Application of Level-set Method to In-Nozzle Flow Calculations

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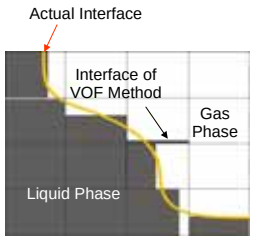
Popular interface tracking method (VOF)

- VOF (Volume of Fluid) method

Liquid volume ratio in each cell is calculated

The interface between the liquid and gas smears with time

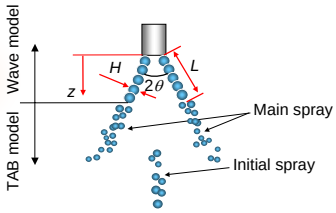
The gradient of interface cannot be well defined



Modeling of Swirl-Type Injector

Accuracy of boundary conditions such as H and L deteriorate

Introduction of a new technique to track the interface correctly is required (Level-set method)



H : Liquid sheet thickness

L : Liquid sheet length

Modeling of spray for swirl-type injector
X. Hu, et al. (2002) based on Han's model

Objectives

- To implement Level-set method to a commercial code (FLUENT6.2)
- To calculate an in-nozzle flow of a swirl-type injector in order to evaluate the model
- To examine the effect of back pressure by making calculations

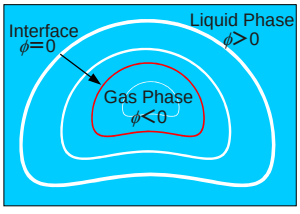
Level-set Method

Transportation equation

$$\frac{\partial \phi}{\partial t} + \mathbf{u} \cdot \nabla \phi = 0$$

ϕ: Level-set function

ϕ=0 at the interface. Local ϕ means the shortest distance from the interface.

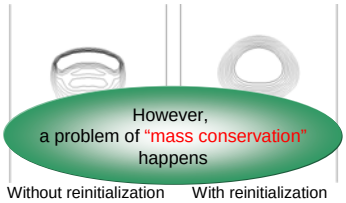


The interface can be well defined as ϕ is a distance function

Re-Initialization

The feature of ϕ as "distance function" will be lost with time

Re-initialization of function can recover the feature



However, a problem of "mass conservation" happens

Without reinitialization With reinitialization

Mass conservation correction

$$\phi'(t) = \phi(t) + L_{err} \qquad L_{err} = \frac{V(t) - V_{init}}{A(t)}$$

Himeno(2000)

$\phi'(t)$: ϕ after mass correction
$\phi(t)$: ϕ after reinitialization
L_{err} : Correction paragraph
$V(t)$: Gas volume at time=t
V_{init} : Gas volume at time=0
$A(t)$: total area of the gas-liquid interface

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Treatment of outflow boundary

$$L_{err} = \frac{V(t) - V_{init}}{A(t)}$$

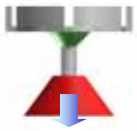
Conventional method cannot account for outflow

$$L_{err} = \frac{V(t) - V_{VOF}(t)}{A(t)}$$

At each time step, a mass compensation made using gas phase volume, V_{init} calculated by VOF

	VOF Method	Level-Set Method
Conserve volume	○	×
Calculate in high rate of density	○	○
Calculate surface tension*	△	○
Capture the gas-liquid interface	×	○

* Surface tension is not accounted



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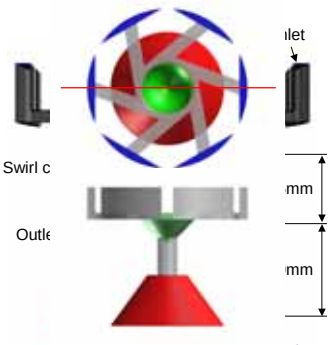
In-Nozzle flow calculation of a Swirl-type injector

- Calculation mesh geometry
  - #Mesh：264550
  - Mesh size：5～50μm
  - Needle lift：10μm
- Boundary conditions
  - Inj. press.：5.0MPa
  - Back press.：0.1, 1.0MPa
  - Fuel：n-heptane



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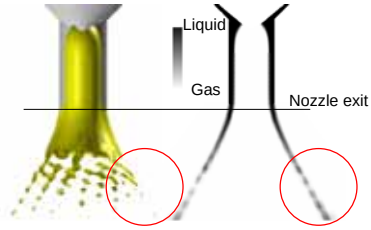
Calculation results using VOF

- Interface is smeared
- Pseudo breakup of liquid was observed as the interface was assumed at the position with a value of VOF function at 0.5



VOF fraction iso surface at 0.5

Contour of volume fraction on center-vertical section

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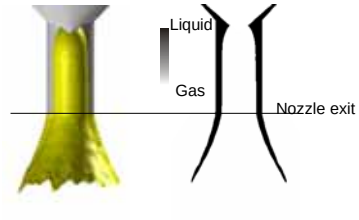
Calculated results with Level-set

- Interface does not smear like VOF

Accurate values such as liquid sheet length and thickness can be given



Level-Set function iso surface at 0

Spatial distribution of liquid fuel on center-vertical section

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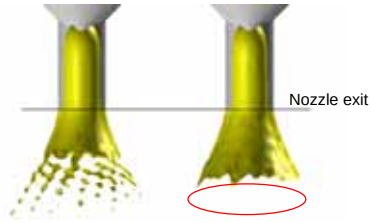
Comparison between VOF and Level-set results

- A long liquid sheet was observed in Level-set

Some liquid regions cannot be captured by VOF

- Liquid phase vanished in the downstream



Volume-of-Fluid Method

Level-Set Method

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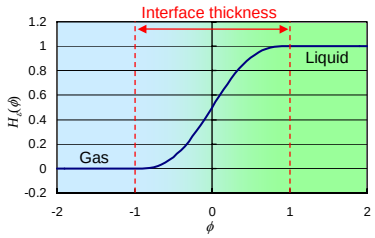
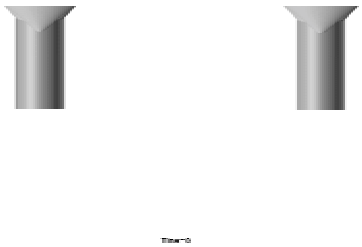
Resolvable liquid thickness



In Level-set method, because a finite length of “virtual interface thickness” is required to stabilize the calculation, a thin liquid sheet less than the “virtual interface thickness” cannot be captured.

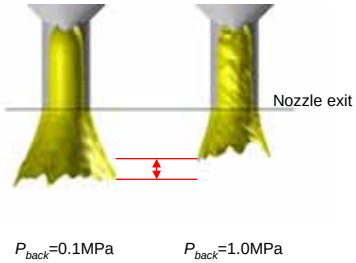
Calculated results with different back pressures



P_{back}=0.1MPa P_{back}=1.0MPa

Discussion

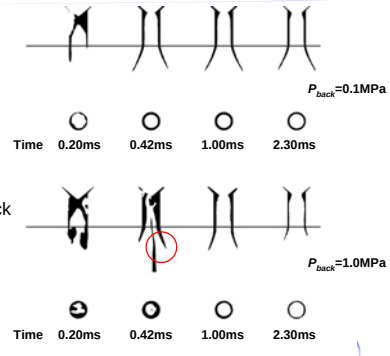
- The thickness of liquid sheet became thin with high back pressure
- Unstable wavy surface appeared with high back pressure



P_{back}=0.1MPa P_{back}=1.0MPa

Liquid phase distribution on center cross section

- It takes longer time to form a conical liquid sheet with high back pressure
- A liquid column appears with high back pressure



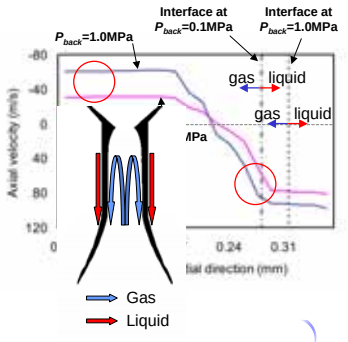
Vertical velocity distribution

- Air entrainment velocity was enhanced with high back pressure

Liquid sheet thickness and stability are affected

- Velocities of liquid and gas are almost the same around the interface

Formation of air vortices



Conclusions

- A Level-set method, that can treat the interface correctly, was implemented into a commercial code of FLUENT6.2 and an in-nozzle flow calculation of a swirl-type injector was achieved
- When VOF model was used, the interface smeared outside nozzle and pseudo breakup was observed. While using Level-set method, the liquid sheet was well reproduced, but the liquid sheet vanished as the thickness becomes very thin due to the lack of spatial resolution
- When the back pressure was raised, it took longer time to form a conical spray and also the liquid thickness became thin.