Simulation of Primary Breakup for Diesel Spray with Phase Transition

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Two Phase Flow with Phase Transition?
Yes, We can!

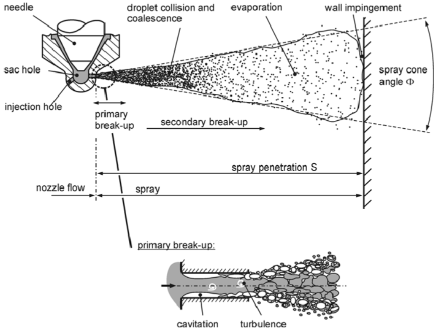
Outline

Spray Combustion

The Spray Model we have

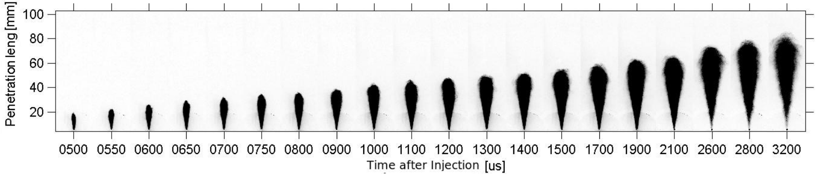
- semi-Empirical nature for breakup.
- model Parameters.
- experimental data for calibration.

Primary Breakup, the beginning of the spray, is particularly poorly understood.

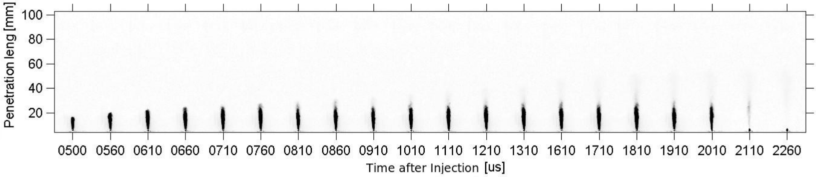


Breakup of diesel spray
source: Baumgarten 2006

Phase Transition Effect on Primary breakup?



injection by $T = 293K$



injection by $T = 800K$

Outline

Governing Equations without evaporation

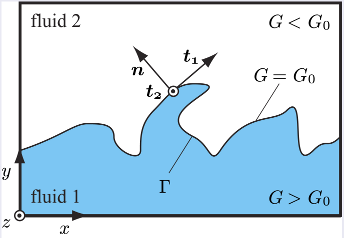
Navier-Stokes

$$\frac{\partial \boldsymbol{u}}{\partial t} + \boldsymbol{u} \cdot \nabla \boldsymbol{u} = -\frac{1}{\rho}\nabla p + \frac{1}{\rho}\nabla \cdot (\mu(\nabla \boldsymbol{u} + \nabla^T \boldsymbol{u})) + \boldsymbol{g} + \frac{1}{\rho}\boldsymbol{T}_\sigma$$

$$\nabla \cdot \boldsymbol{u} = 0$$

Level-Set

$$\frac{\partial G}{\partial t} + \boldsymbol{u} \cdot \nabla G = 0$$



Properties at interface cells

$$\rho = \psi\rho_1 + (1-\psi)\rho_2$$

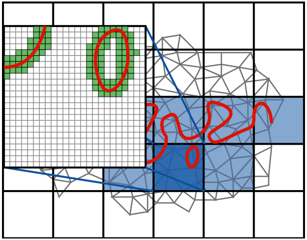
$$\mu = \psi\mu_1 + (1-\psi)\mu_2$$

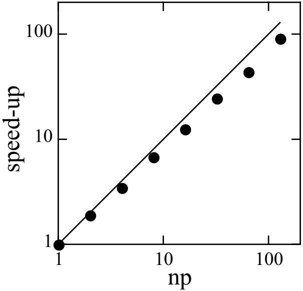
Surface Tension Force

$$\boldsymbol{T}_\sigma(\boldsymbol{x}) = \sigma\kappa\delta(\boldsymbol{x} - \boldsymbol{x}_f)\boldsymbol{n}$$

$$\boldsymbol{n} = \frac{\nabla G}{|\nabla G|}, \quad \kappa = \nabla \cdot \boldsymbol{n}$$

Numerics and Performance of two-phase flow solver



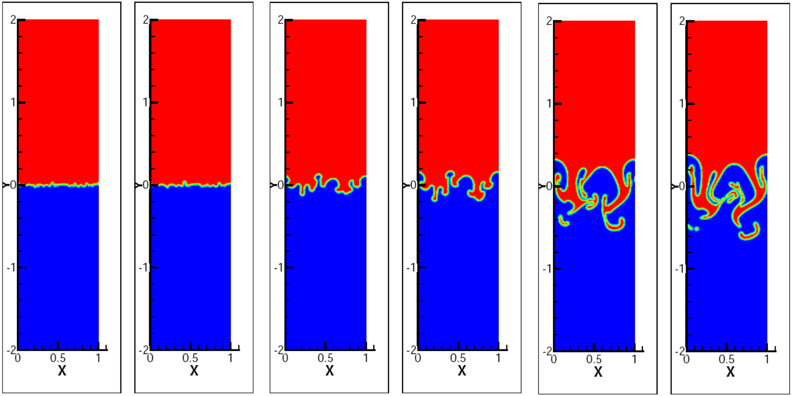


Refined Level Set Grid Method

- Introduce equidistant Cartesian super-grid (blocks)
- Activate (store) only narrow band of blocks
- Active blocks consist of an equal-distant Cartesian fine G-grid
- Activate (store) only narrow band of fine G-grid

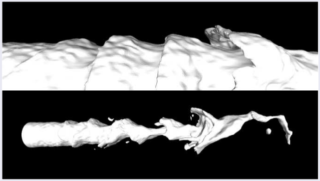
⇒ Advantages: low cost of storage, efficient domain decomposition, straightforward parallelization, fast and accurate Cartesian solution mothods (5th order WENO)

Rayleigh-Taylor Instability

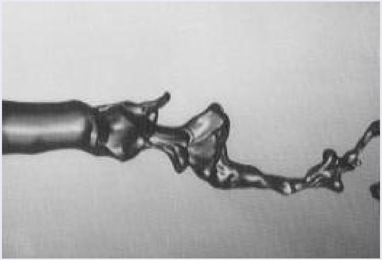


Liquid Interface dynamic

Simulation



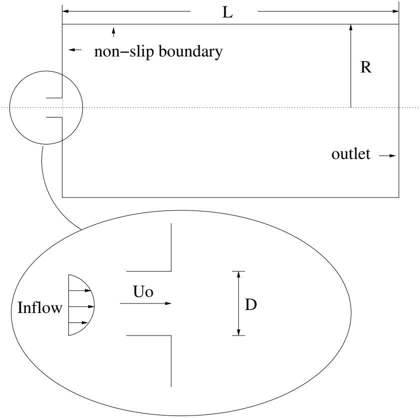
Experiment



source: Lasheras et al.
JFM 1998

Outline

Simulation Geometry



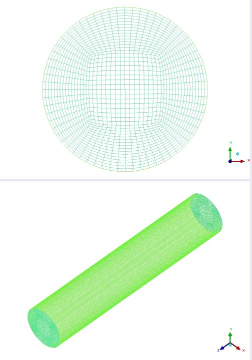
Computational domain

- Nozzle diameter
  D = 0.138 mm
- Chamber Length
  L = 90 mm
- Chamber Radius
  R = 40 mm
- Inflow Velocity
  Uo = 300 m/s

- Source:
  Spiekermann et al.
  Atomization & Spray 09

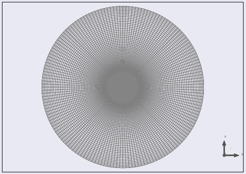
Computational Grid and Simulation setup

Pipe Inflow



- DNS of Turbulent pipe flow

Refined Grid



$$Re_D = \frac{\rho U_0 D}{\mu} \simeq 15 \times 10^4$$

$$We_l = \frac{\rho_l U_0^2 D}{\sigma} \simeq 27 \times 10^4$$

$$\eta \sim 1 \mu m$$

$$\Delta x \simeq 3\eta \sim 4\eta$$

Liquid

- Temperature $T_l = 550K$
- Density $\rho_l = 600kg/m^3$
- Dynamic viscosity $\mu_l = 1.0 \times 10^{-4} Pa * s$
- Surface Tension $\sigma = 0.025N/m$

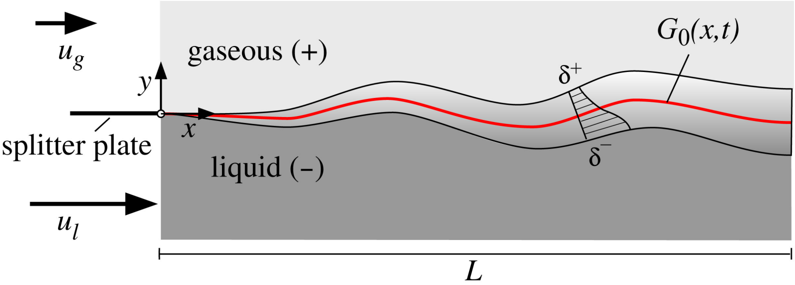
Gaseous

- Temperature $T_g = 700K$
- Density $\rho_g = 25kg/m^3$
- Dynamic viscosity $\mu_g = 1.0 \times 10^{-5} Pa * s$

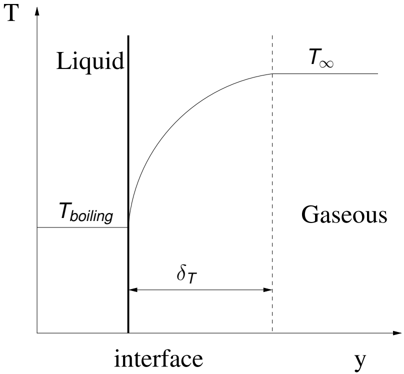
Outline

The Problem Formulation

- we consider an evaporating liquid with surface tension, which has a uniform temperature T_L. The gaseous phase has much higher temperature, leading to strong evaporation at the interface.



Evaporation with Surface regression velocity S_p



Temperature boundary layer

In the temperature boundary layer, all the conducted heat is consumed by evaporation.

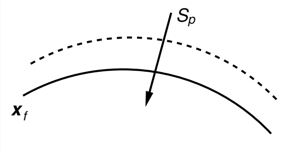
$$\frac{\rho_g \nu_g}{Pr}\frac{\partial T}{\partial y} = \frac{\dot{m} h_L}{C_p}$$

where $\dot{m} = \rho_l S_p$ is mass flow rate per unit area.

$$S_p = \frac{1}{Pr}\frac{\rho_g}{\rho_l}\frac{C_p(T_\infty - T_{Boiling})}{h_L}\frac{\nu_g}{\delta_T}$$

New G equation

Interface equation including evaporation



$$\frac{d\boldsymbol{x}_f}{dt} = \boldsymbol{u} + S_P \boldsymbol{n}$$

$$\frac{\partial G}{\partial t} + \boldsymbol{u} \cdot \nabla G + S_P |\nabla G| = 0$$

New theory

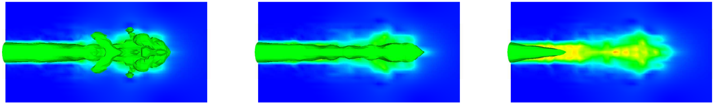
based on asymptotic analysis of the boundary layers,

$$S_P = \varepsilon S_{P0} + \varepsilon^2 S_{P1}, \quad \varepsilon^2 = 1/Re$$

$S_{P0} = \mathcal{F}(\delta_T, \Delta T, \dots)$ and $S_{P1} = \mathcal{G}(\kappa, \Delta T, \dots)$
we are developing a new theory for interface equation

$$\frac{\partial G}{\partial t} + (\boldsymbol{u} \cdot \nabla) G + \varepsilon S_{P0} |\nabla G| + \varepsilon^2 S_{P1} |\nabla G| = 0$$

$S_p = 0.0, S_p = 0.01, S_p = 0.1$



Conclusion and Perspective

- Level-set method has been used for two-phase flow interface tracking.
- The surface regression velocity is introduced for phase transition.
- Asymptotic analysis of the interface evolution equation is going on.

Reference

Norbert Peters.
Turbulent Combustion.
Cambridge University Press, 2000.

Marcus Herrmann.
A balanced forced Refined Level Set Grid method for two-phase flows on unstructured flow solver grids.
Journal of Computational Physics, 227, 2674-2706, 2008

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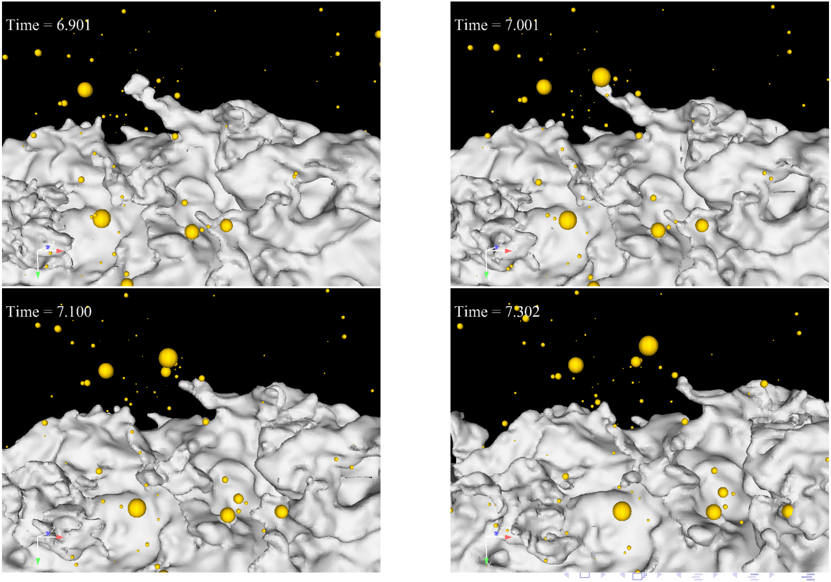
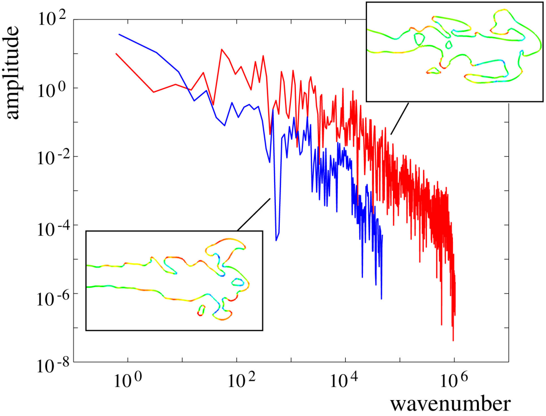
submitted to*ICLASS 2009*

Droplets Formation



Curvature Spectrum



- Fourier transformation of local curvature along the ligaments
- red, with evaporation; blue, without evaporation

Droplet size distributions