ノズル内キャビテーションと液体噴流微粒化の数値解析

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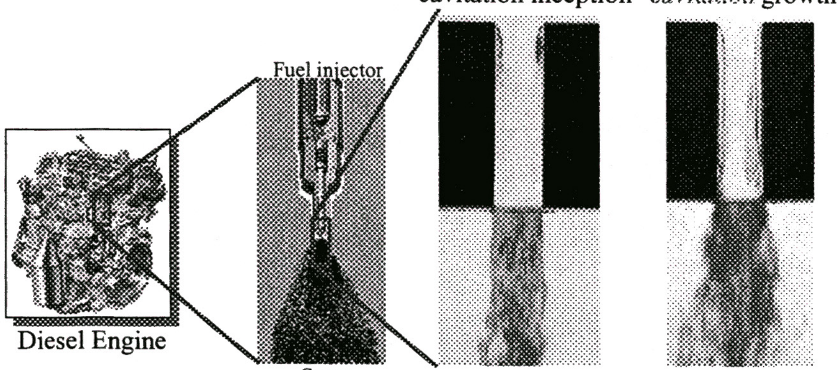


宋　明良（神戸大学）

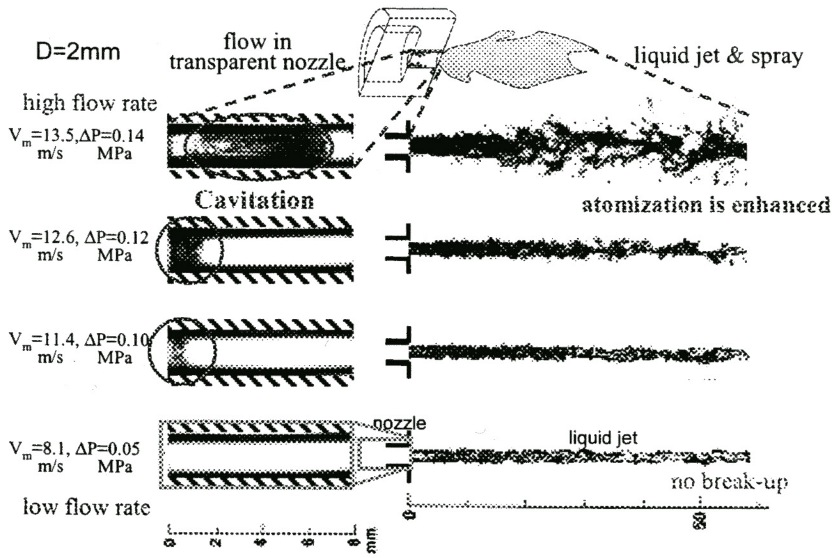
1. Observation of Cavitation in a Nozzle

2. Hybrid Cavitating Liquid Jet Model

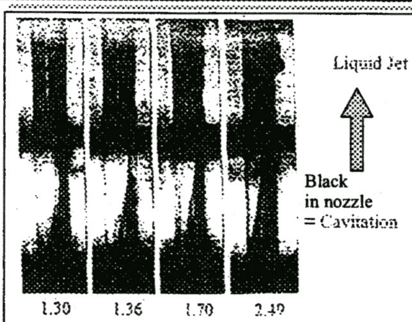
3. An Interface Tracking Model (I-SCA Model)

4. Conclusions

Cavitation in Enlarged Nozzle & Atomization (Hiroyasu, Tamaki)

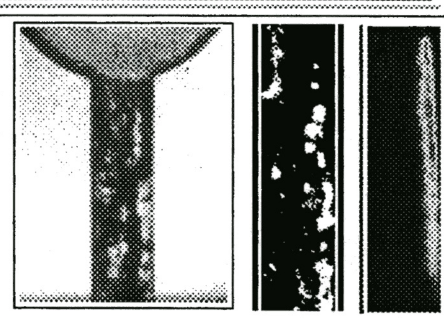


Background (Observation of Cavitation in Diesel Injectors)

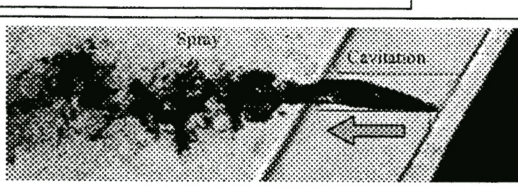


pressure difference [MPa] Round nozzle, D=0.20mm

H. Chaves, et al., (SAE 1995)



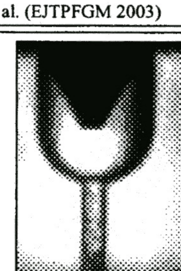
Lance, et al. (EJTPFGM 2003)



P_{inj}=2.65 MPa, Ca=17.35

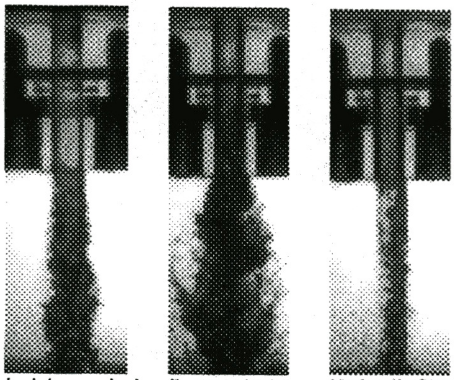
VCO nozzle, D=0.30 mm

R. Miranda, et al., (ICLASS 2003)



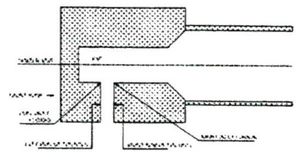
C. Badock, et al. (IFHFF, 1999)

Observations of Cavitation in an Enlarged Nozzle



Incipient cavitation Supercavitation Hydraulic flip

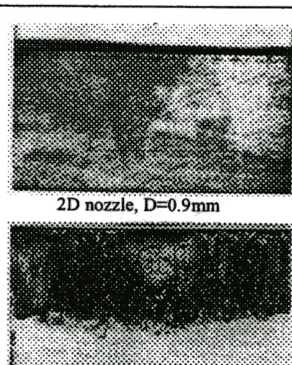
Y. Laoonual, et al.
(ILASS-Europe 2001)



D=4.7mm

L. C. Ganippa, et al. (CAV2001)

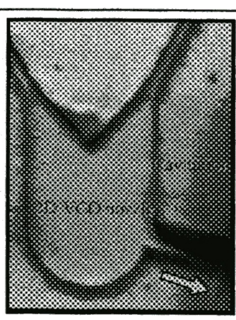
Observations of Cavitation in 2D Nozzle



2D nozzle, D=0.9mm

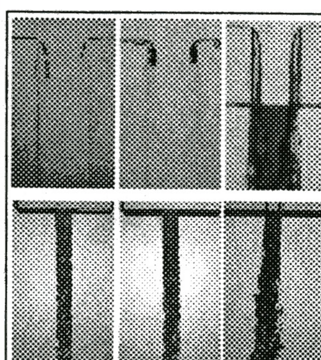
2D nozzle, D=1.4mm

M. E. Henry & S. H. Collicot,
(Atom. & Sprays, 2000)



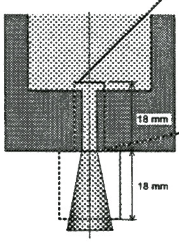
D=0.40mm, t_{EX}=33ms

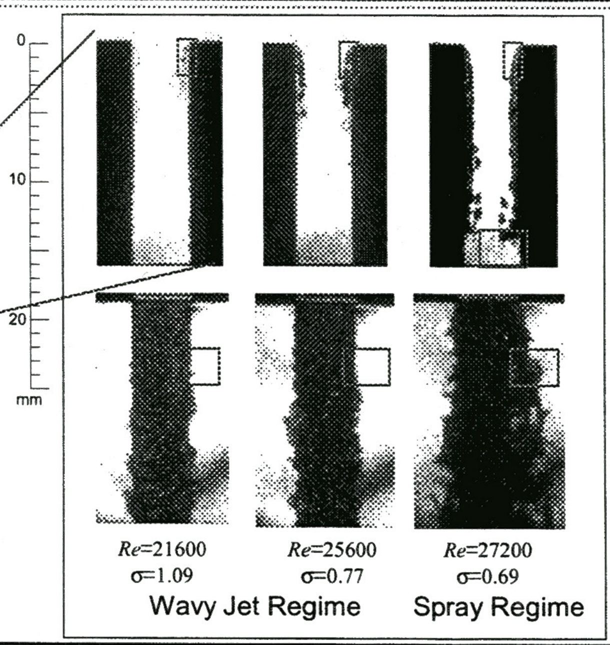
H. Iida, et al., (ICLASS 2000)



Daikoku, et al. (ICLASS, 2003)

Cavitation in a Nozzle & Liquid Jet (18μm/pixel)

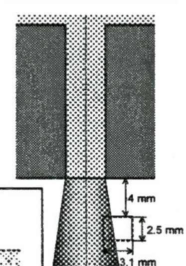


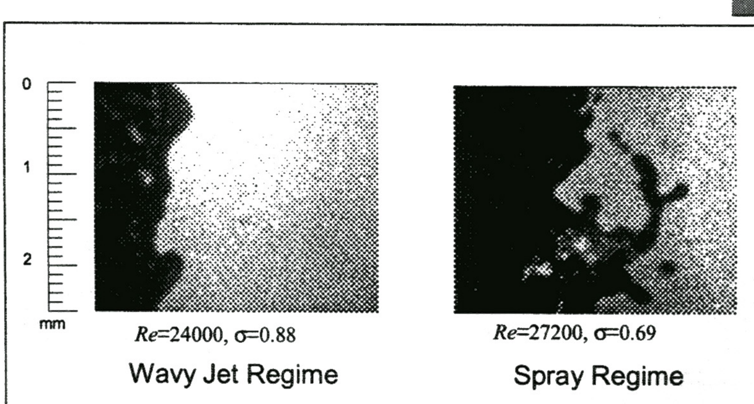


$$Re = \frac{VD}{\nu}$$

$$\sigma = \frac{p_\infty - p_v}{\frac{1}{2}\rho V_\infty^2}$$

Enlarged Images of Liquid Jet Interface (2.5μm/pixel)

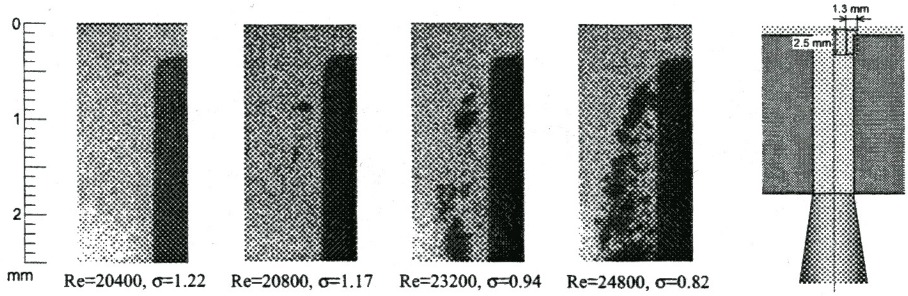


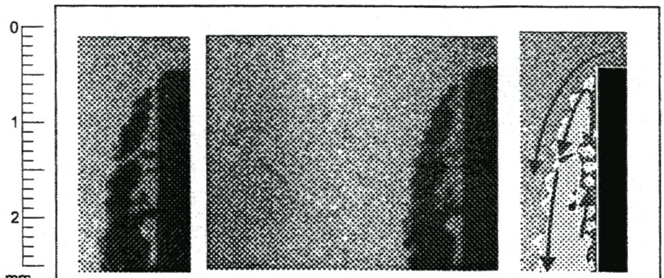


$$Re = \frac{VD}{\nu}$$

$$\sigma = \frac{p_\infty - p_v}{\frac{1}{2}\rho V_\infty^2}$$

Enlarged Image of Undteady Cavitation (2.5μm/pixel)

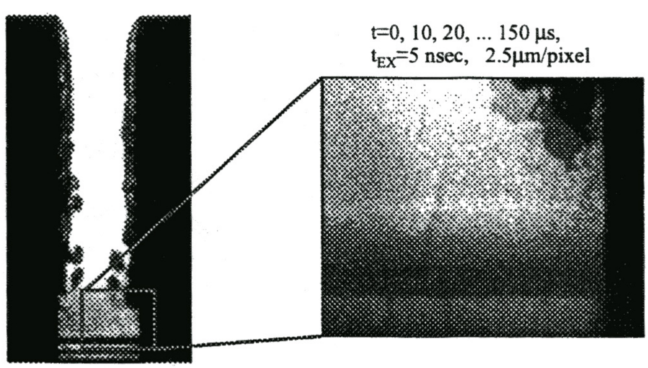




Re=25600, σ=0.77, t_{EX}=5nsec

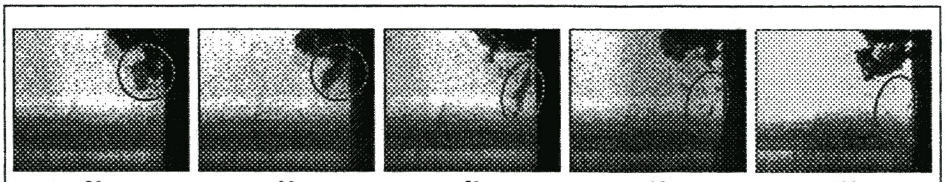
Collapse of Cavitation above the Nozzle Exit

Re=27200, σ=0.69, t_{EX}=5nsec



$$Re = \frac{VD}{\nu}$$

$$\sigma = \frac{p_\infty - p_v}{\frac{1}{2}\rho V_\infty^2}$$



1. Observation of Cavitation in a Nozzle

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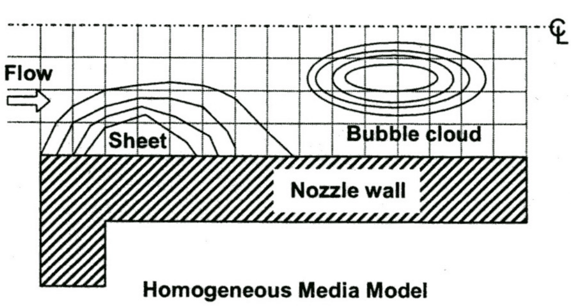
4. Conclusions

Cavitation Model : HM Model



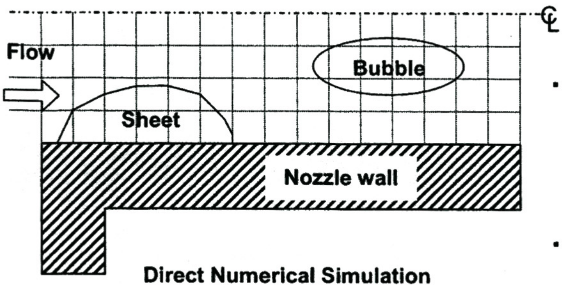
Homogeneous Media Model

- Gas-liquid two-phase Homogeneous Medium model
- mixture density; $\rho=\rho(P)$

Effects of cavitation is averaged.

Effects of cavitation is not easy to be correctly considered.

Cavitation Model : DNS



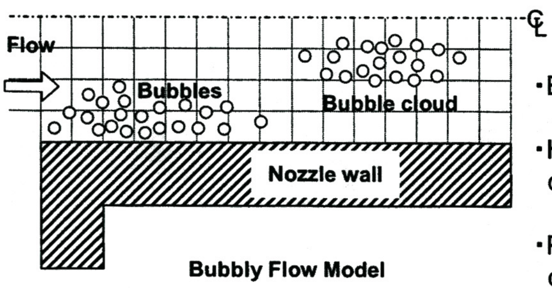
- Direct Numerical Simulation taking into account the jump condition at the gas-liquid interface.
- BEM, VOF, ...

Fine grid have to be assigned.

↓

Simulation including many tiny cavitation bubbles requires huge amount of computer memory & CPU time.

Cavitation Model : Bubbly Flow Model

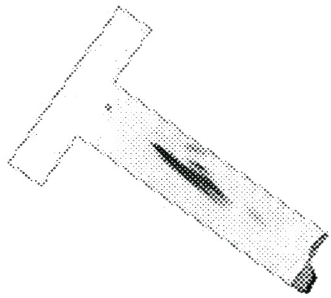


- Bubble Tracking Simulation
- Has a potential to predict cavitation induced turbulence
- Prediction of bubble cavitation, cloud cavitation.

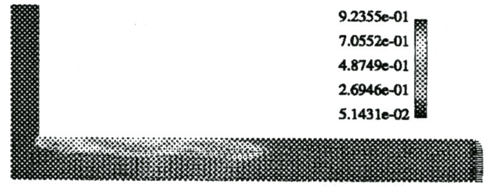
The applicability of Bubbly Flow Model to cavitating flow in nozzle has not been examined.

2-way coupled bubble tracking model (Eulerian-Lagrangian model)

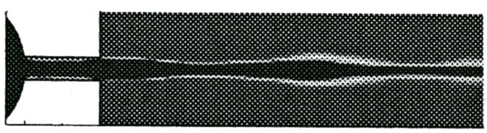
Numerical Simulations of Cavitation in a Nozzle



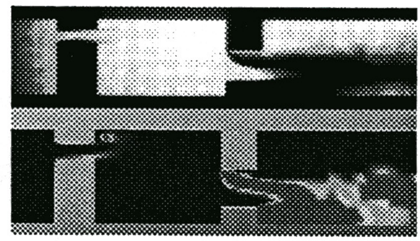
D.P. Schmidt, et al. (SAE1999)



N. Dumont, et al. (CAV2001)



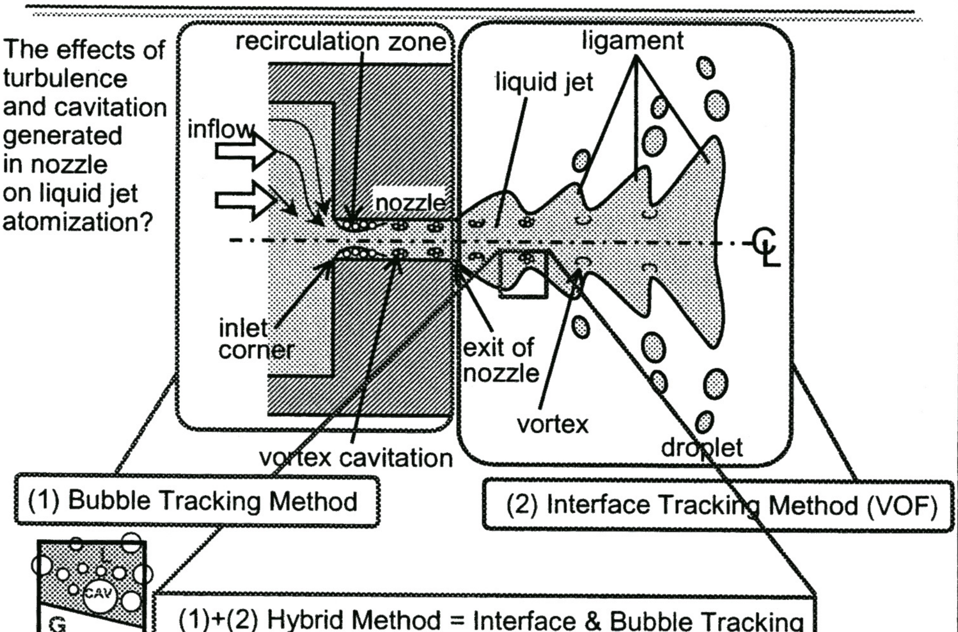
W. Yuan & G.H. Schnerr (FEDSM2002)



A. Alajbegovic, et al. (EJTPFGM, 2003)

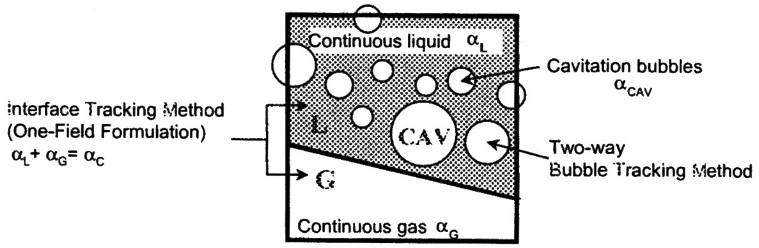
Numerical Simulation of Internal Flow & External Liquid Jet

The effects of turbulence and cavitation generated in nozzle on liquid jet atomization?



Hybrid Numerical Model

Hybrid Model = Bubble Tracking Model + Interface Tracking Model



By using the hybrid basic equation:

if α_G=0 in a cell:	Hybrid model → Bubble Tracking Model
if α_{CAV}=0 in a cell:	Hybrid model → Interface Tracking Model
if $\alpha_G=\alpha_{CAV}$=0 in a cell:	Hybrid model → Liquid Flow
if $\alpha_L=\alpha_{CAV}$=0 in a cell:	Hybrid model → Air Flow

Basic Equations

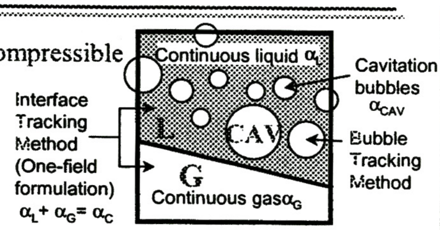
mass conserv. eqs.

incompressible

L: $$\frac{\partial \alpha_L}{\partial t} + \nabla \cdot \alpha_L \boldsymbol{V}_L = -\frac{\rho_{CAV}}{\rho_L}(\gamma_{GEN} - \gamma_{COL})$$

G: $$\frac{\partial \alpha_G}{\partial t} + \nabla \cdot \alpha_G \boldsymbol{V}_G = 0$$

CAV: $$\frac{\alpha_{CAV}^{n+1} - \alpha_{CAV}^{n}}{\Delta t} + \nabla \cdot (\alpha_{CAV} \boldsymbol{V}_{CAV}) = \gamma_{GEN} - \gamma_{COL}$$



$\alpha_L + \alpha_G + \alpha_{CAV} = 1$

$\alpha_L + \alpha_G = \alpha_C$

mass conserv. eq.

$$\nabla \cdot \alpha_C \boldsymbol{V}_C = \frac{\alpha_{CAV}^{n+1} - \alpha_{CAV}^{n}}{\Delta t} + \frac{\rho_{CAV}}{\rho_L}(\gamma_{GEN} - \gamma_{COL})$$

ITM (one-field form.)

$$\boldsymbol{V}_G = \boldsymbol{V}_L = \boldsymbol{V}_C$$

$$\rho_C = \frac{\alpha_G \rho_G + \alpha_L \rho_L}{\alpha_G + \alpha_L}$$

eq. of motion of bubble (BTM)

$$(\rho_{CAV} + C_{VM}\rho_L)\frac{d\boldsymbol{u}_{CAV}}{dt} = -\nabla P + C_{VM}\rho_L \frac{d\boldsymbol{V}_L}{dt} - \boldsymbol{f}_D - \boldsymbol{f}_{LF}$$

$$\alpha_{CAV\,lmn} = \frac{1}{V_{lmn}} \sum_{i=1}^{N} \gamma_{lmn}^{i} V^{i}$$

momentum eq. of continuous phases (one-field form.)

$$\alpha_C \rho_C \left(\frac{\partial \boldsymbol{V}_C}{\partial t} + \boldsymbol{V}_C \cdot \nabla \boldsymbol{V}_C \right)$$
$$= -\alpha_C \nabla P + \boldsymbol{M}_{VM} + \boldsymbol{M}_D + \boldsymbol{M}_{LF} + \boldsymbol{F}_{VIS} + \boldsymbol{F}_{COL} + \boldsymbol{F}_S + \boldsymbol{M}_{PC}$$

$$\boldsymbol{M} = \frac{1}{V_{lmn}} \sum_{i=1}^{N} \gamma_{lmn}^{i} V^{i} \boldsymbol{f}$$

Solution Procedure of the Hybrid Method

(1) Bubble Tracking Step

(1-1) Calculate all terms at each bubble position for solving equation of bubble motion.

(1-2) Calculate all forces acting on bubble.

(1-3) Calculate time advanced $\boldsymbol{u}_{CAV}$ and $\boldsymbol{x}_{CAV}$ of each cavitation bubble. (BTM)

(2) Cavitation Step

(2-1) Calculate the generation and the collapse of cavitation bubble. γ_{GEN} & γ_{COL}

(2-2) Calculate collapse-induced effect $\boldsymbol{F}_{COL}$.

(2-3) Calculate time advanced α_{CAV} and α_{C}.

(3) Fluid Step

(3-1) Calculate all the phasic interactions. (2-way coupling)

(3-2) Calculate advanced V_C & P of continuous gas and liquid phases.

(4) Interface Tracking Step

(4-1) Calculate time advanced α_G and α_L.

(4-2) Calculate density of continuous phases. (one-field form.)

(4-3) Calculate surface tension force $\boldsymbol{F}_S$ acting on an interface. (CSF)

Constitutive Models (Cavitation Model, LES, etc.)

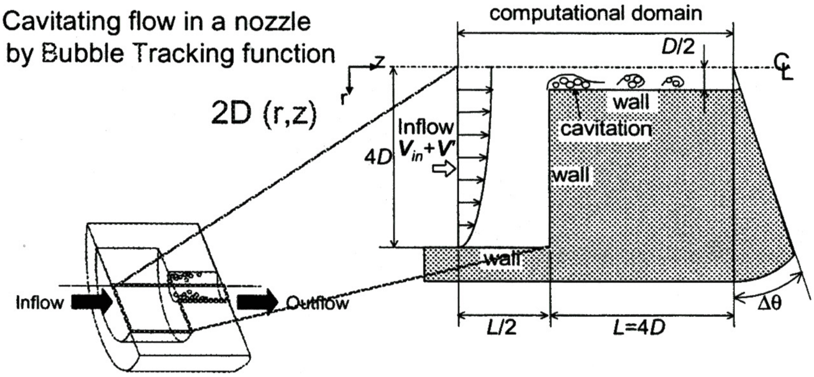
Turbulent diffusion model
(standard LES = Smagorinsky model, Van Driest's wall function)

Cavitation model
(spherical bubbles model)
(constant nuclei concentration)
(cavitation collapse pressure)

Forces acting on a bubble
(a drag model for a single bubble in stagnant liquid)
(a lift force model for a single bubble in linear shear flow)

Cavitating Flow in a Nozzle (Tamaki)

(1) Cavitating flow in a nozzle by Bubble Tracking function



Case	V_m	Re	σ
1	8.1 m/s	16200	1.94
2	12.6 m/s	25200	0.84

Reynolds number

$$Re = \frac{\rho_L V_m D}{\mu_L}$$

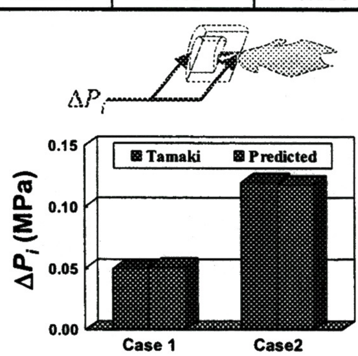
Cavitation number

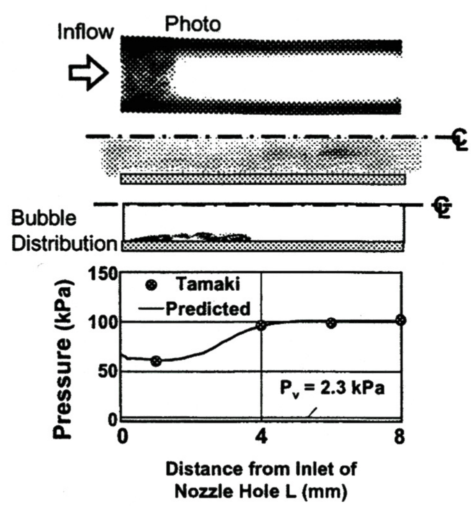
$$\sigma = \frac{P_e - P_v}{\Delta P_i}$$

Calculated vs. Measured Pressure

Injection pressure

ΔP_i (MPa)	Measured by Tamaki	Predicted by BTM
Case 1	0.05	0.051
Case 2	0.12	0.118

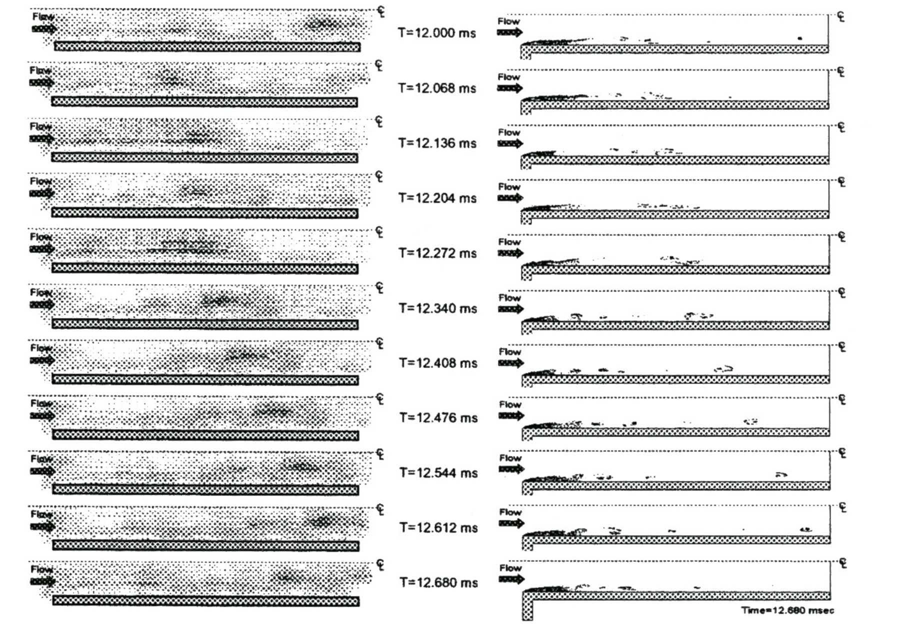




Pressure distribution & injection pressure are well predicted.

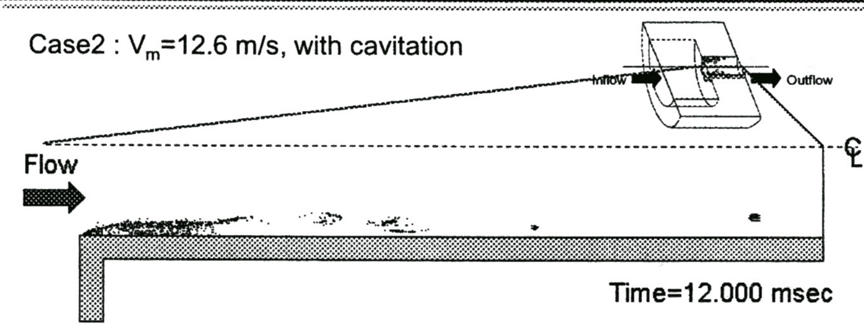
Case 2: V_m=12.6 m/s with Cavitation

Velocity field & Cavitation



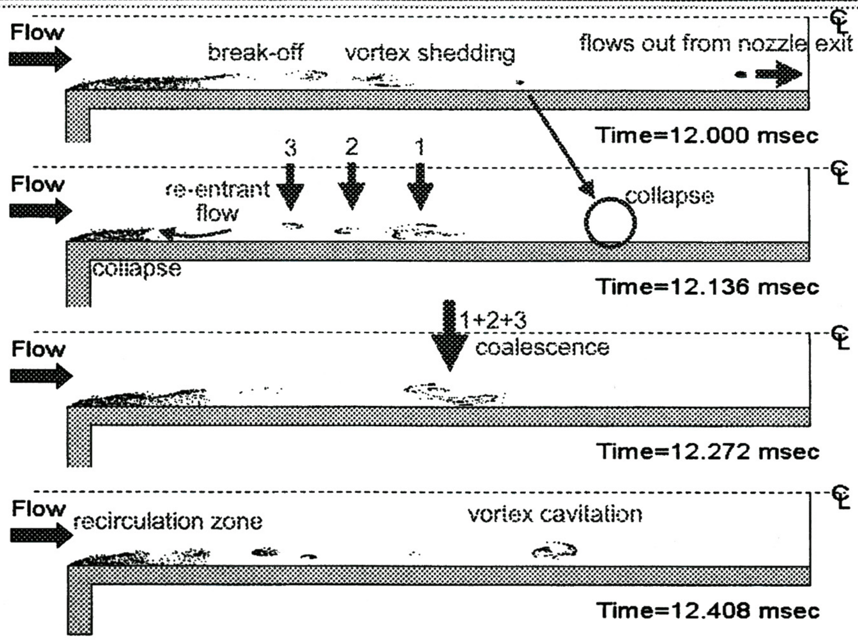
Time History of Cavitation Behavior in a Nozzle

Case2 : V_m=12.6 m/s, with cavitation



- The formation of recirculation zone[Ganippa et al.] at vena contracta
- Vortex cavitation (periodic vortex shedding + bubble cloud)[Sato et al.]
- Coalescence[Sato et al.] & collapse or flowing out of vortex cavitations
- Break-off & Re-entrant flow[Sato et al.] & Collapse of bubbles

Unsteady Cavitation Behavior in a Nozzle

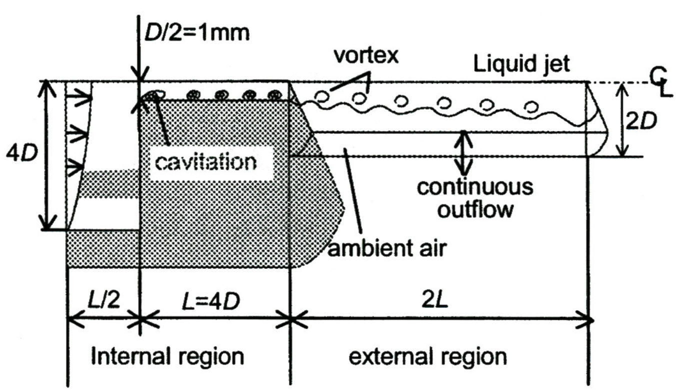


Hybrid Simulation of Liquid Jet Deformation

(1)+(2) Hybrid Simulation
= Internal & external flows

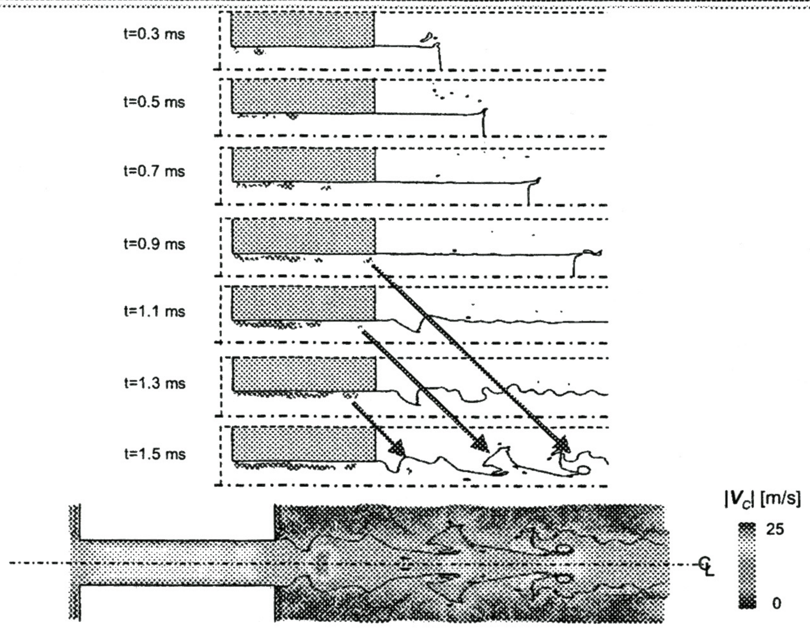
Case2 : V_m=12.6 m/s
with cavitation

Case	Flow in a Nozzle	Cavitation
3	Calculated	Calculated
4	Not Calculated	Not used



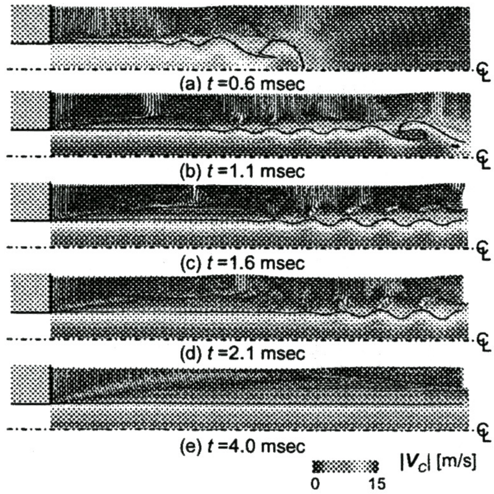
water jet deformation injected into initially stagnant air through a round nozzle

Collapse of Bubble Clouds in a Liquid Jet (Case 3)



Effects of Vortex & Cavitation Generated in Nozzle

Predicted by ITM (Case 4) no internal flow calculated



Vortices and cavitation generated in a nozzle play important role in liquid jet deformation.

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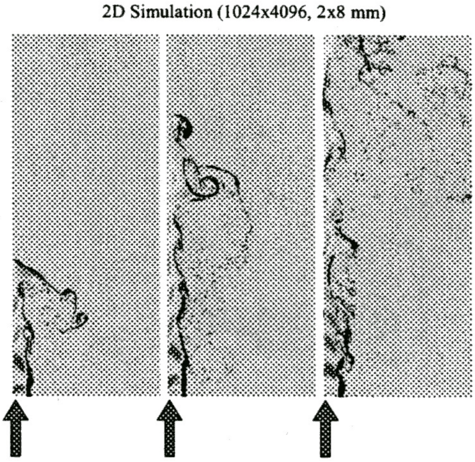
4. Conclusions

Numerical Simulation of Liquid Jet Atomization

Interface Tracking Simulation by SURFER Code (Zaleski, S., et al., EJTPFGM 2003)

2D Simulation (1024x4096, 2x8 mm)

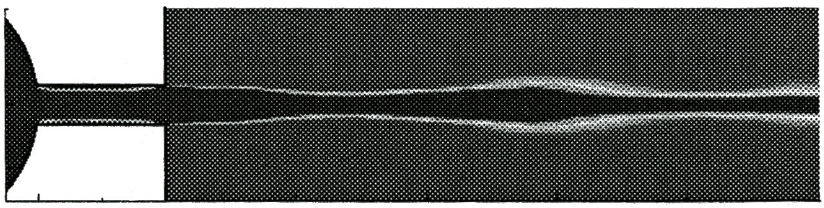


Diesel engine liquid jet injection (with vortices in nozzle)

3D Simulation (256x128x128, 2x1x1 mm)

It is likely that the 3D problem will be sufficiently resolved circa 2010. (Zaleski, S.)

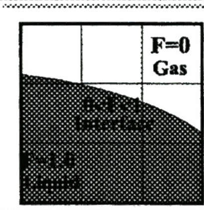
Problems on Interface Tracking Method



W. Yuan & G.H. Schnerr (FEDSM2002)

(1) Numerical diffusion of gas-liquid interface
(2) Mass (volume) conservation
(3) Accurate shape prediction of interface after the advection

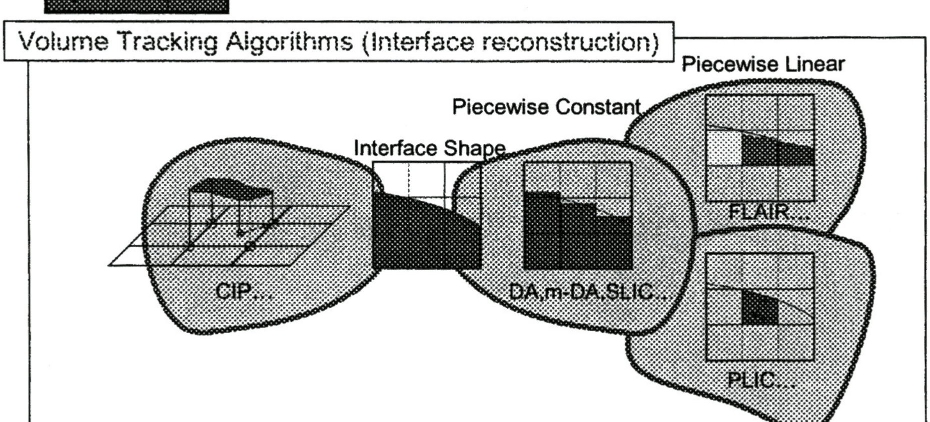
Interface Tracking Method



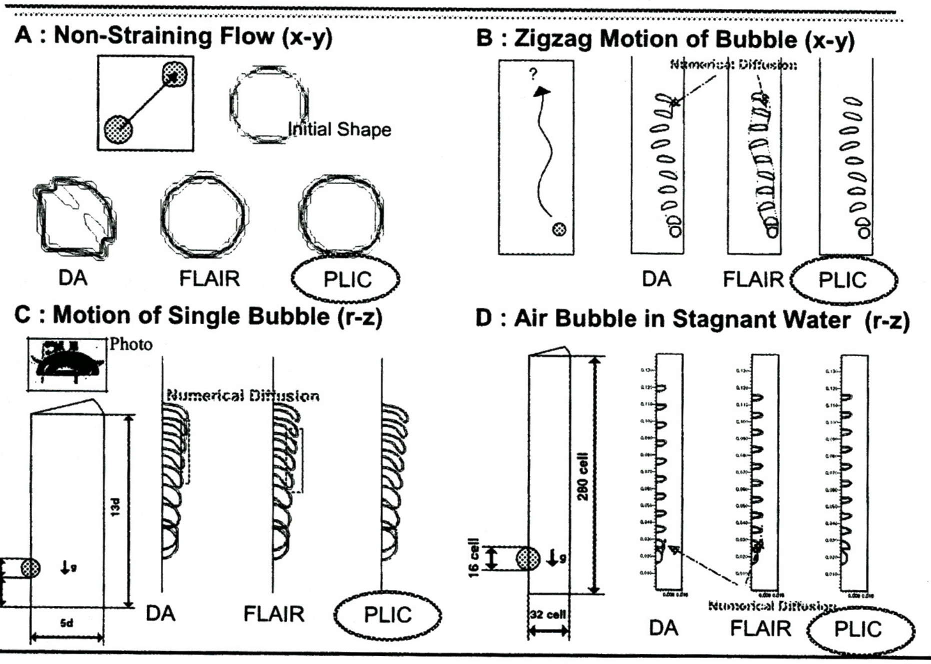
volume fraction
$F(t,\mathbf{x})$

Liquid advection eq.

$$\frac{\partial F}{\partial t} + \underbrace{(v \cdot \nabla) F}_{\text{advection of F}} = 0$$



Evaluation of Volume Tracking Algorithms



Interface Reconstruction Schemes

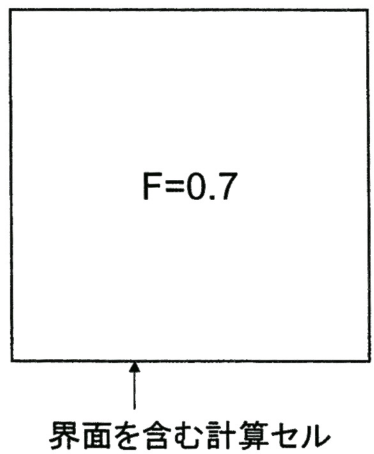
Good ⟷ Poor

	予測形状の精度	Fの数値的な拡散防止	体積の保存	計算手順の簡易さ	三次元化の容易さ
I-SCA	Good		Good		Good
SCA			Poor		Good
PLIC/ MARS	Good				
FLAIR		Poor			
DA	Poor	Poor	Poor		

I-SCA : Improved-Simple Counting Algorithm
SCA : Simple Counting Algorithm
PLIC : Piecewise Linear Interface Calculation
MARS : Multi-interfaces Advection and Reconstruction Solver
FLAIR : Flux Line-segment Advection and Interface Reconstruction
DA : Donor-Acceptor

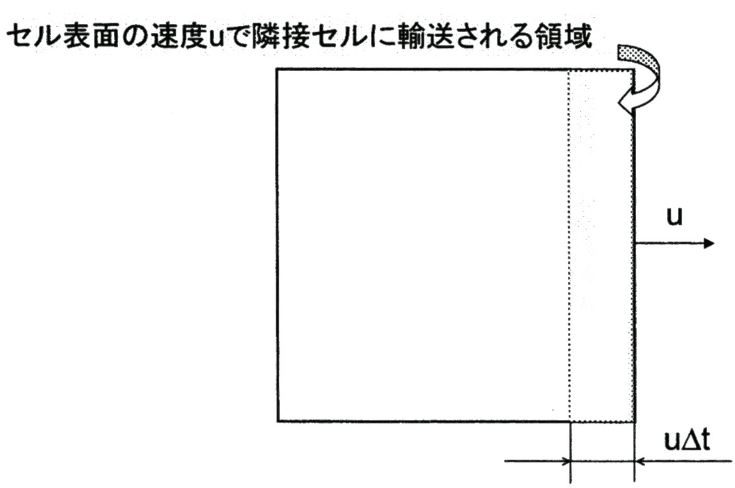
Improved-Simple Counting Algorithm

①界面を含むセル(0<F<1)を特定する



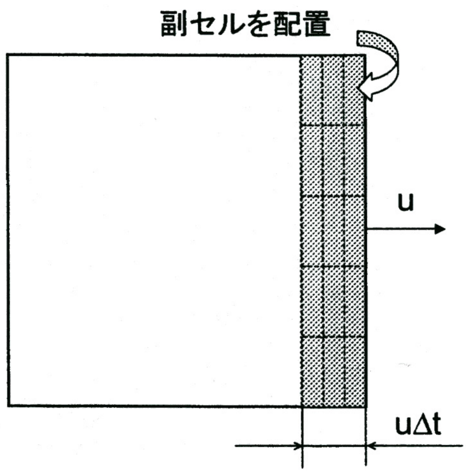
Improved-Simple Counting Algorithm

②計算セル内に副セルを配置する



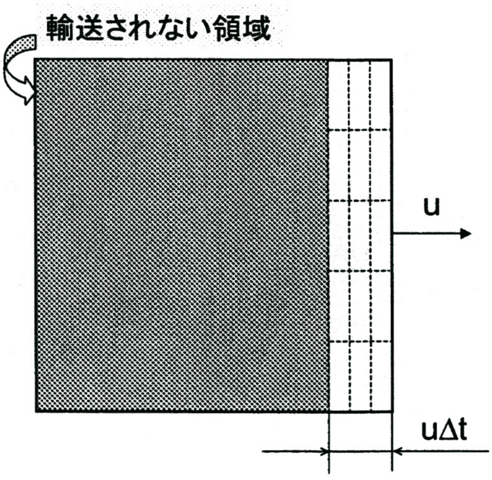
Improved-Simple Counting Algorithm

②計算セル内に副セルを配置する



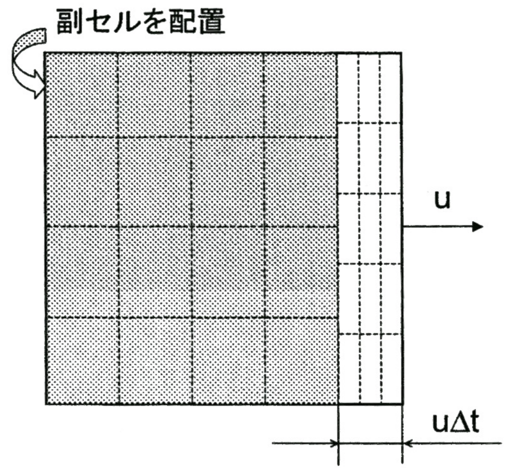
Improved-Simple Counting Algorithm

②計算セル内に副セルを配置する



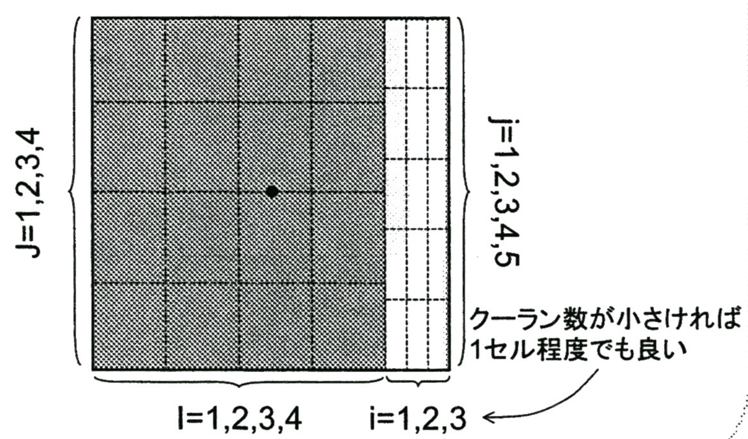
Improved-Simple Counting Algorithm

②計算セル内に副セルを配置する



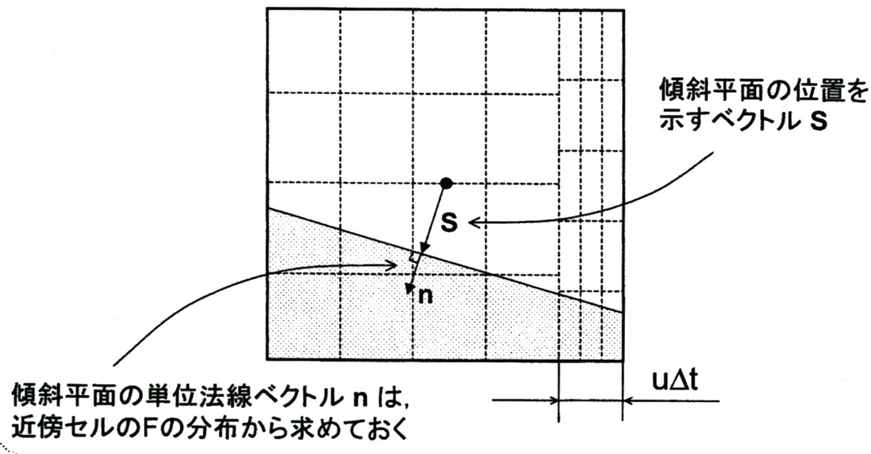
Improved-Simple Counting Algorithm

②計算セル内に副セルを配置する



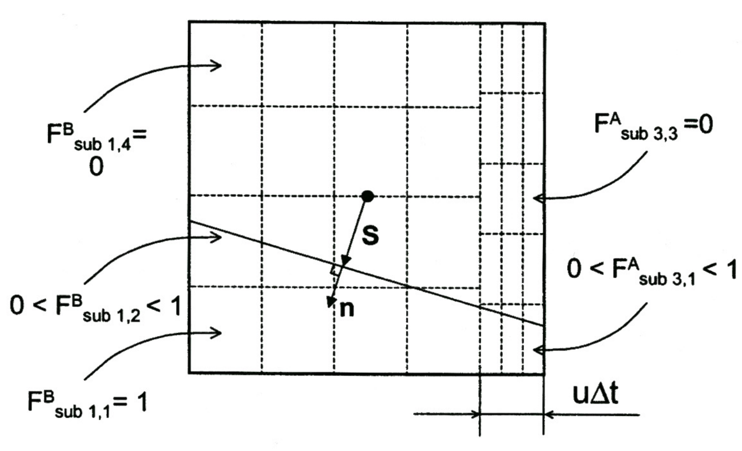
Improved-Simple Counting Algorithm

③傾斜平面の初期位置を決める（→Sの初期値を設定する）



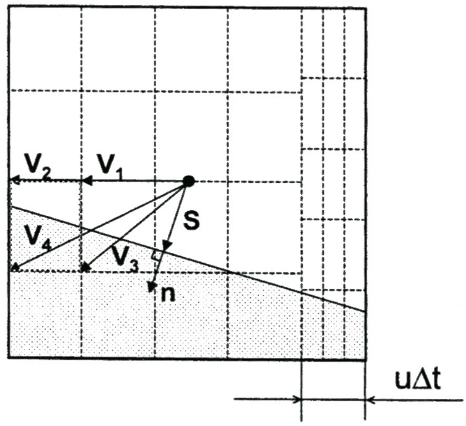
Improved-Simple Counting Algorithm

S（傾斜平面位置）に対して各副セルの体積率F_{sub}を求める



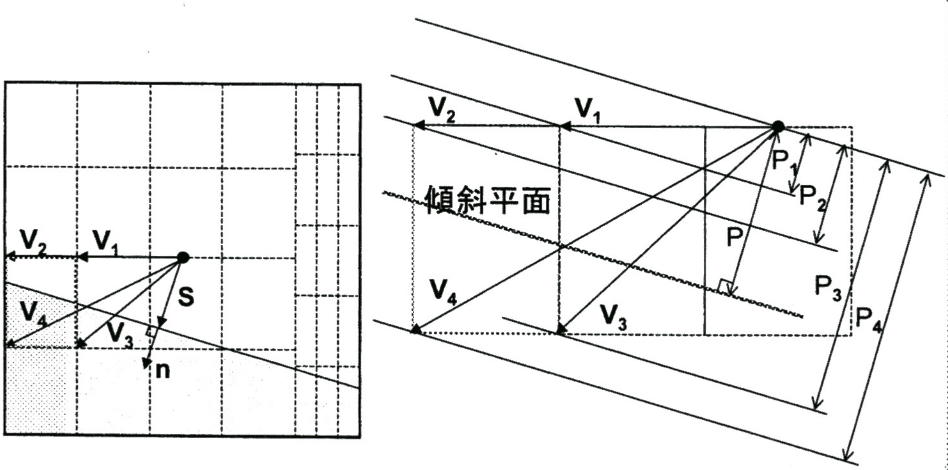
Improved-Simple Counting Algorithm

◎ $0<F_{sub}<1$ の場合



Improved-Simple Counting Algorithm

◎ $0<F_{sub}<1$ の場合

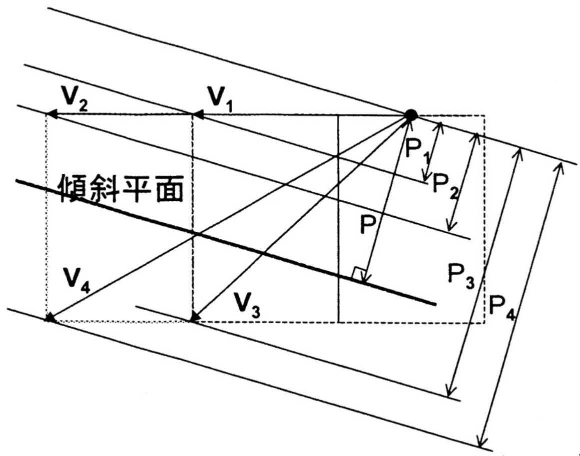


Improved-Simple Counting Algorithm

◎ $0<F_{sub}<1$ の場合

$$F_{sub} = \begin{cases} 1 & ;P \le P_{12} \\ \dfrac{P_{34}-P}{P_{34}-P_{12}} & ;P_{12} < P < P_{34} \\ 0 & ;P_{34} \le P \end{cases}$$

$$P_{12} = \frac{P_1+P_2}{2} \qquad P_{34} = \frac{P_3+P_4}{2}$$

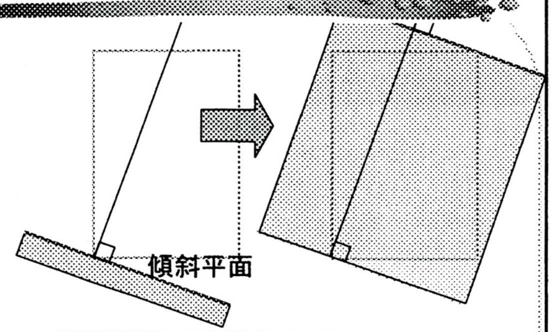


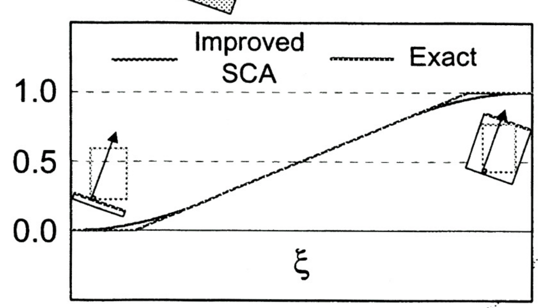
Improved-Simple Counting Algorithm

◎ $0<F_{sub}<1$ の場合

$$F_{sub} = \begin{cases} 1 & ;P \le P_{12} \\ \dfrac{P_{34}-P}{P_{34}-P_{12}} & ;P_{12} < P < P_{34} \\ 0 & ;P_{34} \le P \end{cases}$$

$$P_{12} = \frac{P_1+P_2}{2} \qquad P_{34} = \frac{P_3+P_4}{2}$$

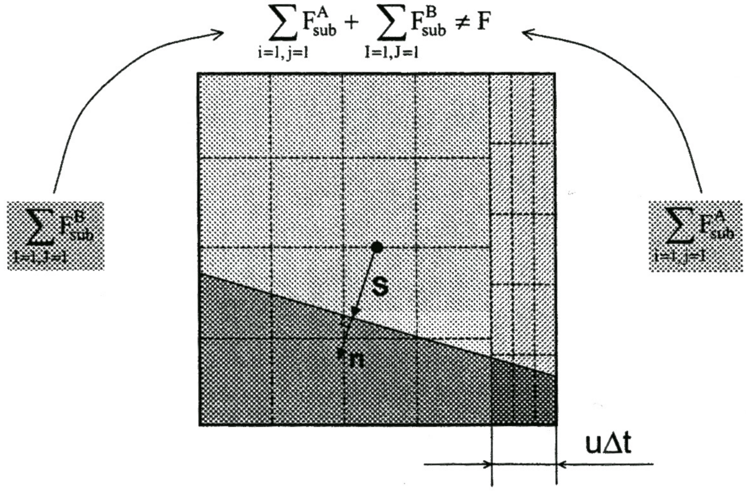




Improved-Simple Counting Algorithm

F_{sub}の総和をとると，セルの体積率Fと一致しない

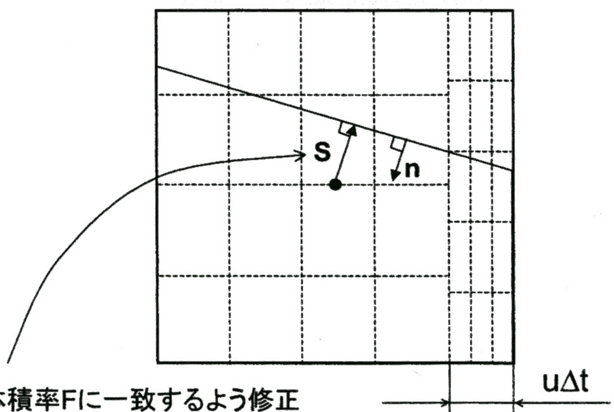
$$\sum_{i=1,j=1} F_{sub}^{A} + \sum_{I=1,J=1} F_{sub}^{B} \neq F$$



Improved-Simple Counting Algorithm

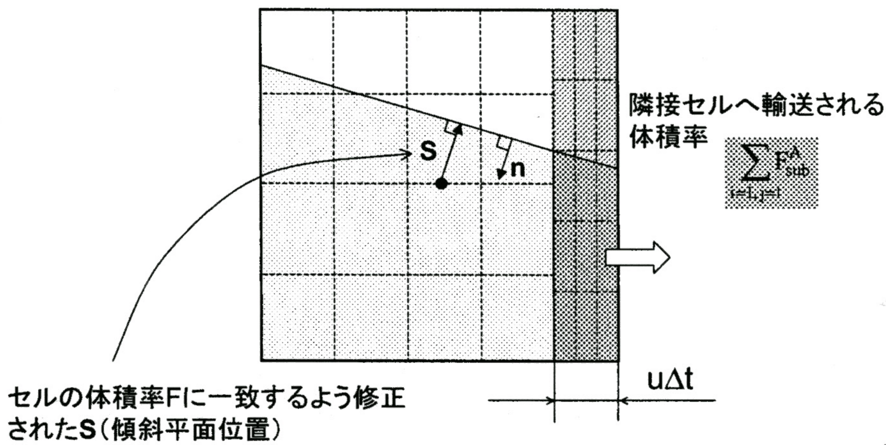
④繰り返し計算により，**S**（傾斜平面位置）を修正

$$\sum_{i=1,j=1} F_{sub}^{A} + \sum_{I=1,J=1} F_{sub}^{B} = F = 0.7$$

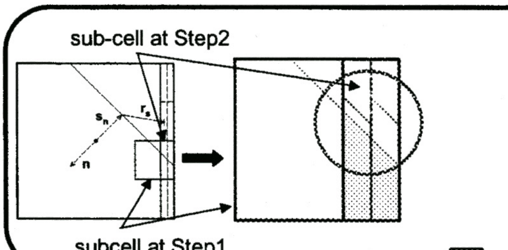


Improved-Simple Counting Algorithm

⑤隣接セルへ体積率を輸送する



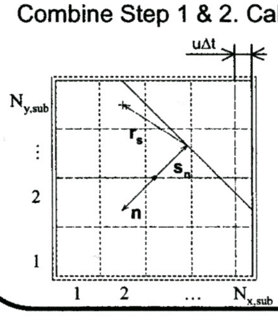
Improved-SCA (I-SCA) (宋ら,機論,2004,掲載決定)

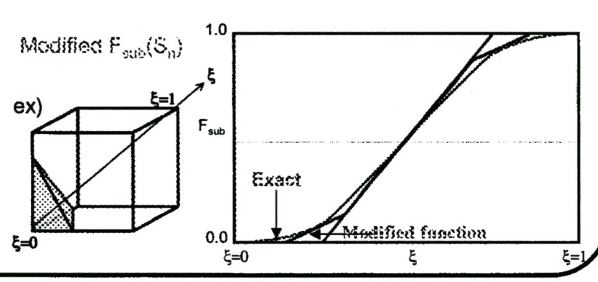


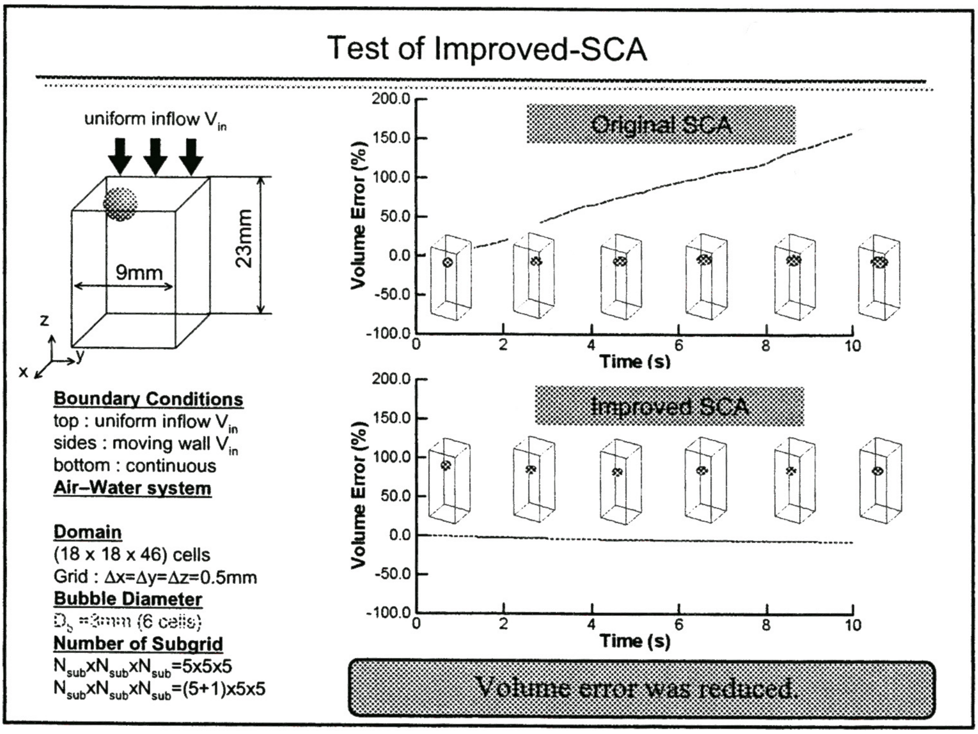
Volume error take place between Step1 and Step2 in the original SCA.

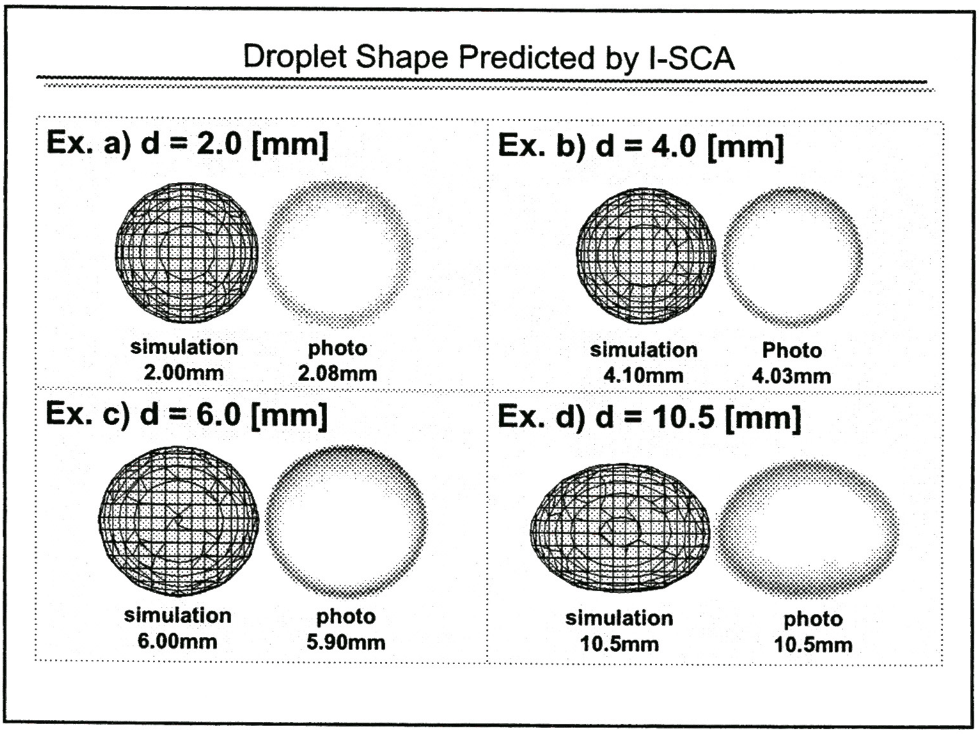
Volume error

Combine Step 1 & 2. Calculate advected F in single step. Variable sub-cells.

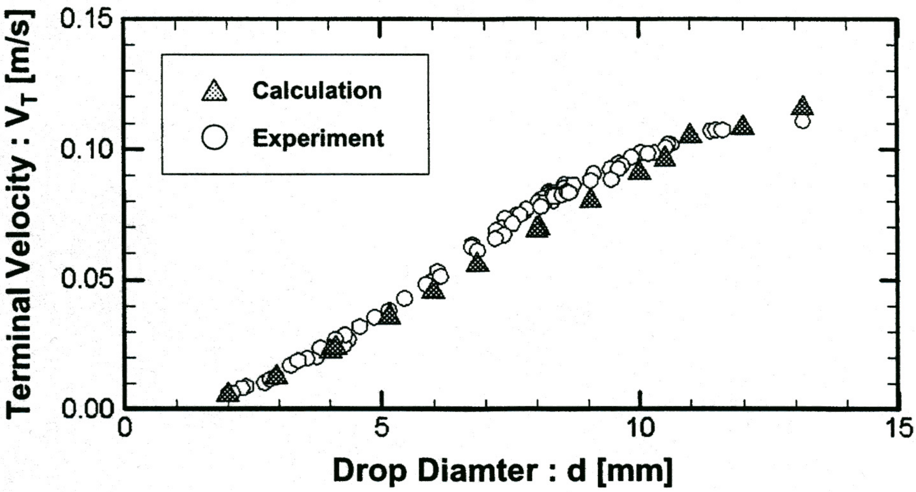




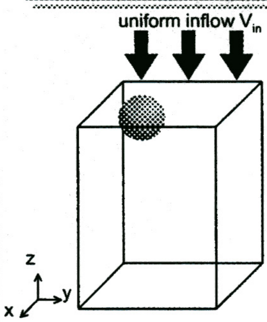

Test of Improved-SCA
uniform inflow V_in
9mm
23mm
z
y
x
Boundary Conditions
top : uniform inflow V_in
sides : moving wall V_in
bottom : continuous
Air–Water system
Domain
(18 x 18 x 46) cells
Grid : Δx=Δy=Δz=0.5mm
Bubble Diameter
D_b =3mm (6 cells)
Number of Subgrid
N_sub x N_sub x N_sub =5x5x5
N_sub x N_sub x N_sub =(5+1)x5x5
Original SCA
Volume Error (%)
200.0
150.0
100.0
50.0
0.0
-50.0
-100.0
0
2
4
6
8
10
Time (s)
Improved SCA
Volume Error (%)
Time (s)
Volume error was reduced.

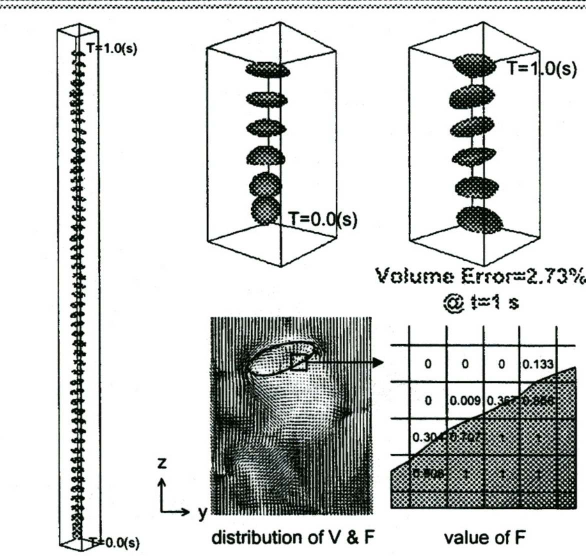

Droplet Shape Predicted by I-SCA
Ex. a) d = 2.0 [mm]
simulation
2.00mm
photo
2.08mm
Ex. b) d = 4.0 [mm]
simulation
4.10mm
Photo
4.03mm
Ex. c) d = 6.0 [mm]
simulation
6.00mm
photo
5.90mm
Ex. d) d = 10.5 [mm]
simulation
10.5mm
photo
10.5mm

Droplet Terminal Velocity Predicted by I-SCA



Air Bubble in Water by 3D-SCA





Boundary Conditions
top : uniform inflow V_{in}
sides : moving wall V_{in}
bottom : continuous
Air–Water system

Domain
(48 x 48 x 80) cells
Grid : $\Delta x = \Delta y = \Delta z$
Bubble Diameter
D_b =8mm (16 cells)
Number of Subgrid
$N_{sub} x N_{sub} x N_{sub}$=5x5x5

No numerical diffusion of Interface (F)

1. Observation of Cavitation in a Nozzle

2. Hybrid Cavitating Liquid Jet Model

3. An Interface Tracking Model (I-SCA Model)

4. Conclusions

Conclusions

(1) Unsteady behavior of cavitation clouds consisting of many tiny bubbles was clearly observed.

(2) A hybrid model (= Interface Tracking Model & Bubble Tracking Model) to predict cavitating flow in a nozzle and liquid jet deformation was proposed.

(3) The hybrid cavitation flow model gives good prediction for pressure and bubble distributions, injection pressure.

(4) Transient cavitation behavior, i.e. shedding and collapse of cavitation clouds, and liquid jet deformation were simulated by the hybrid cavitation model.

(5) For future 3D simulations, an interface reconstruction & advection scheme (= Improved-Simple Counting Algorithm) was proposed and its validity was confirmed.