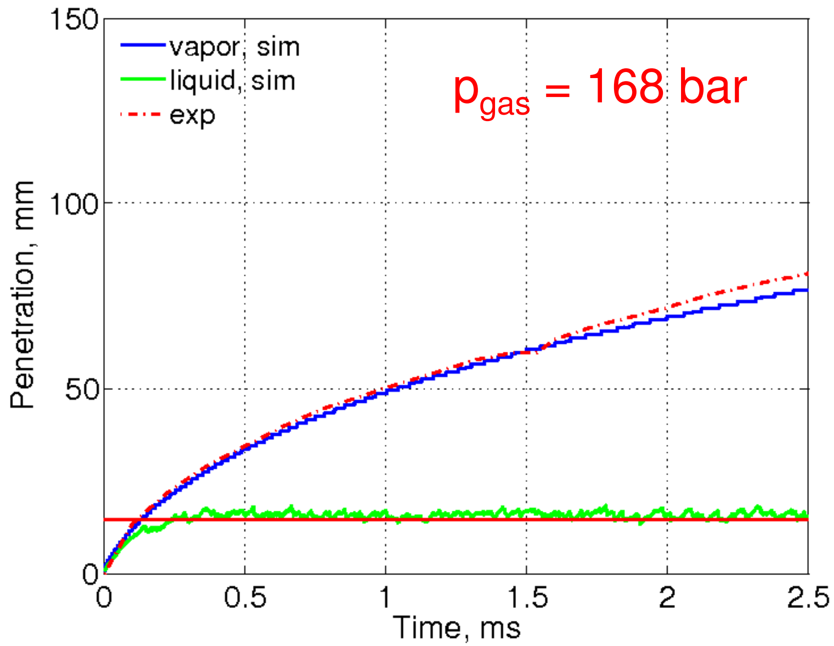
(SAE 2011-01-0842)

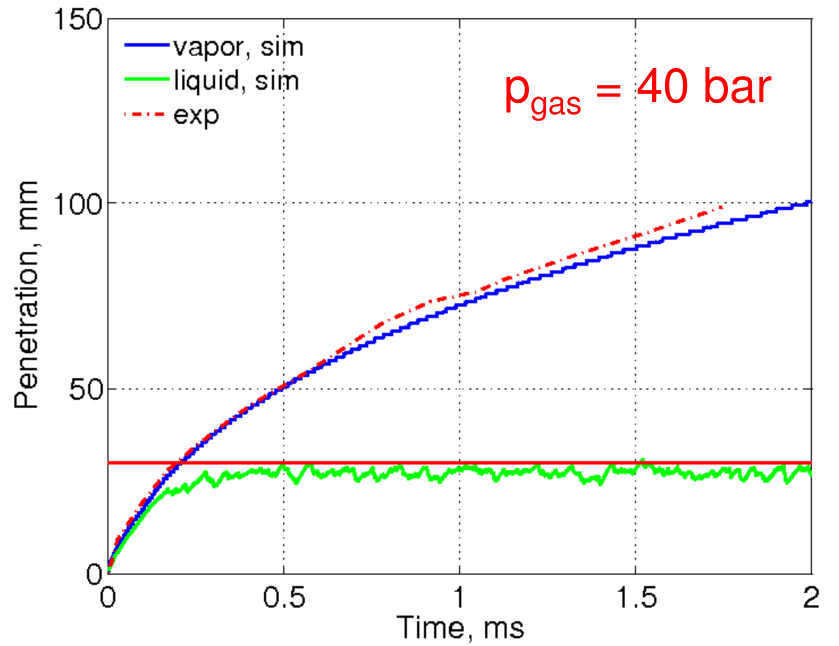
Experiments:

Siebers & Naber

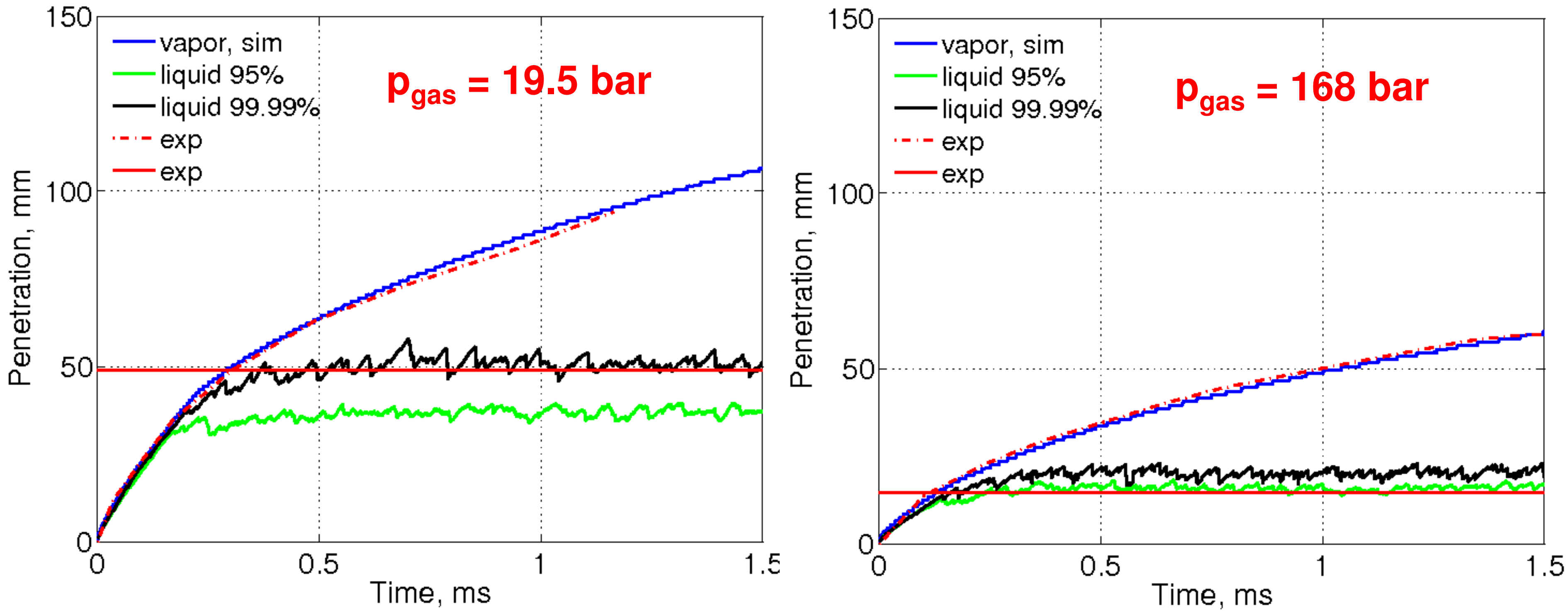
(SAE 960034, SAE 980809)







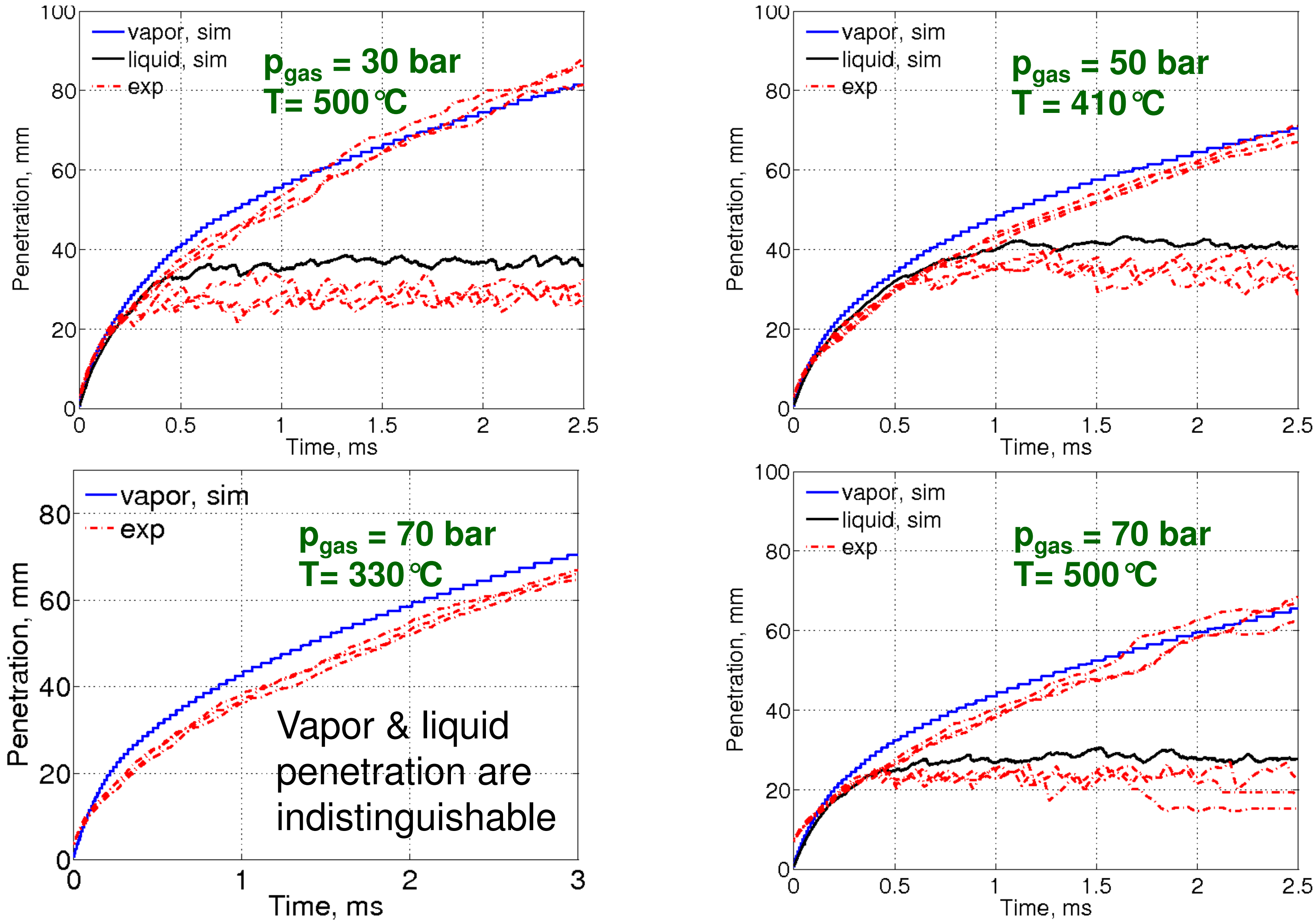
Definition of liquid penetration



Chalmers HP/ HT spray rig*

P_{inj} = 600 bar

(SAE 2011-01-0842)

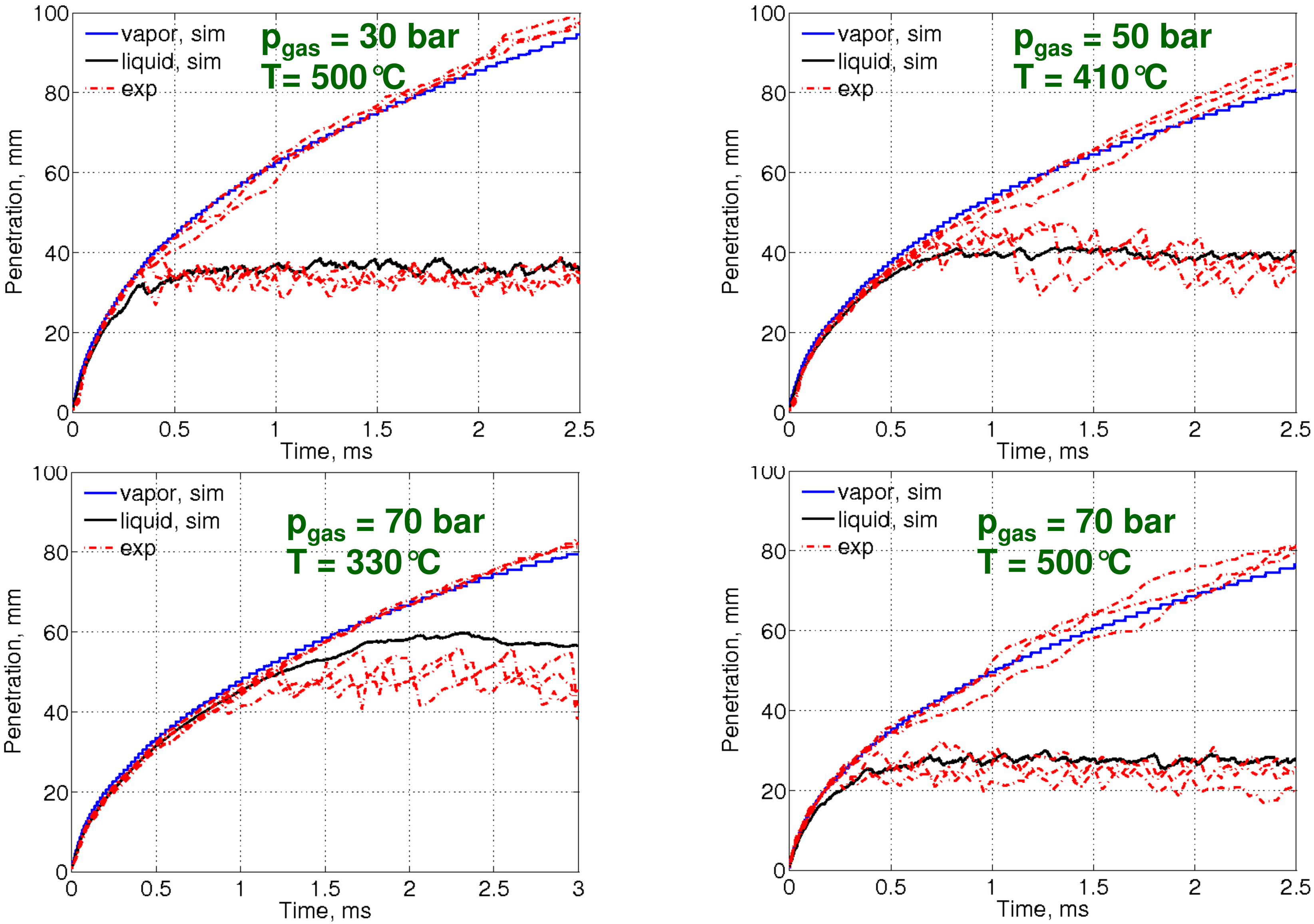


*experiments by Raúl Ochoterena, Chalmers University of Technology

Chalmers HP/ HT spray rig*

P_{inj} = 1200 bar

(SAE 2011-01-0842)



*experiments by Raúl Ochoterena, Chalmers University of Technology

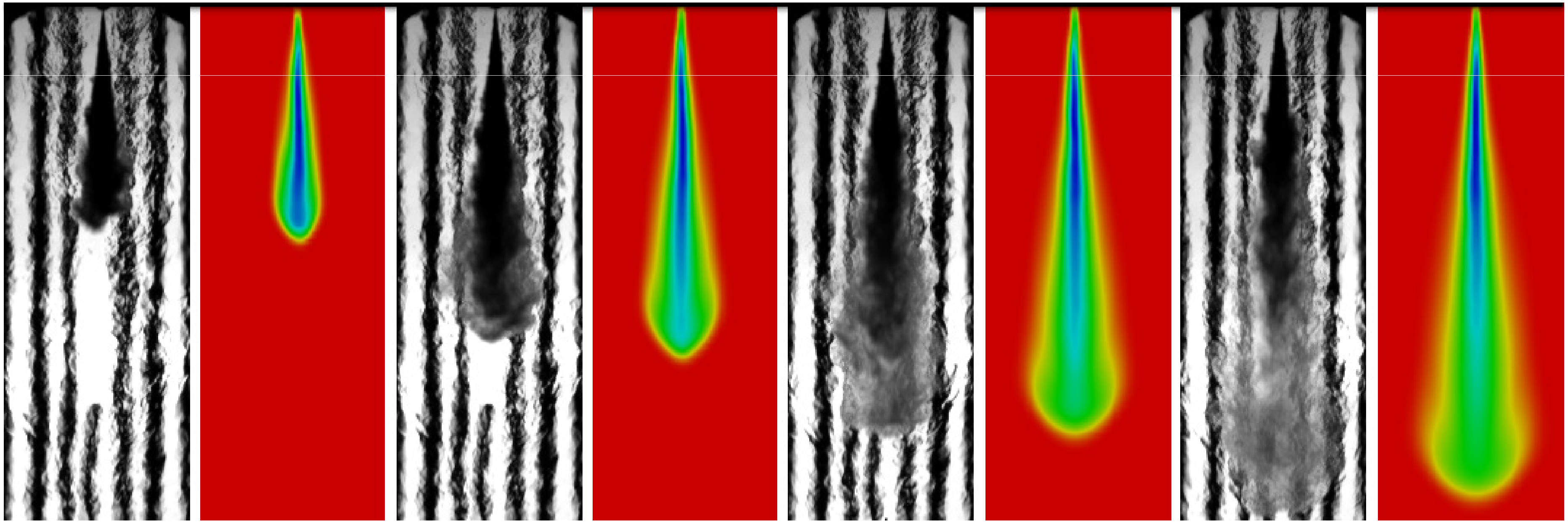
Chalmers HP/HT spray rig, spray shape

(SAE 2011-01-0842)

Exp: Shadowgraphs
Sim: Temperature

P_{inj} = 1200 bar
T_{gas} = 683 K
p_{gas} = 50 bar

t = 0.4 ms **t = 0.9 ms** **t = 1.4 ms** **t = 1.9 ms**



Discussion

- **Robustness + +**
- **Tuning parameters + +**
  (sub models)

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- **Robustness + +**
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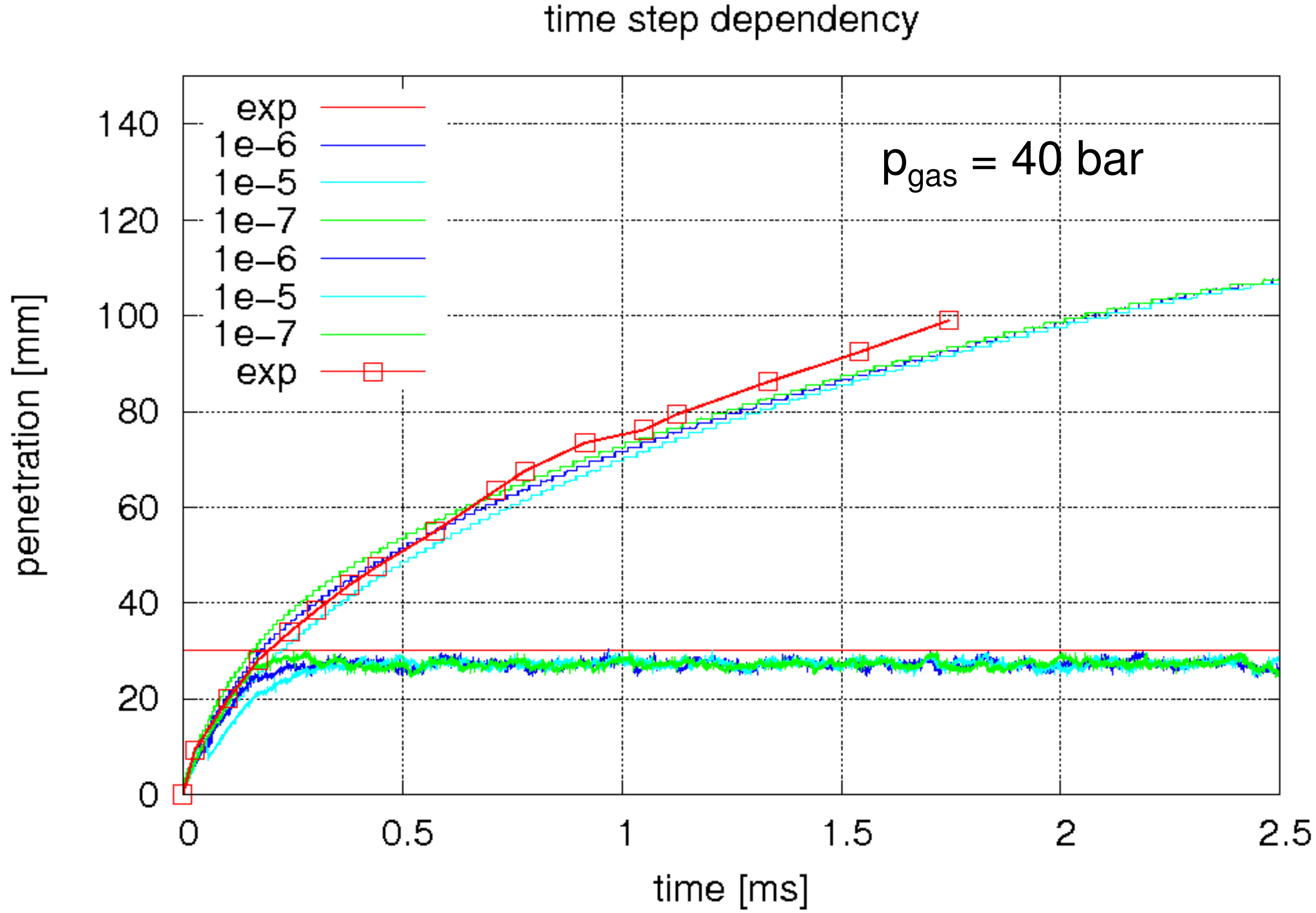
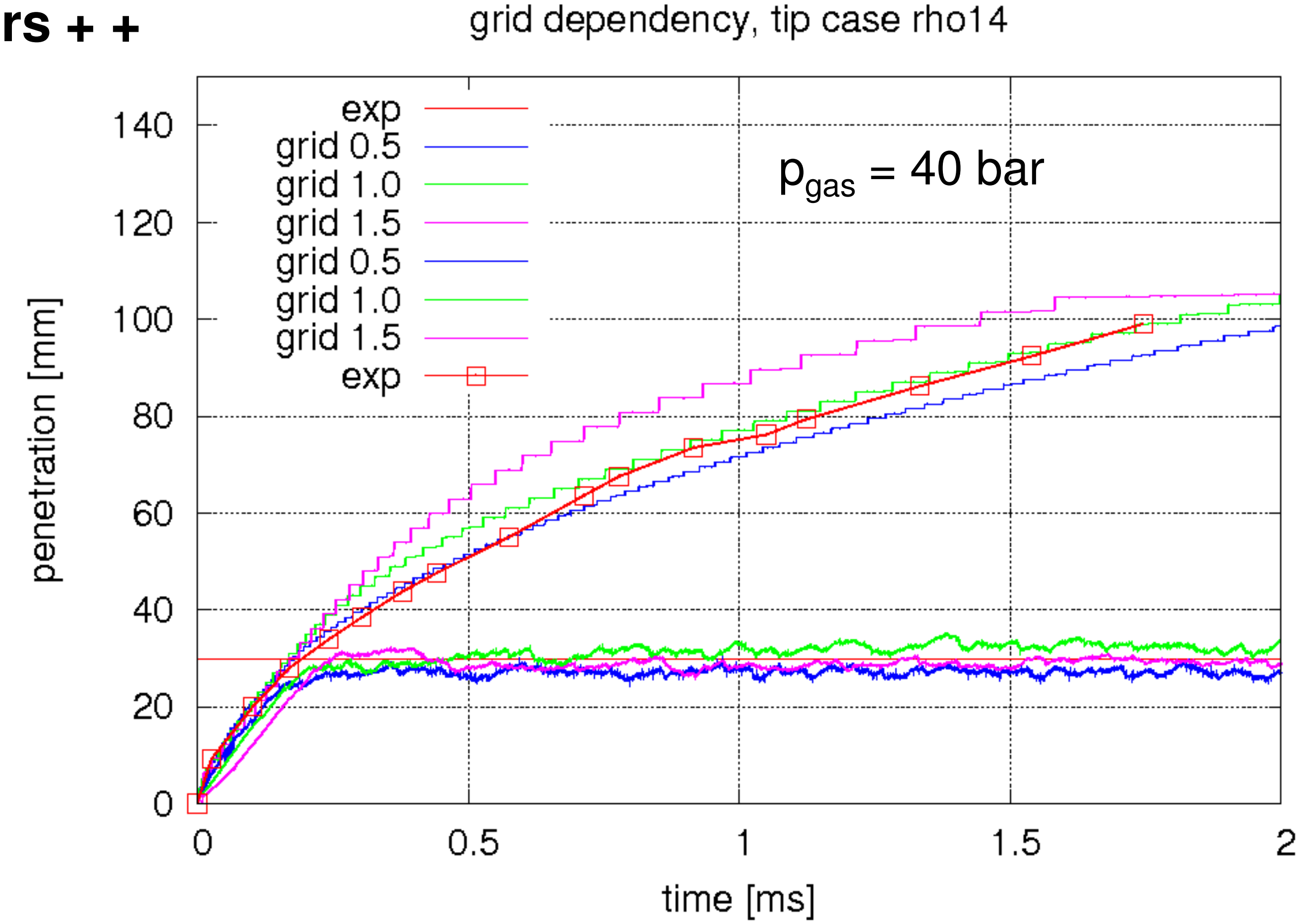


Discussion

- **Grid dependence**
- **Time step dependence +**
- **Robustness + +**
- **Tuning parameters + +**
  (sub models)



Conclusions

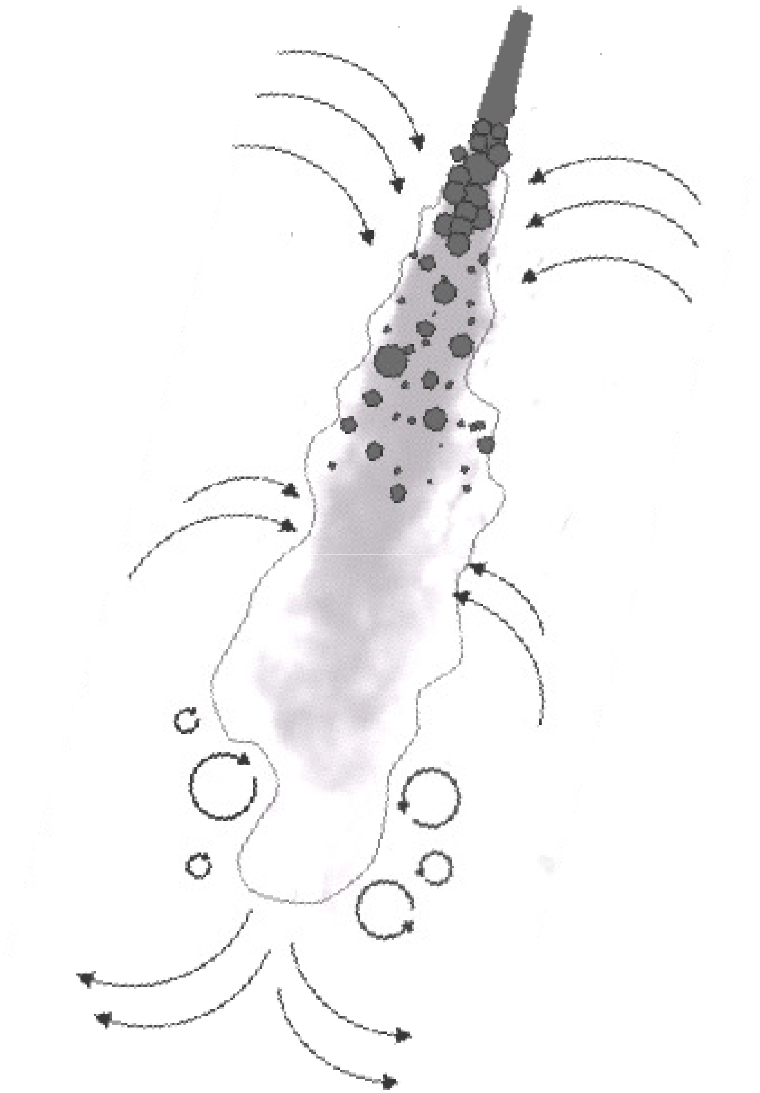
- VSB2 spray model was successfully implemented in OpenFOAM
- VSB2 spray model combined with a tuned k-ε model predicts vapor and liquid penetration well under all tested conditions
- Robust!

Ongoing Work

- Combustion

  (Modification of Partially Stirred Reactor (PaSR model))

Thank you for your attention!



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