Continuous Casting Consortium

Ladle Mixing and Inclusion Removal by Bubbles

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May, 2004

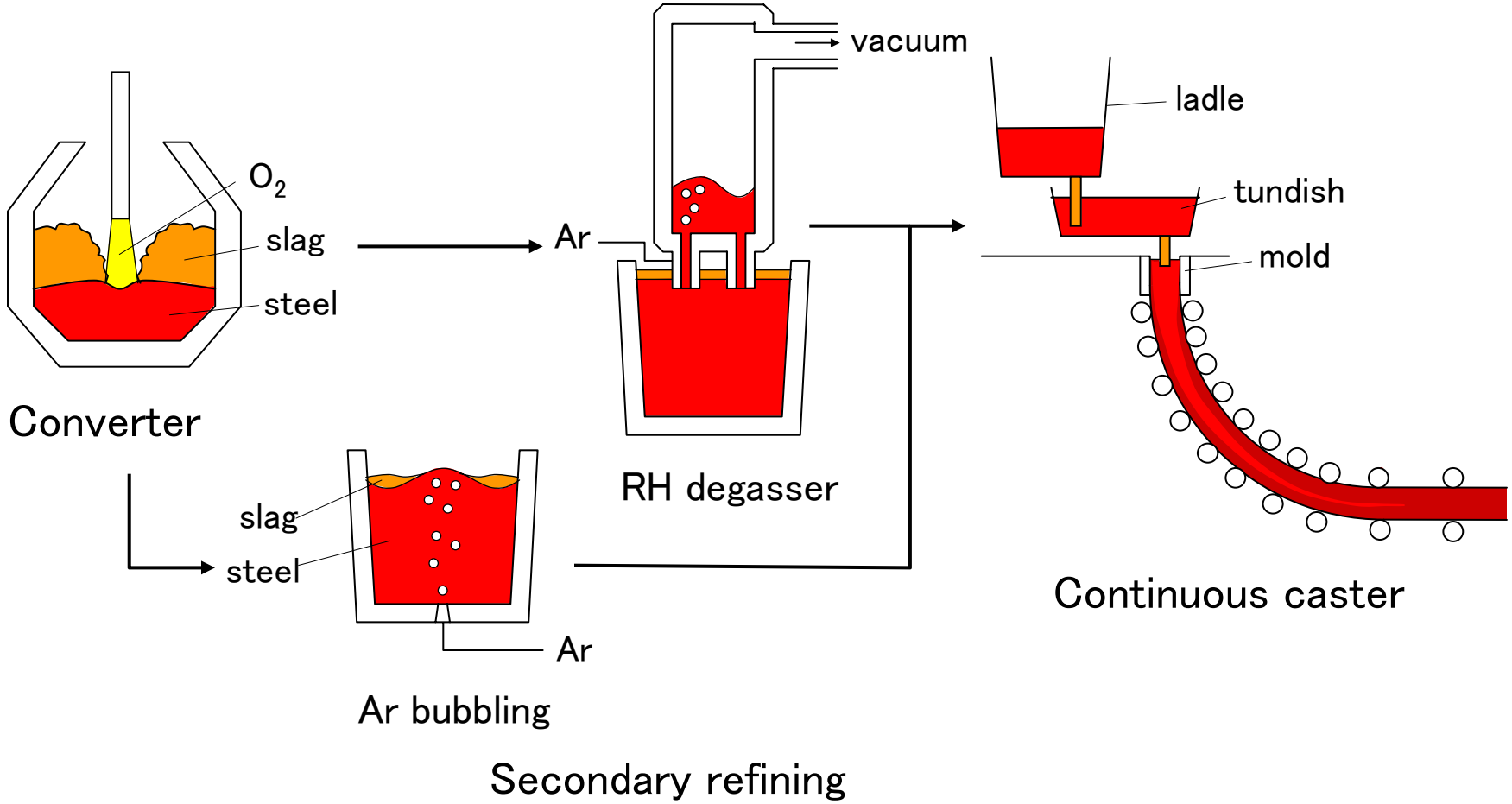
Acknowledgments

- Professor Brian G. Thomas
- Dr. Lifeng Zhang
- The Continuous Casting Consortium

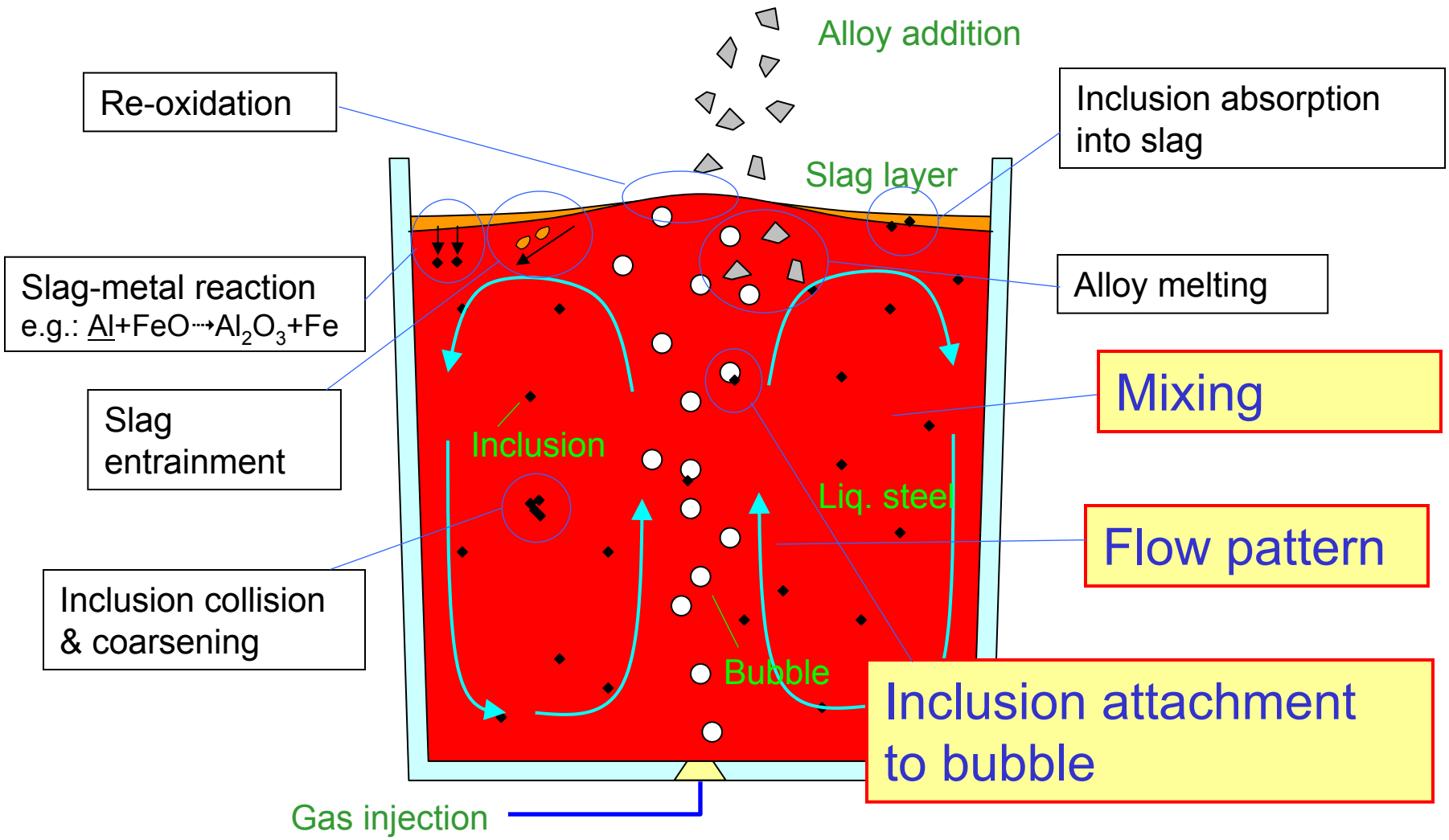
- J. Peter and Dr. K. D. Peaslee; University of Missouri-Rolla
- Nucor Steel
  - Funding
  - Experimental measurements

- FLUENT Inc., Lebanon, NH
  - Providing software

Background


O_2
slag
steel
Converter
Ar
vacuum
RH degasser
ladle
tundish
mold
Continuous caster
slag
steel
Ar
Ar bubbling
Secondary refining

Key Phenomena in Ladle Refining



1. 3D Simulation of Ladle Mixing

Objectives

- Develop quantitative computational models to predict flow and mixing in metallurgical vessels.
- Study 3D multiphase flow in a gas-stirred ladle.
- Study mixing during alloy addition in ladle refining.

  – Optimize gas blow rate and porous plug position & number.

  – Minimize refining time.

  – Improve homogeneity.

Model Outline

1. Flow field calculation in ladle with off-centered Ar injection
   - Standard k-ε model for turbulence
   - Discrete phase model for Ar bubbles

↓

2. Species Diffusion model for alloy

Equations for turbulent flow of molten steel

Continuity $\nabla \cdot \underline{v} = 0$

Momentum conservation

$$\rho\left(\frac{\partial \underline{v}}{\partial t} + \underline{v} \cdot \nabla \underline{v}\right) = -\nabla p + (\mu + \mu_t)\nabla^2 \underline{v} - \rho \underline{g} + \sum_{bubbles} F_D(\underline{v} - \underline{v}_b) Q_g dt$$

Transport equation for turbulent kinetic energy

$$\rho\left(\frac{\partial k}{\partial t} + \underline{v} \cdot \nabla k\right) = \nabla\left(\frac{\mu_t}{\sigma_k}\nabla k\right) + G_k - \rho\varepsilon$$

Transport equation for dissipation rate

$$\rho\left(\frac{\partial \varepsilon}{\partial y} + \underline{v} \cdot \nabla \varepsilon\right) = \nabla\left(\frac{\mu_t}{\sigma_\varepsilon}\nabla \varepsilon\right) + C_1 \frac{\varepsilon}{k} G_k - C_2 \rho \frac{\varepsilon^2}{k}$$

Turbulent viscosity

$$\mu_t = C_\mu \rho \frac{k^2}{\varepsilon}$$

Generation of k

$$G_k = \mu_t\left(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i}\right)\frac{\partial v_i}{\partial x_j}$$

$\underline{v}$: Time averaged fluid velocity
$\underline{v}_b$: Velocity of bubble
ρ : Density of fluid
p : Pressure
μ : Viscosity of fluid
μ_t : Turbulent viscosity
$\underline{g}$: Gravitational acceleration
Q_g : Gas flow rate
F_D : Drag force from bubble
k : Turbulent kinetic energy
ε : Dissipation rate of k
C_1, C_2, C_μ, σ_k, σ_ε : Empirical constants (=1.44, 1.92, 0.09, 1.0, 1.3)

Equations for gas bubbles (Discrete phase model)

Force balance on bubble

$$\frac{d\underline{v}_b}{dt} = F_D(\underline{v} - \underline{v}_b) - \frac{(\rho - \rho_b)}{\rho_b}\underline{g}$$

Drag force

$$F_D = \frac{18\mu}{\rho_b d_b^2}\frac{C_D \mathrm{Re}}{24}$$

Particle Reynolds number

$$\mathrm{Re} = \frac{|\underline{v} - \underline{v}_b| d_b \rho}{\mu}$$

Drag coefficient (non-spherical model in FLUENT)

$$C_D = \frac{24}{\mathrm{Re}}\left(1 + b_1 \mathrm{Re}^{b_2}\right) + \frac{b_3 \mathrm{Re}}{b_4 + \mathrm{Re}}$$

$$b_1 \sim b_4 = f(\phi) \qquad \phi = \frac{s(\text{equivolume sphere's surface area})}{S(\text{actual surface area})}$$

Bubble trajectory

$$\underline{x}_b = \int (\underline{v}_b + \underline{v}'_b)dt$$

Random walk model by turbulence

$$\int \frac{\underline{v}'_b(t)\underline{v}'_b(t+s)}{\overline{\underline{v}'^2_b}} ds = C_L \frac{k}{\varepsilon}$$

ρ_b : Density of bubble
d_b : Diameter of bubble
C_D : Drag coefficient
$b_1 \sim b_4$: Parameters in non-spherical model
ϕ : Shape factor
$\underline{x}_b$: Bubble position
$\underline{v}'_b$: Bubble fluctuation velocity
C_L : Empirical constant (=0.15)

Equations for alloy mixing

Turbulent diffusion of alloy element i

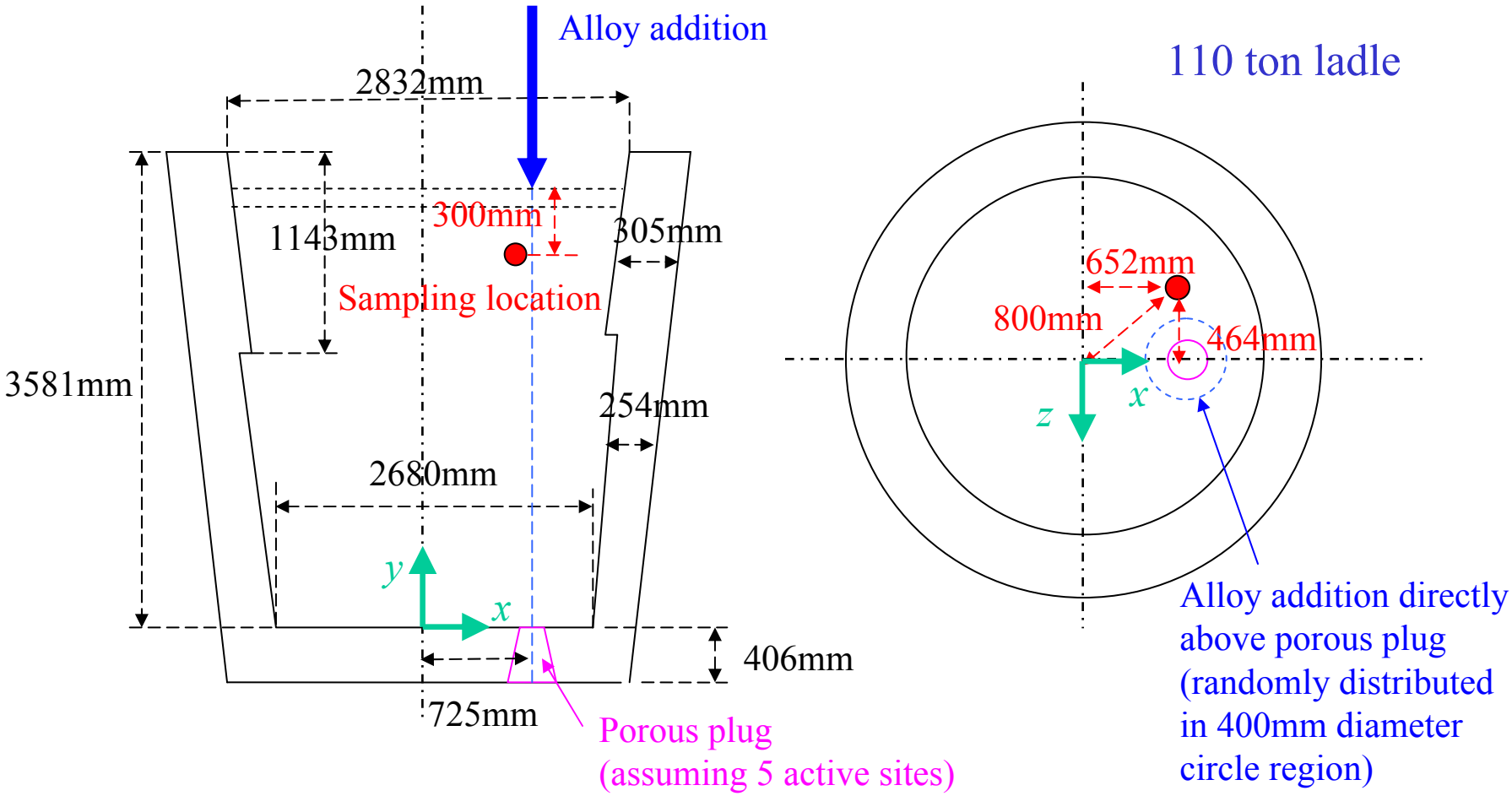
$$\frac{\partial}{\partial t}(\rho C_i) + \nabla \cdot (\rho \underline{v} C_i) = -\nabla \cdot \underline{J}_i$$

Diffusion flux of i

$$\underline{J}_i = -\left(\rho D_{i,m} + \frac{\mu_t}{Sc_t}\right)\nabla C_i$$

C_i : Mass fraction of element i
$D_{i,m}$: Diffusion coefficient of element i in fluid m
J_i : Diffusion flux of I
Sc_t : Turbulent Schmidt number (=0.7)

Ladle Size



Ladle of Nucor Yamato Steel (Sketched by Jörg Peter)

Bubble Size and Shape

Argon flow rate : Q_{Ar}=0.17Nm^3/min = 5.055x10^{-3}kg/s

Gas bubble size : d_{Ar}=28.2mm

$$d_{bubble} \approx 0.35\left(Q^2/g\right)^{0.2}$$ Johansen and Boysan (1988)

Bubble shape : spheroid e(eccentricity)=3.61

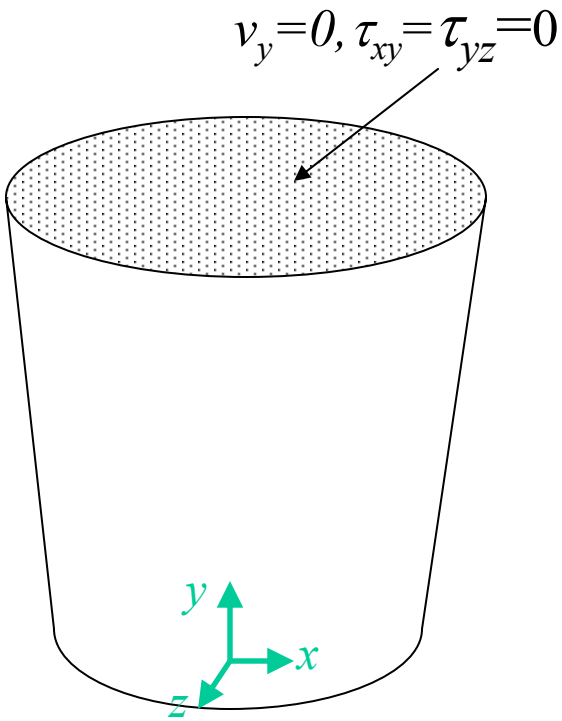
$$e = 1 + 0.163 Eo^{0.757}$$ Wellek, Agrawal and Skelland (1966)

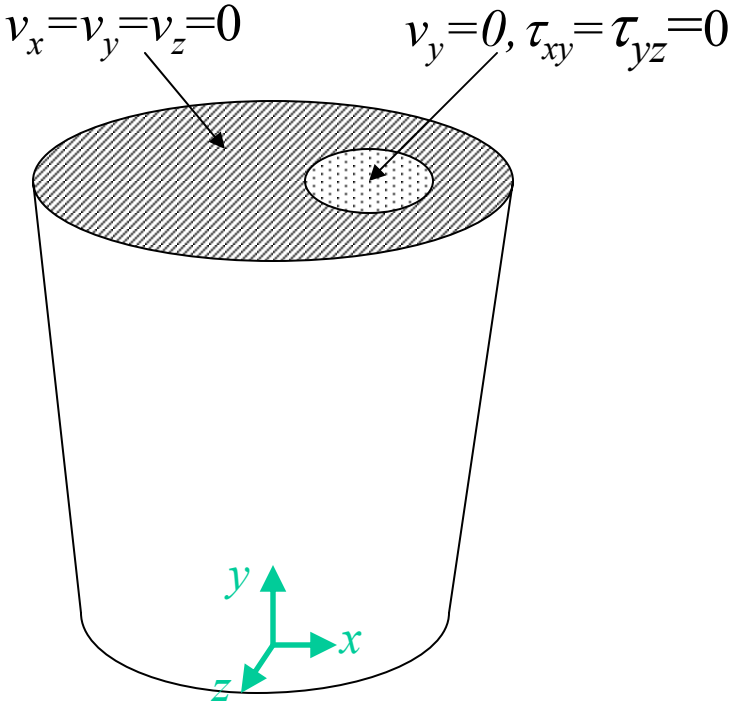
$$Eo = \frac{g d_b^2 (\rho - \rho_b)}{\sigma}$$

e : Eccentricity
Eo : Eotvos number (buoyancy force / surface tension force)
σ : Surface tension

Shape factor : ϕ=s/S=0.736

Liquid Steel Top Surface Boundary Conditions

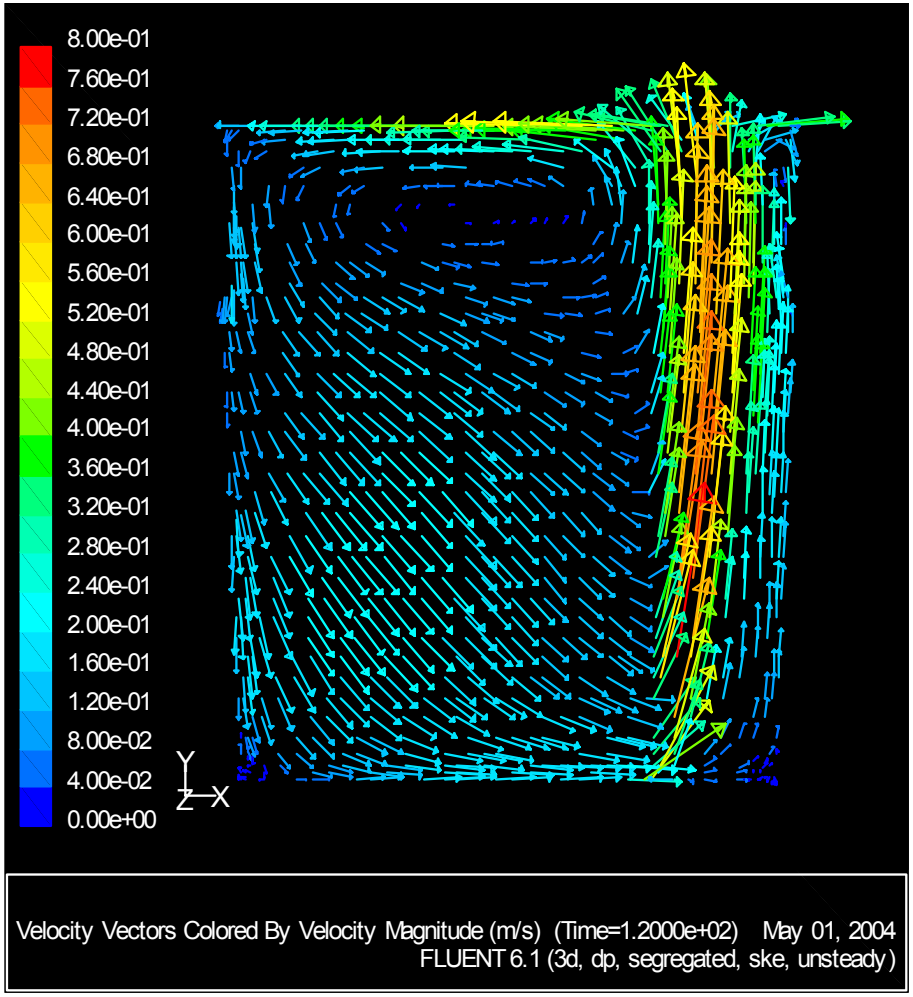


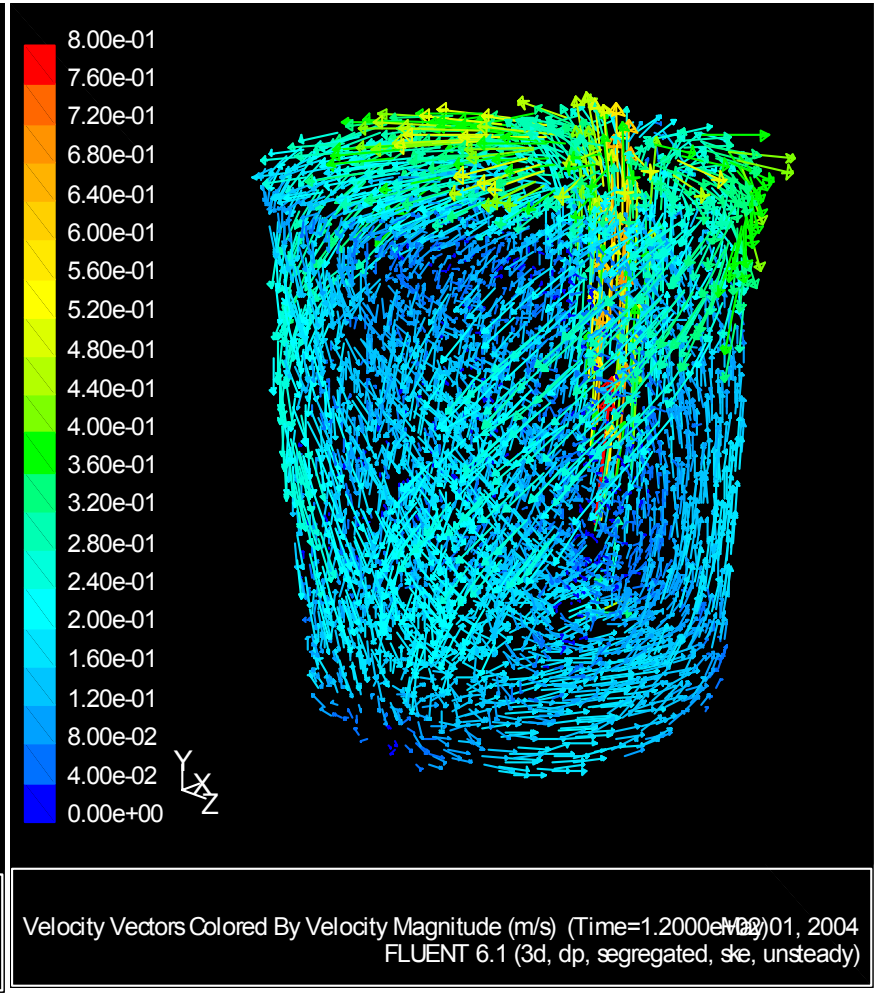


1. Free shear surface

2. Partly constrained surface (simulating slag layer with eye)

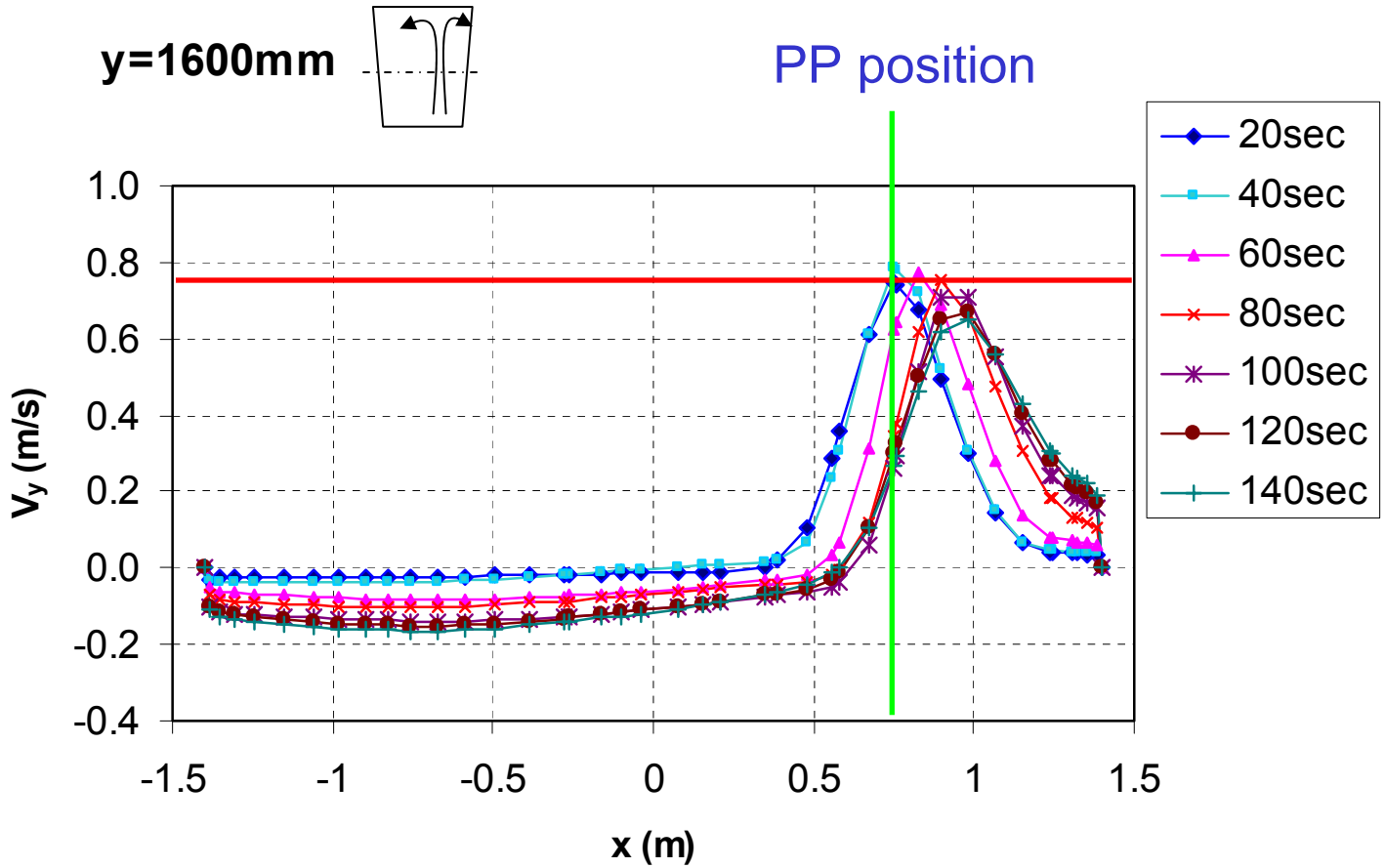
Flow Field (FLUENT6.1 output)





Free Shear Surface BC, t=120sec

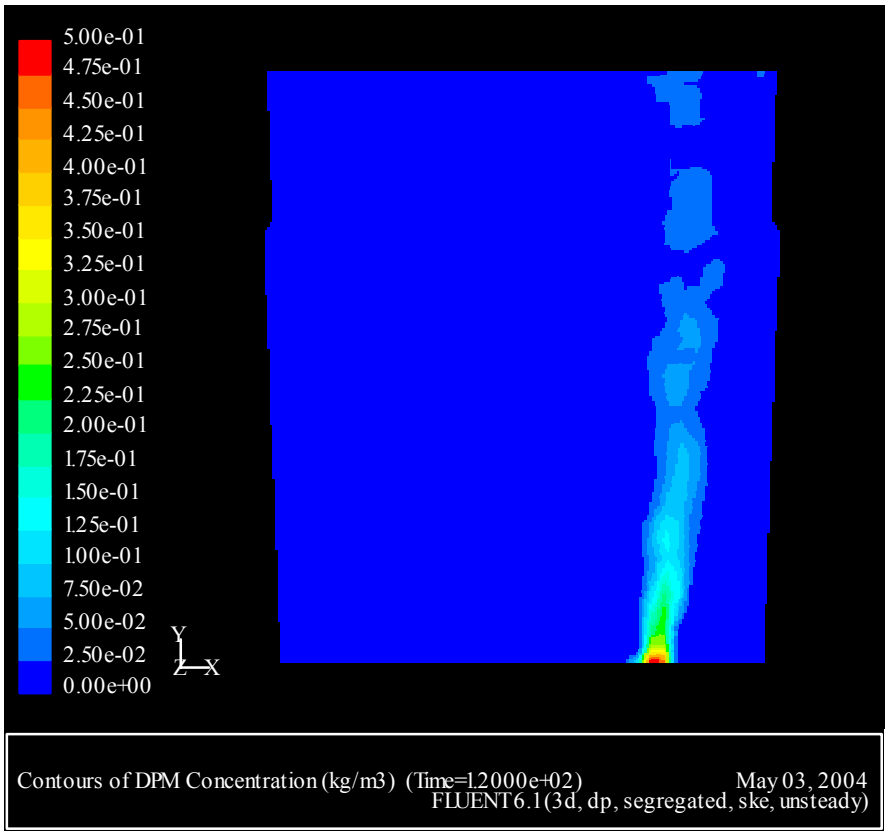
Plume Velocity

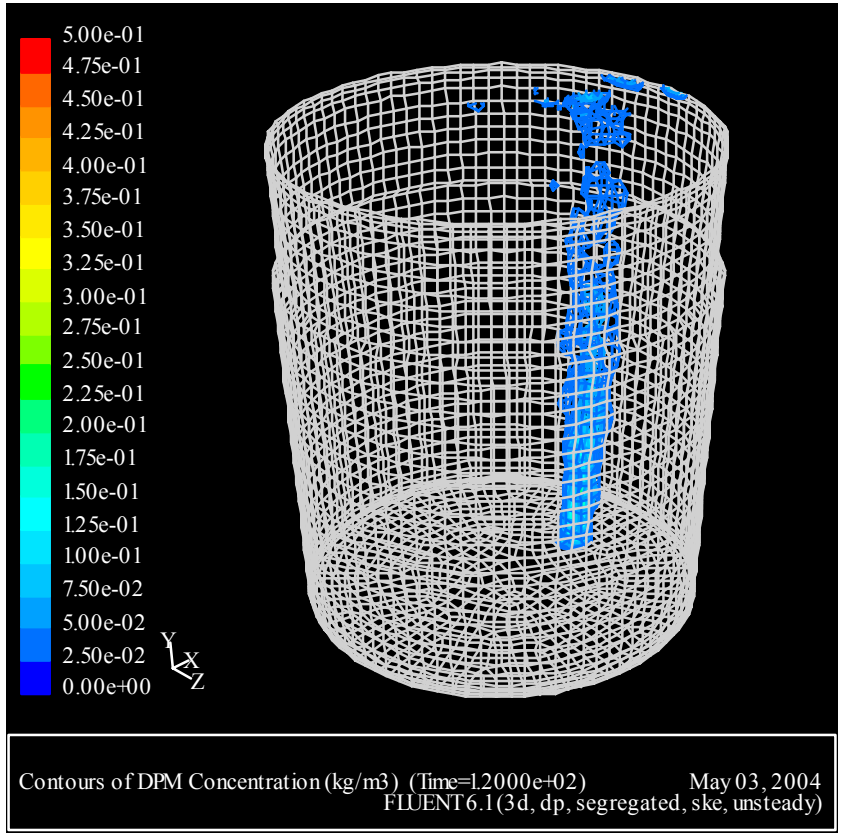


Red Line : empirical equation by Xie and Oeters (1992)

$v_{y,max}=8.64Q^{0.25}=0.76$m/sec

Gas Bubble Distribution in Ladle
(FLUENT6.1 output)

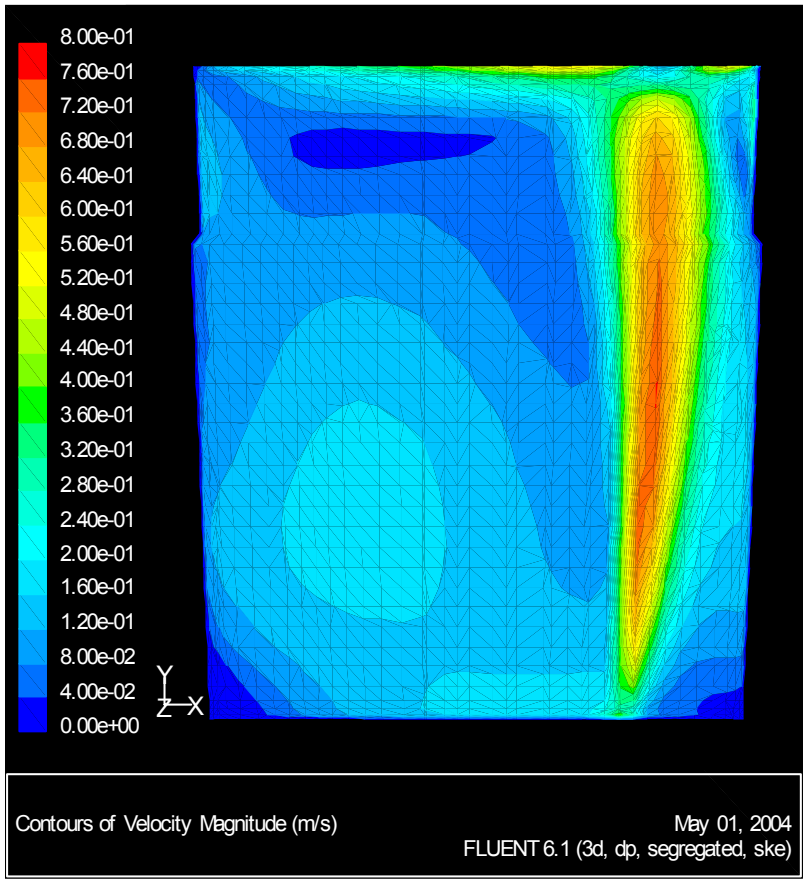




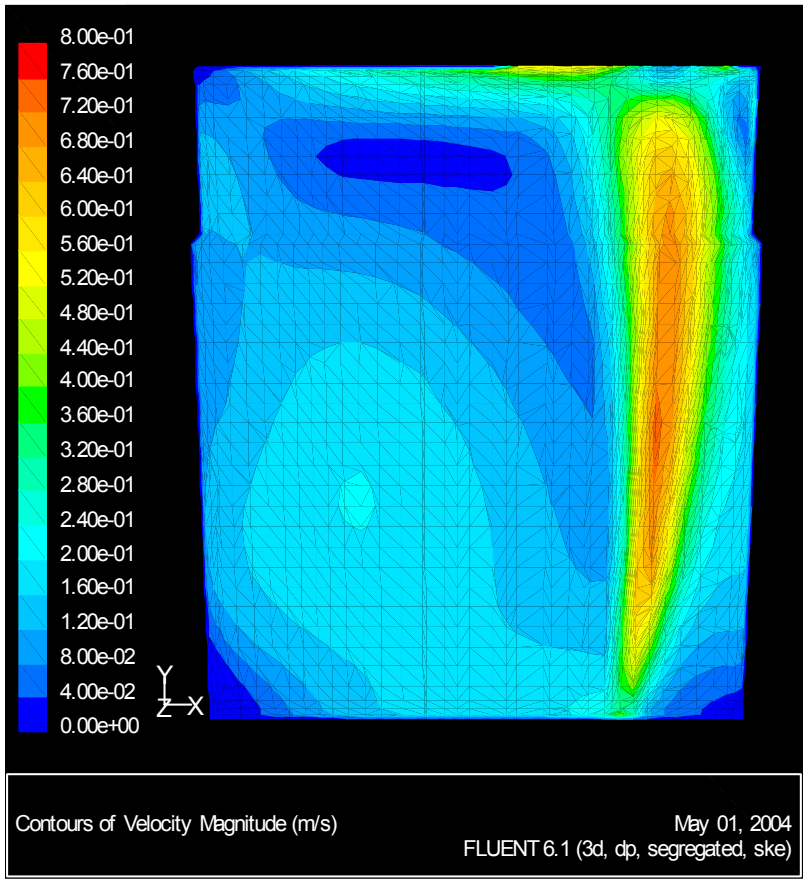
Free Shear Surface BC, t=120sec

About 1,700 bubbles are distributed in ladle in steady state

Effect of Top Slag on Flow field
(FLUENT6.1 output)



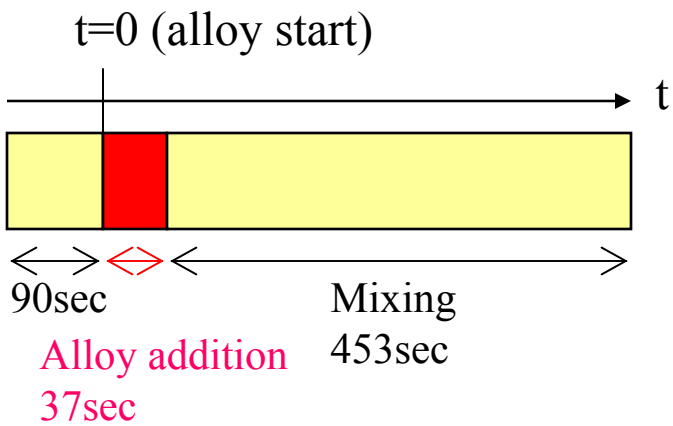
Free Shear Surface BC
(Without Slag)



Partly Constrained Surface BC
(Simulating Slag layer with eye)

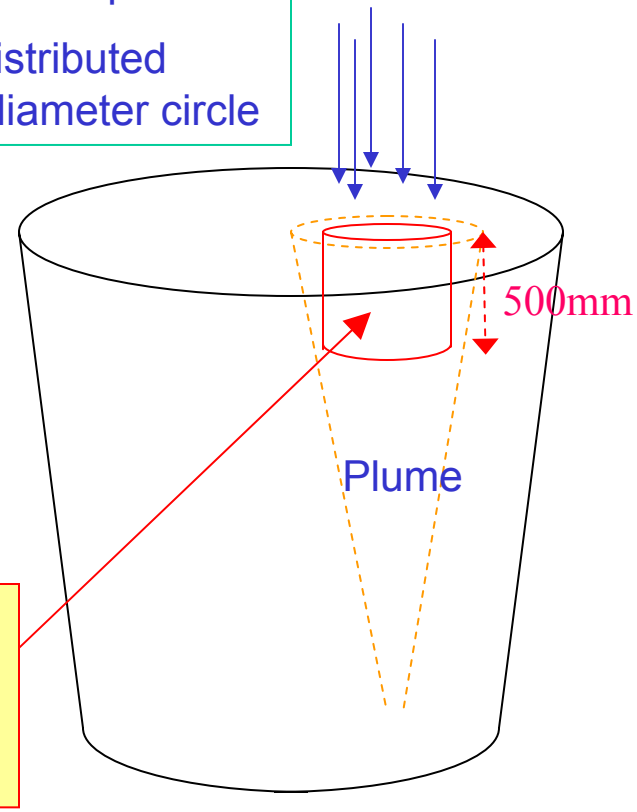
Conditions of Alloy Addition in Nucor Yamato Steel and in simulation

Operating Condition in NYS



Alloy addition on plume

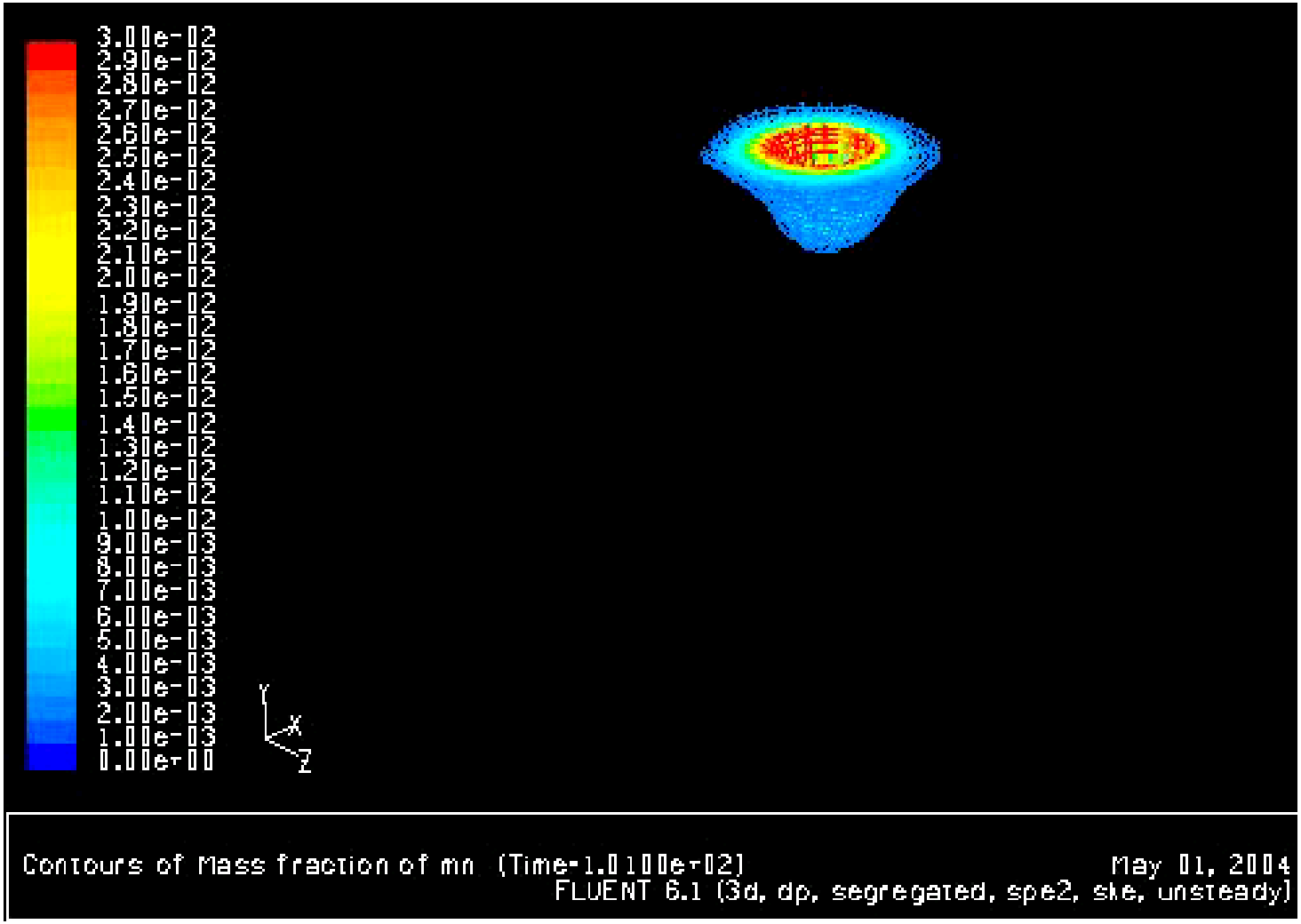
randomly distributed
in 400mm diameter circle



Assumption :

Immediate alloy melting in the 400mm radius and 500mm height cylindrical region

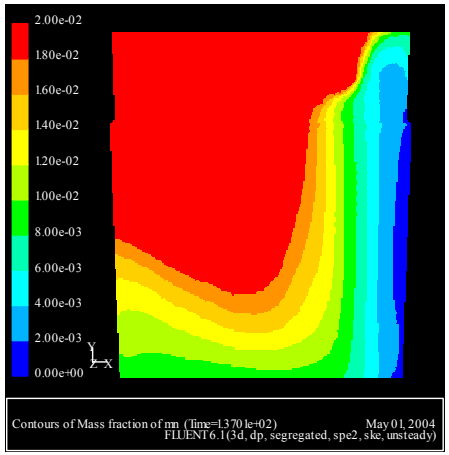
3D Mixing Behavior
Concentration Evolution after Alloy Addition
(FLUENT6.1 output)



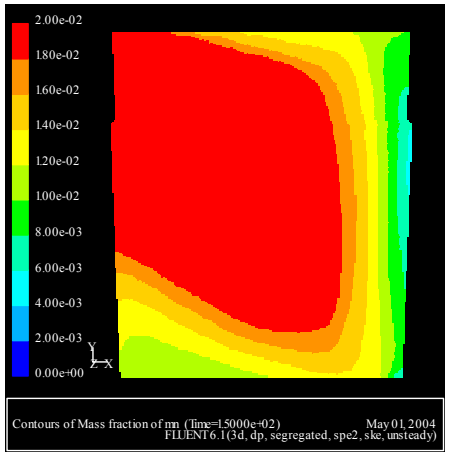
Mixing Behavior in xy centerline sections
(FLUENT6.1 output)

Range:

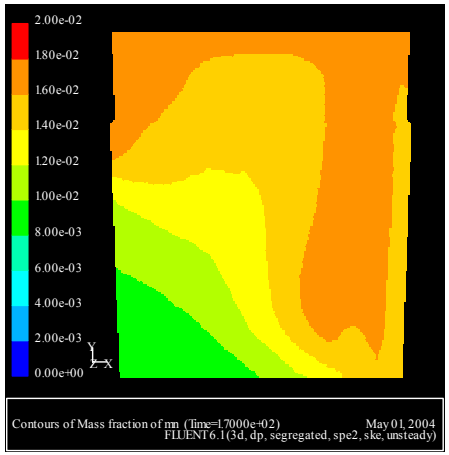
0~2%



t=37sec(alloy end)



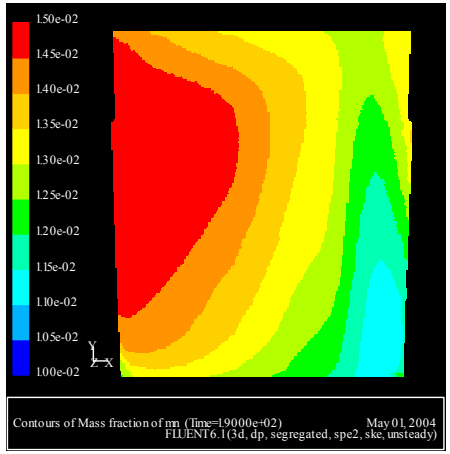
t=50sec



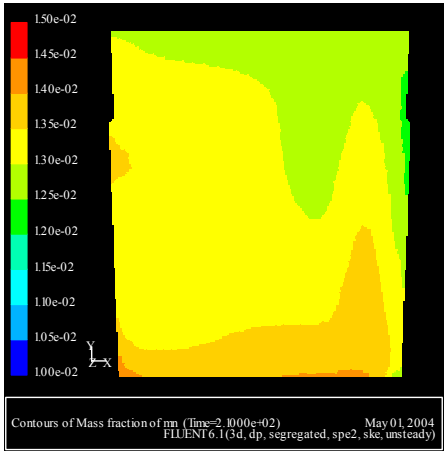
t=70sec

Range:

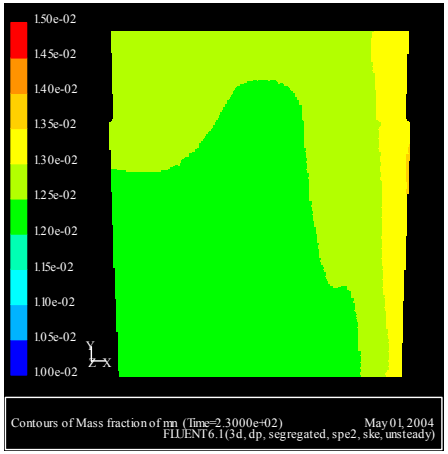
1.0~1.5%



t=90sec

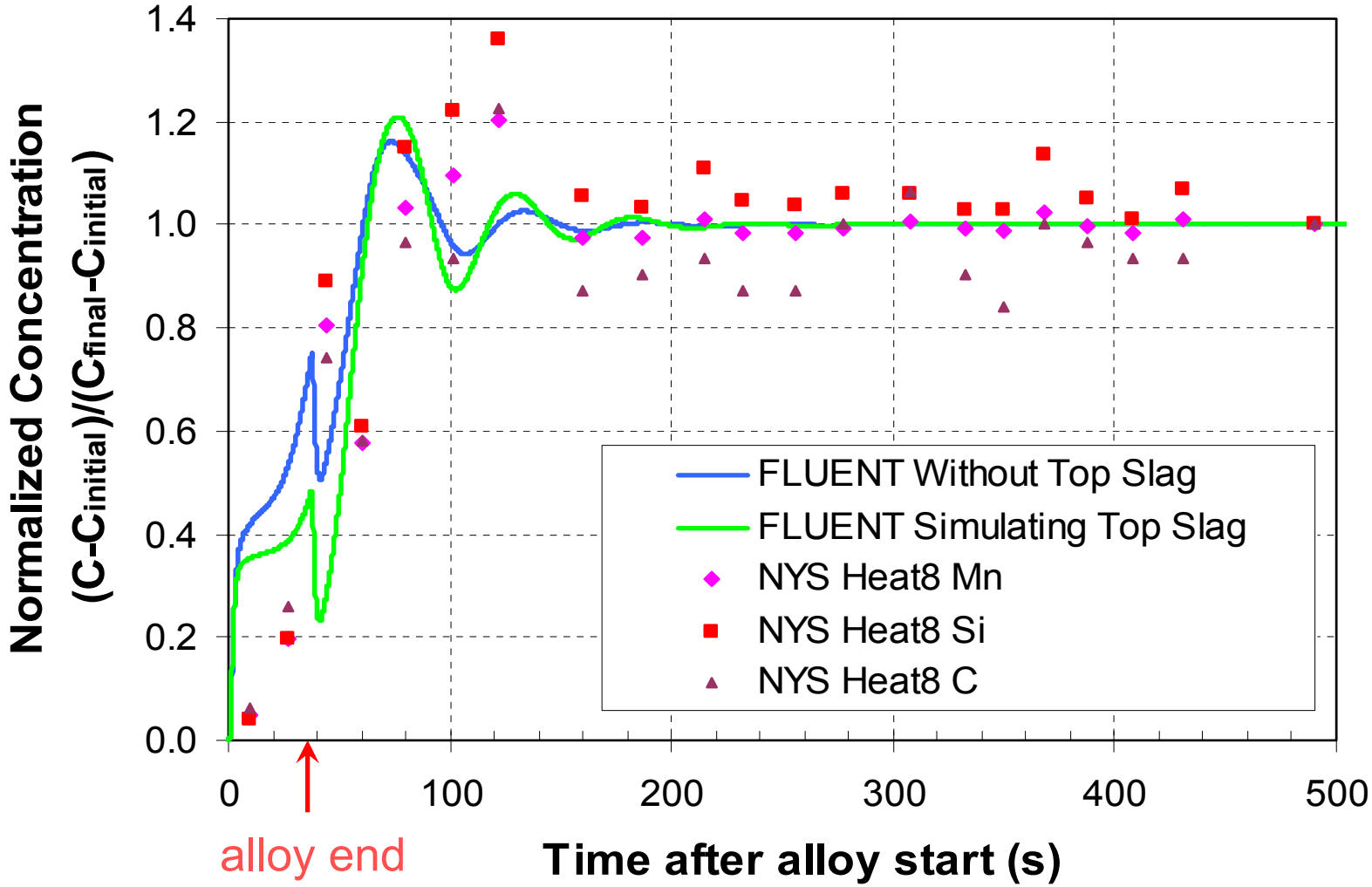


t=110sec



t=130sec

Comparison Between Plant Data



Summary

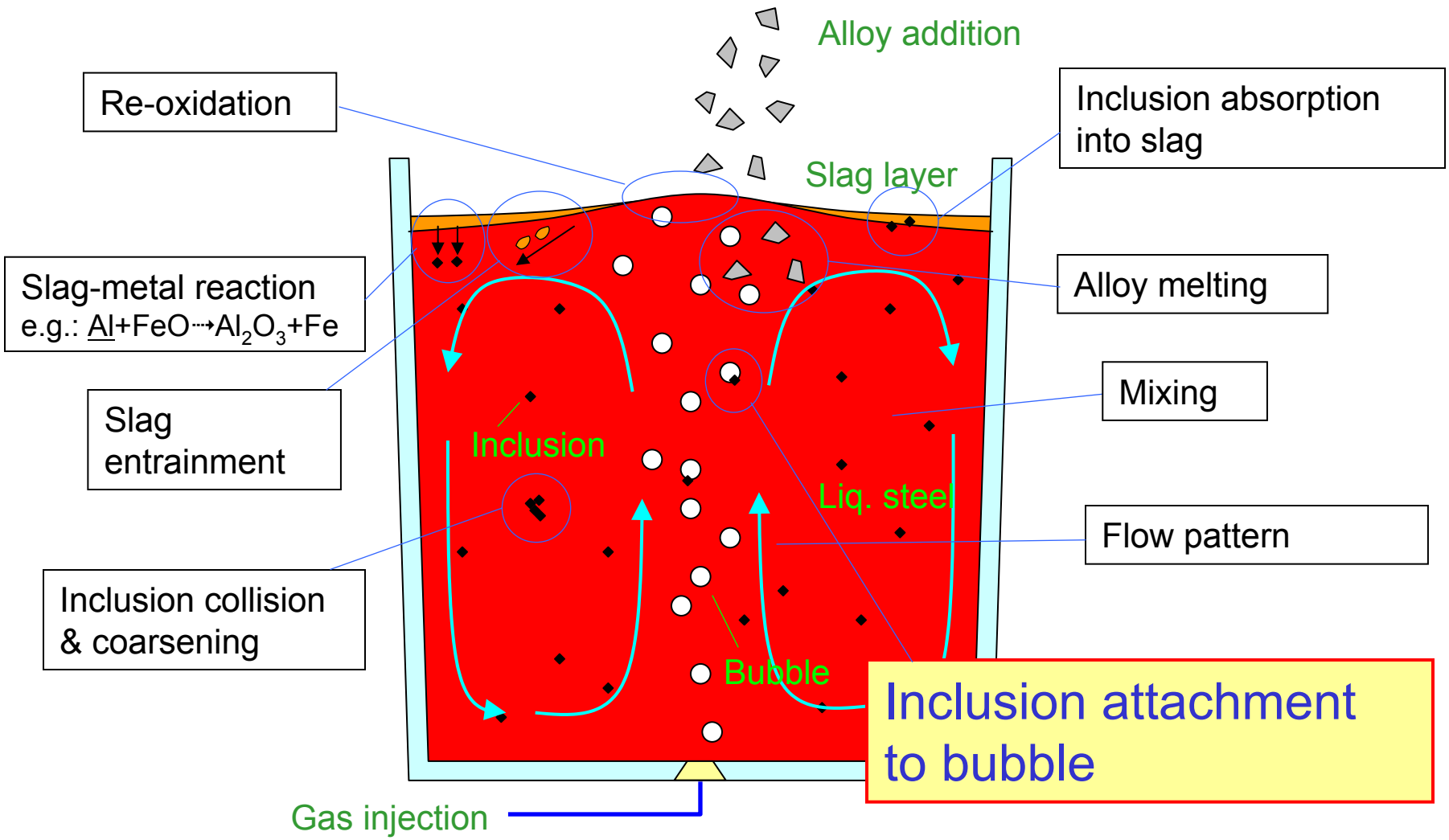
- The multiphase turbulent flow field of Ar stirred ladle refining is simulated. Predicted plume velocity agrees well with an empirical equation.
- Off-center plume causes complex 3D swirling flow pattern.
- About 1700 bubbles are distributed in the steady flow field.
- Using turbulent species diffusion model, the mixing behavior can be reproduced. However, there is time delay in the plant data compared to the simulation which ignores melting.

Future Work

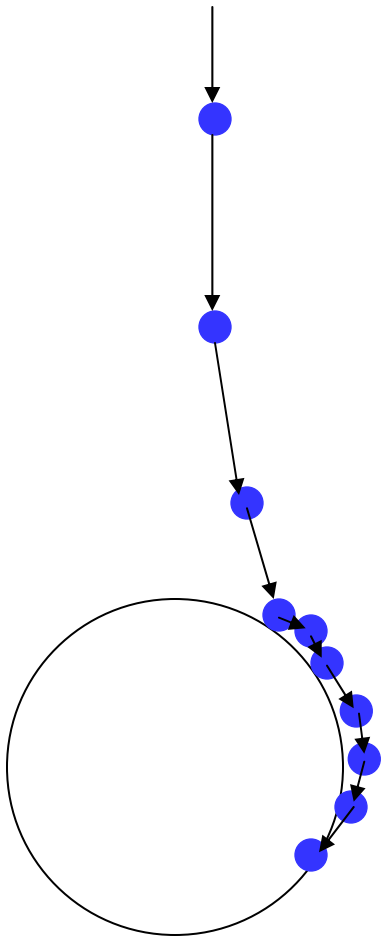
- Find the cause of the delay of mixing time.
  - Consider alloy melting time and incorporate its effect into the model
- Apply model to predict other important metallurgical phenomena (e.g. interface reaction).
- Apply model to predict flow and mixing in other metallurgical vessels.

2. Inclusion removal by bubbles

Key Phenomena in Ladle Refining



Steps of Inclusion Attachment to Bubble



1. Collision
   - Particle trajectory
2. Oscillation
   - Collision time t_c
3. Slide
   - Sliding time t_s
   - Film drainage time t_f
4. Attachment
   - Stability

$t_c = 10^{-7} \sim 10^{-5}$ sec

$t_s = 10^{-3} \sim 10^{-1}$ sec

$t_f = 10^{-6} \sim 10^{-3}$ sec

Zhang and Taniguchi (2001)

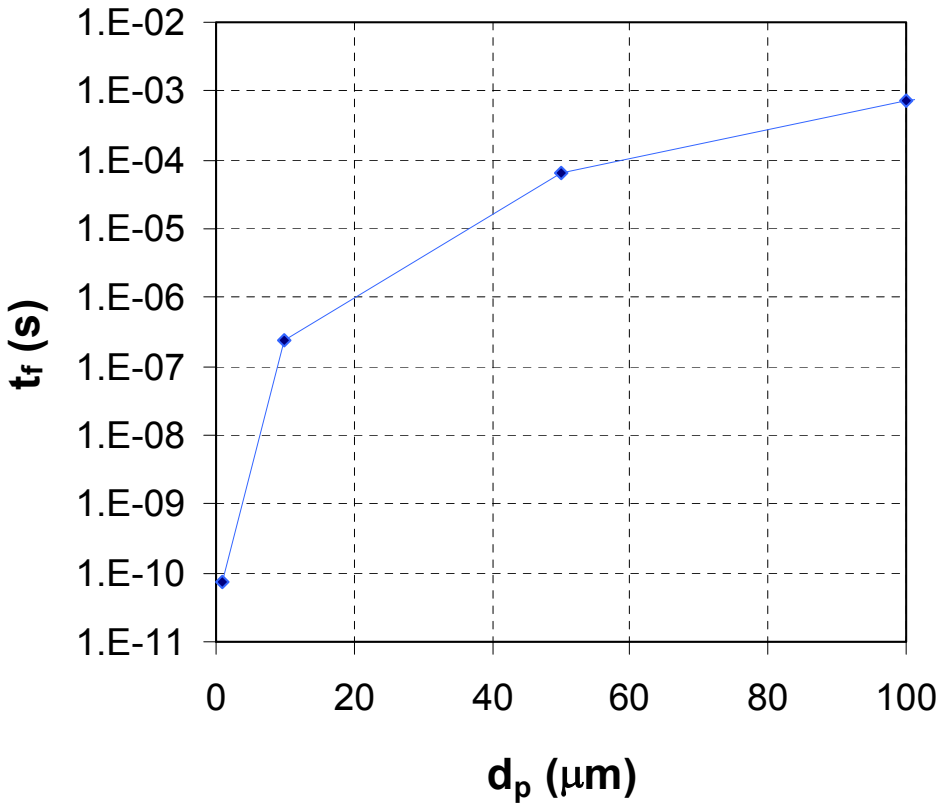
Film Drainage Time, t_f

$$t_f = \frac{64}{3}\mu\frac{\alpha^2}{4\sigma h_{Cr}^2}d_p^3$$

$$\alpha = \arccos\left(1 - 1.02\left(\frac{\pi d_p \rho_p u_R^2}{12\sigma}\right)^{\frac{1}{2}}\right)$$

$$h_{Cr} = 2.33\times10^{-8}\left[1000\sigma(1-\cos\theta)\right]^{0.16}$$

Zhang and Taniguchi (2001)



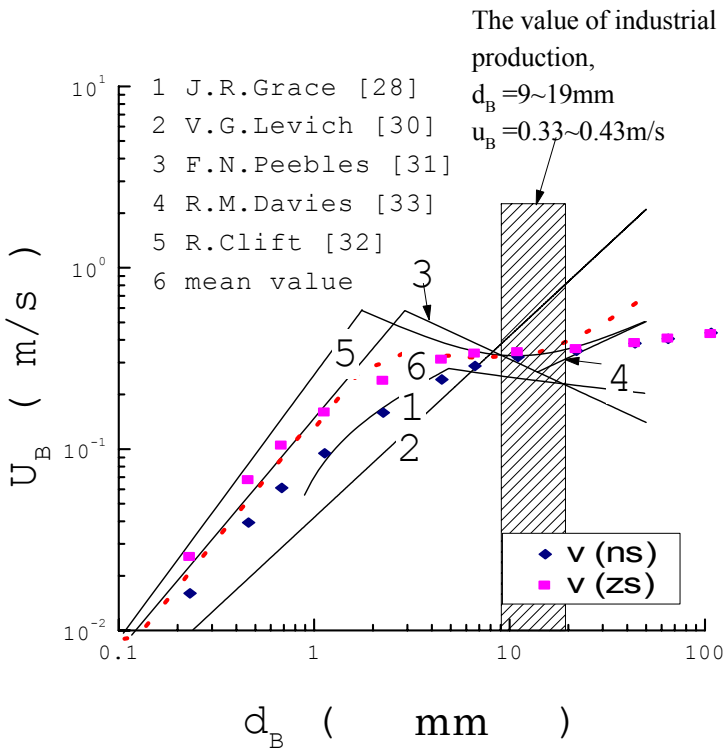
Problem Setting

How many inclusions does a single bubble capture during its trajectory?

- Assume that the criterion for attachment is $t_s > t_f$.
- Develop model to compute t_s as a function of particle size, particle location and bubble size, compare previous theoretical values of t_f, and obtain a particle attachment rate.
- Particle attachment rate : R_A

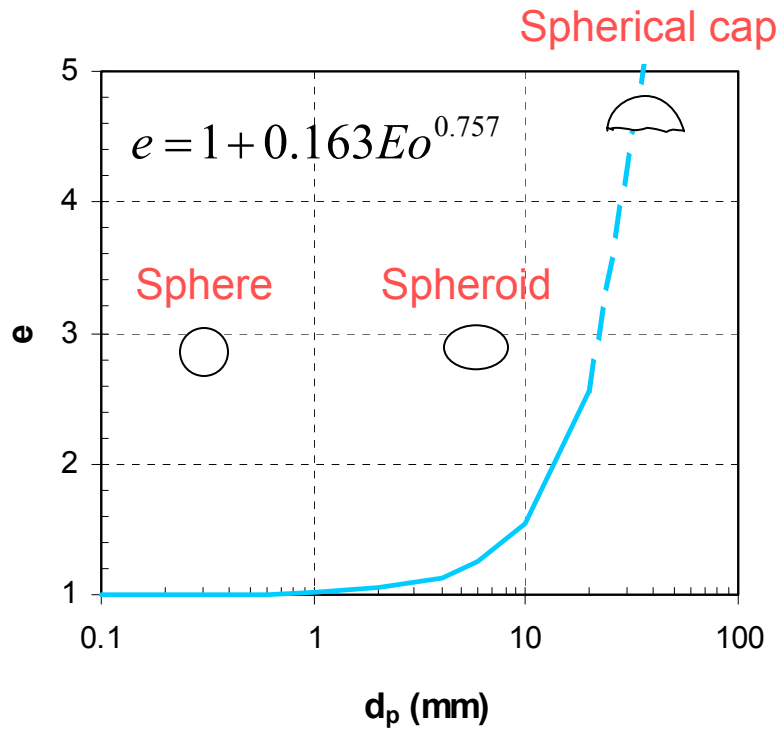
  Number of particle removed per unit bubble travel length

Bubble Velocity and Shape



Bubble terminal velocity

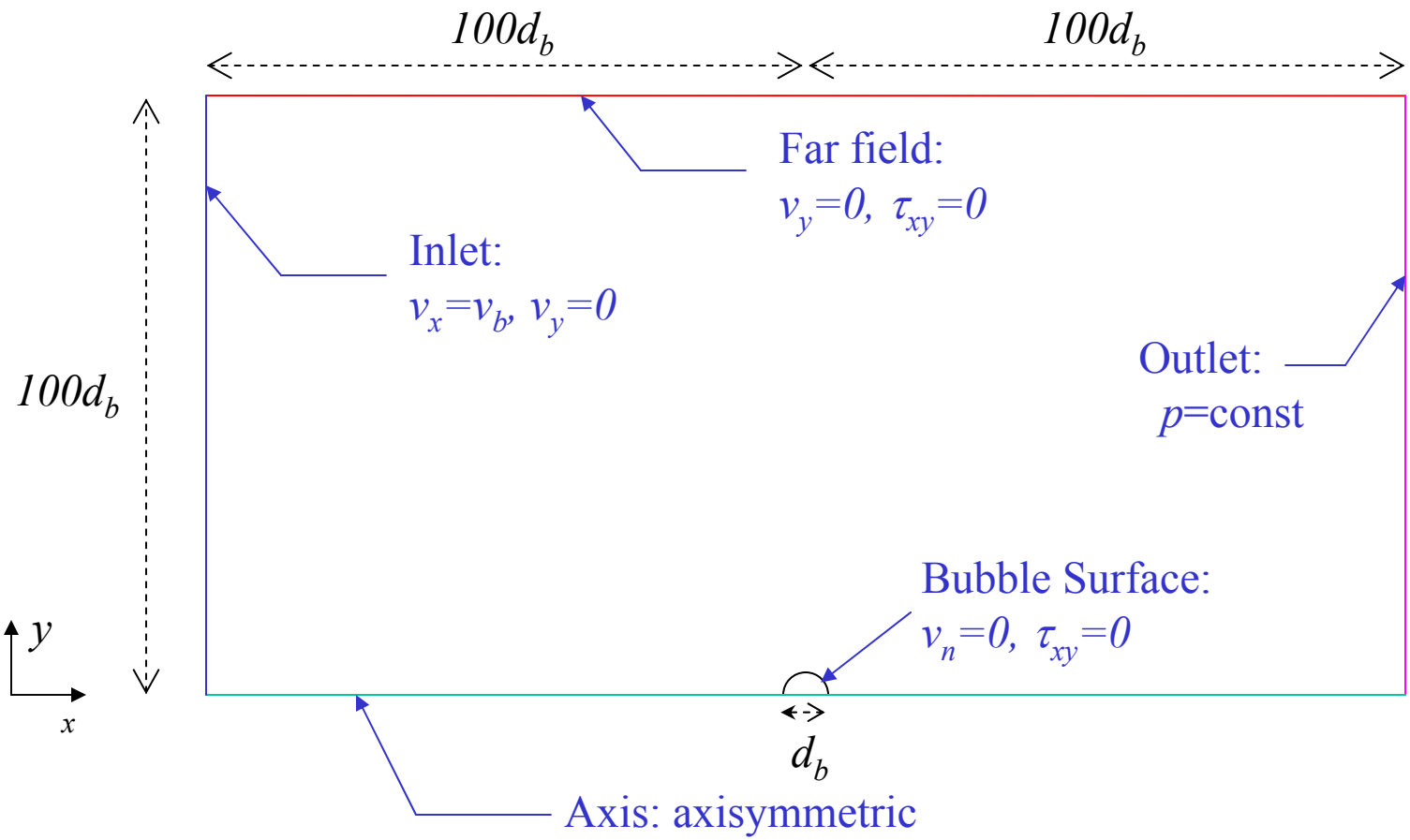
Zhang and Taniguchi (2001)



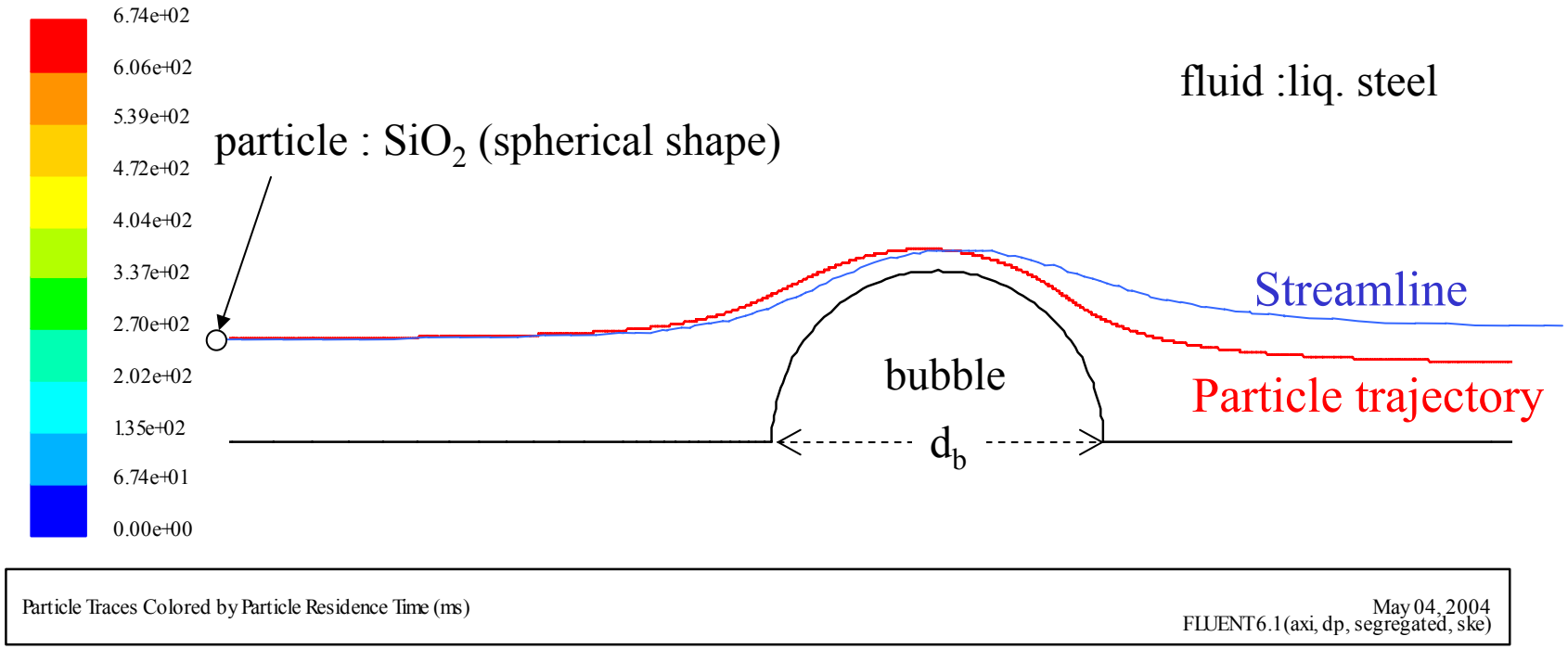
Eccentricity

Wellek, Agrawal and Skelland (1966)

Computational Domain and Boundary Conditions

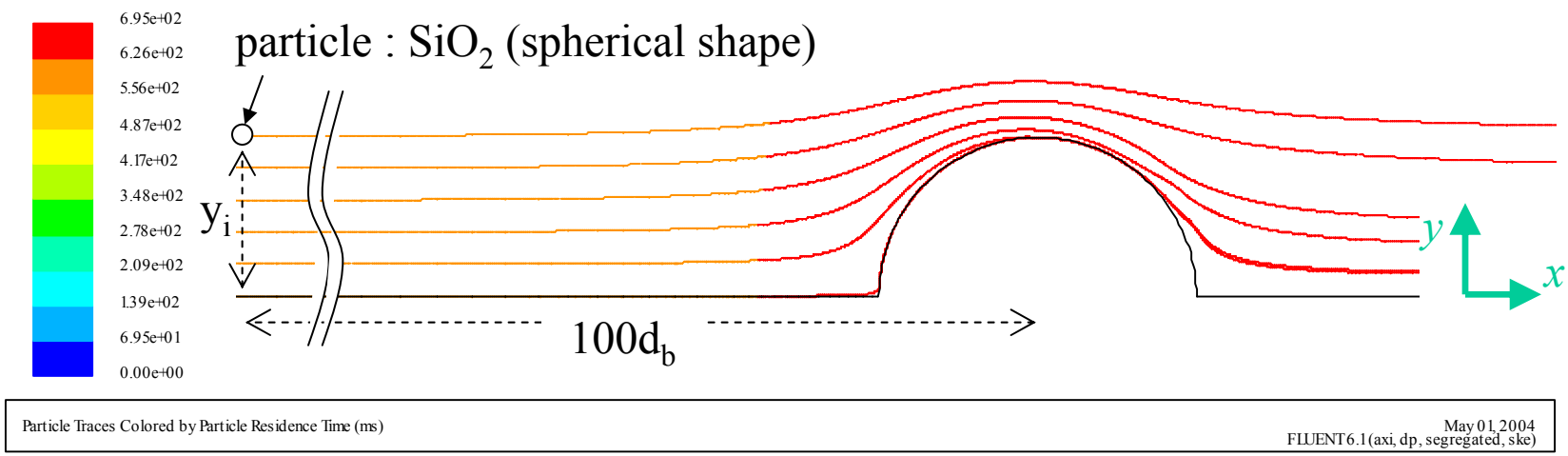


Comparison between Streamline and Particle Trajectory



(d_b=1mm, d_p=100μm, ρ_p=2800kg/m^3, ρ=7000kg/m^3)

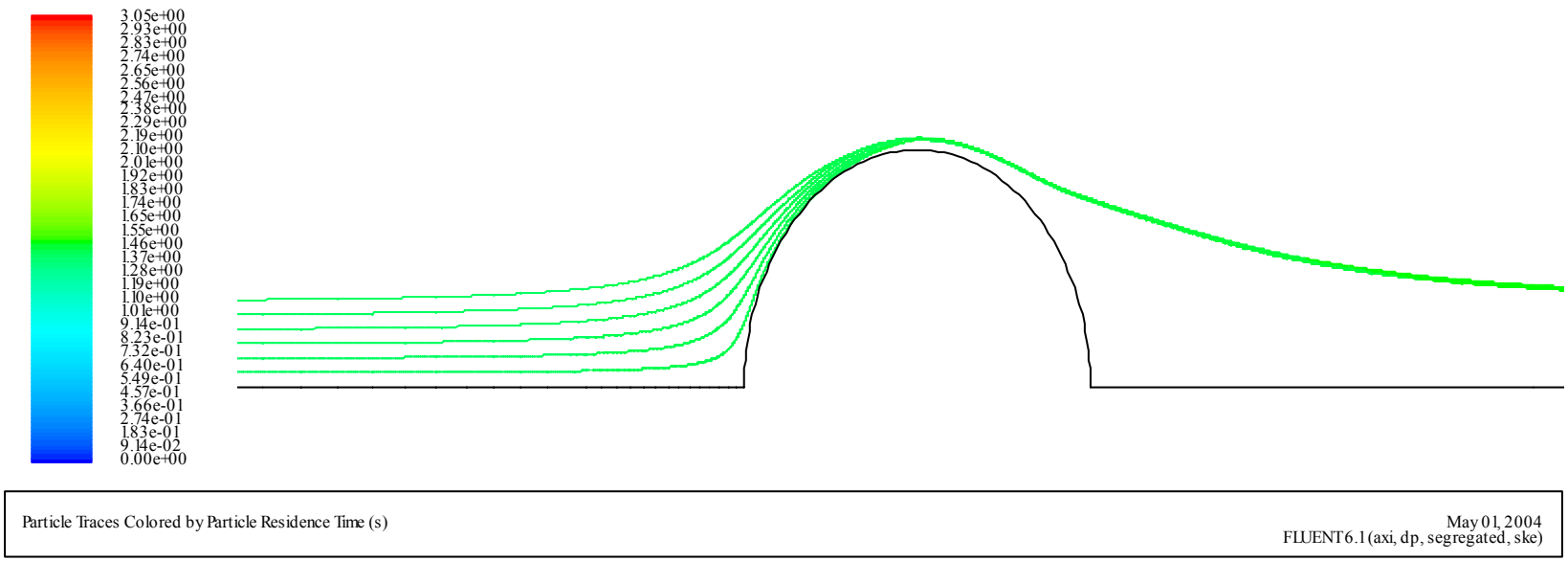
Particle Trajectory Released from 6 different Locations (Time Averaged Turbulent Flow)



100μm silica inclusion trajectory toward 1mm Ar bubble

Particle Trajectory toward Elliptic Bubble

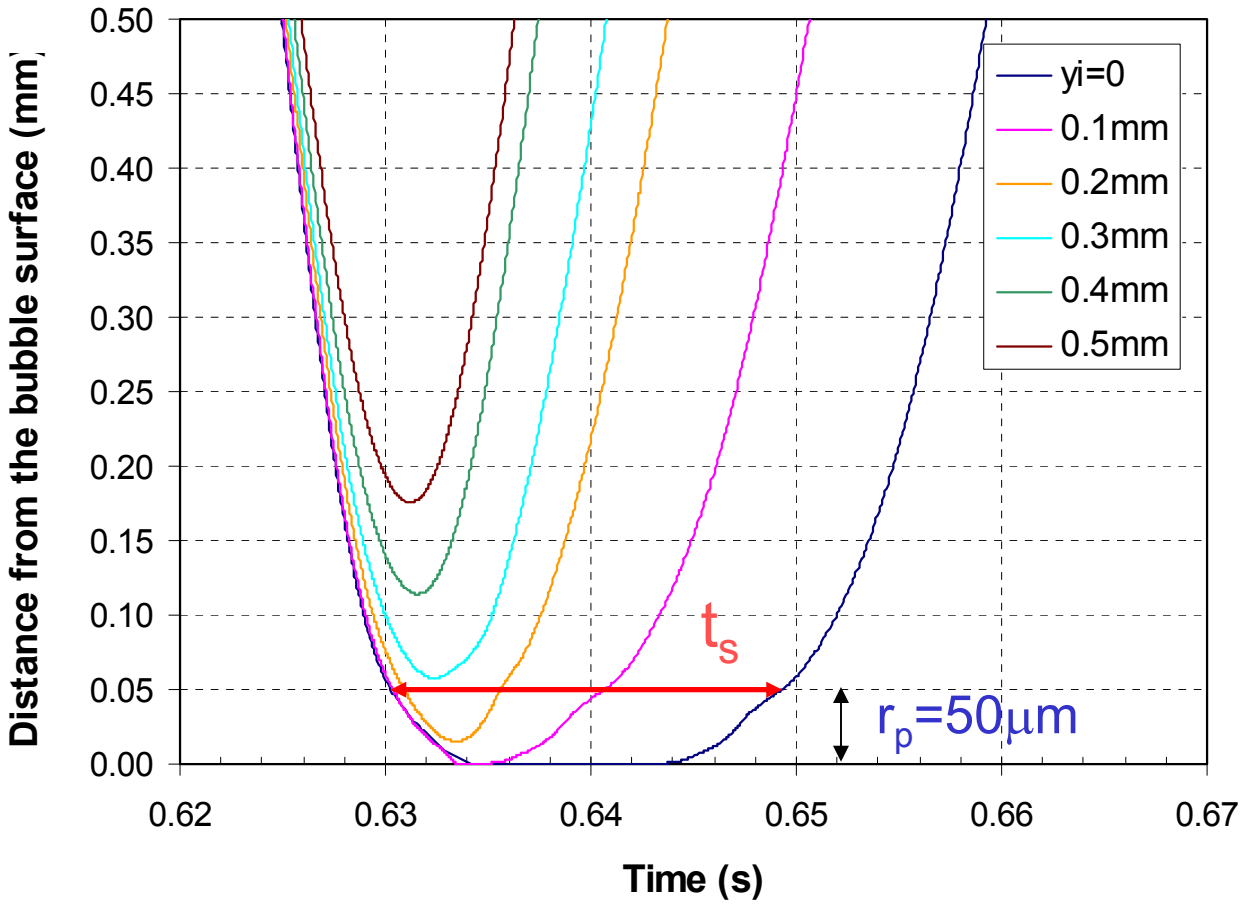
(Ignored wobbling motion)



100μm silica inclusion trajectory toward 6mm Ar bubble

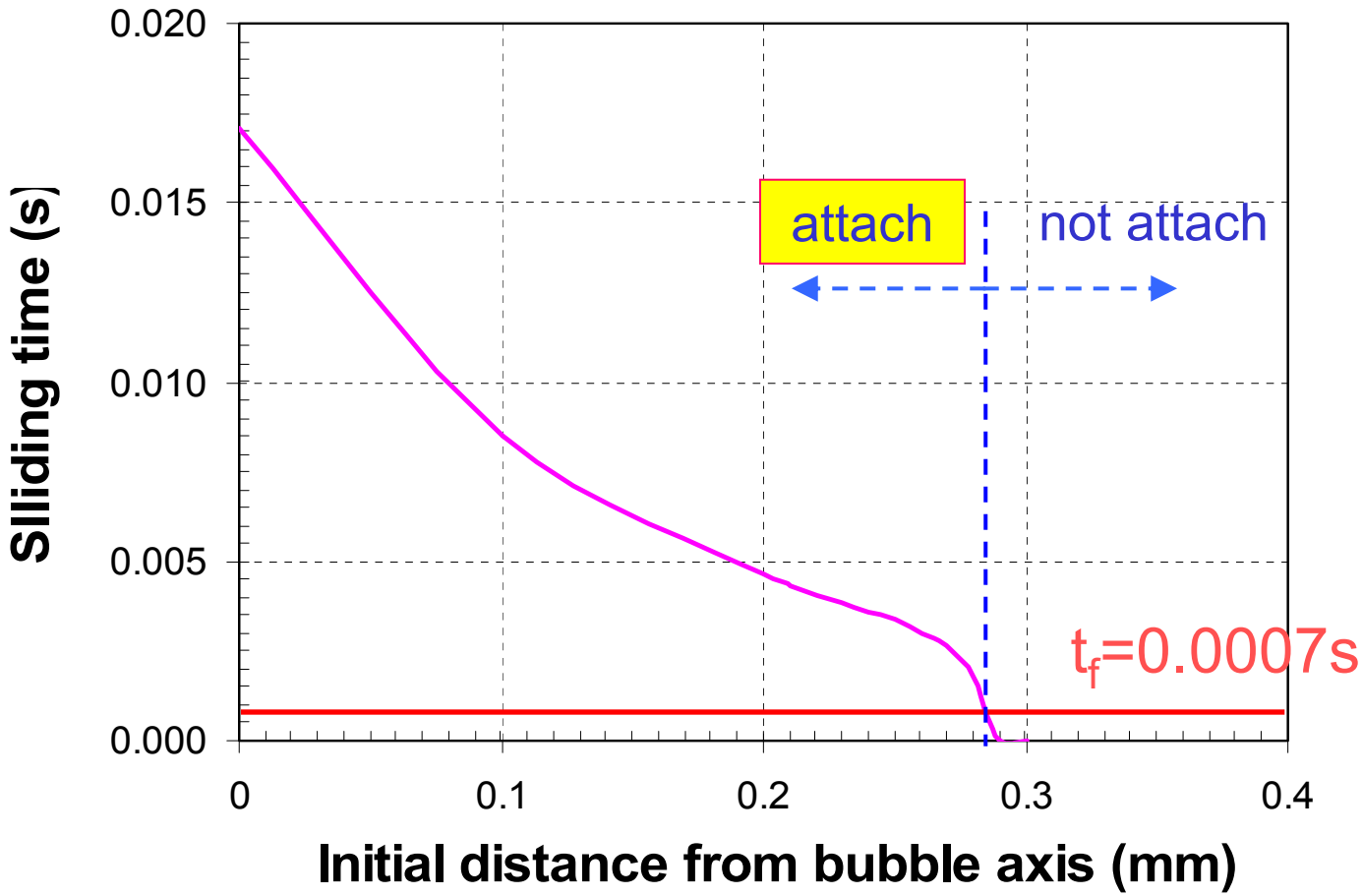
(e=1.37)

Computation of Sliding Time, t_s



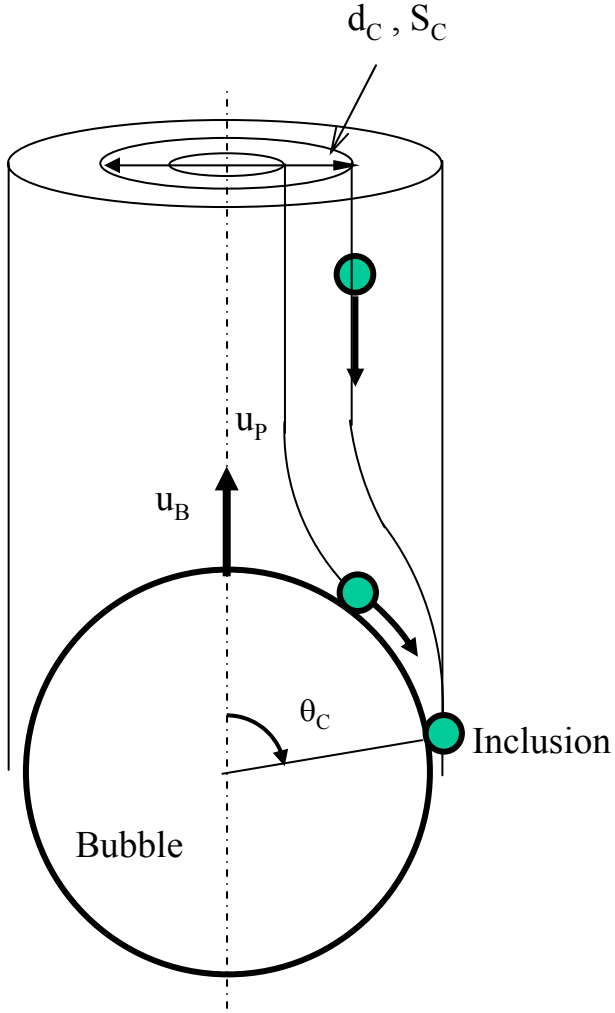
d_b=1mm, d_p=100μm

Sliding Time Decrease for Increasing Particle Initial Distance from Bubble Axis



d_b=1mm, d_p=100μm

Attachment Area Fraction of Particle to Bubble Surface



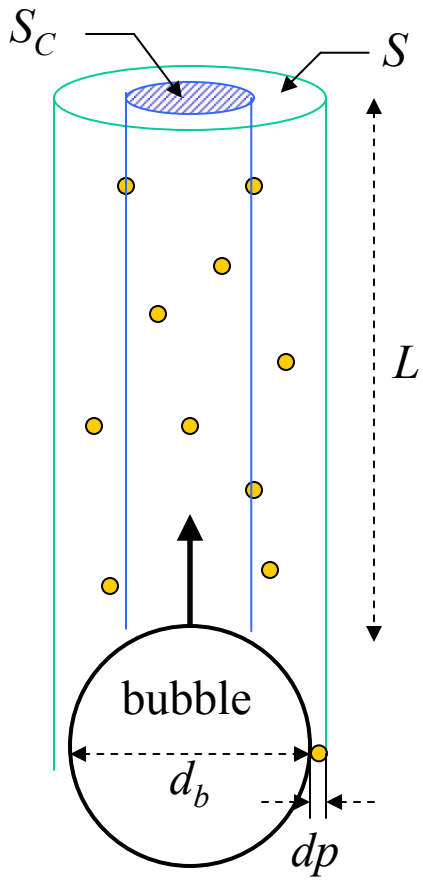
L. Zhang, (2002)

Attachment Area Fraction, F_A

$$F_A = \left(\frac{d_c}{d_b + d_p} \right)^2$$

Assumption:
Inclusion will be attached to bubble surface if sliding time t_s is greater than film drainage time t_f.
The value of d_c can be obtained by sliding time calculation.

Converting F_A (Attachment Area Fraction) to R_A (Particle Attachment Rate)

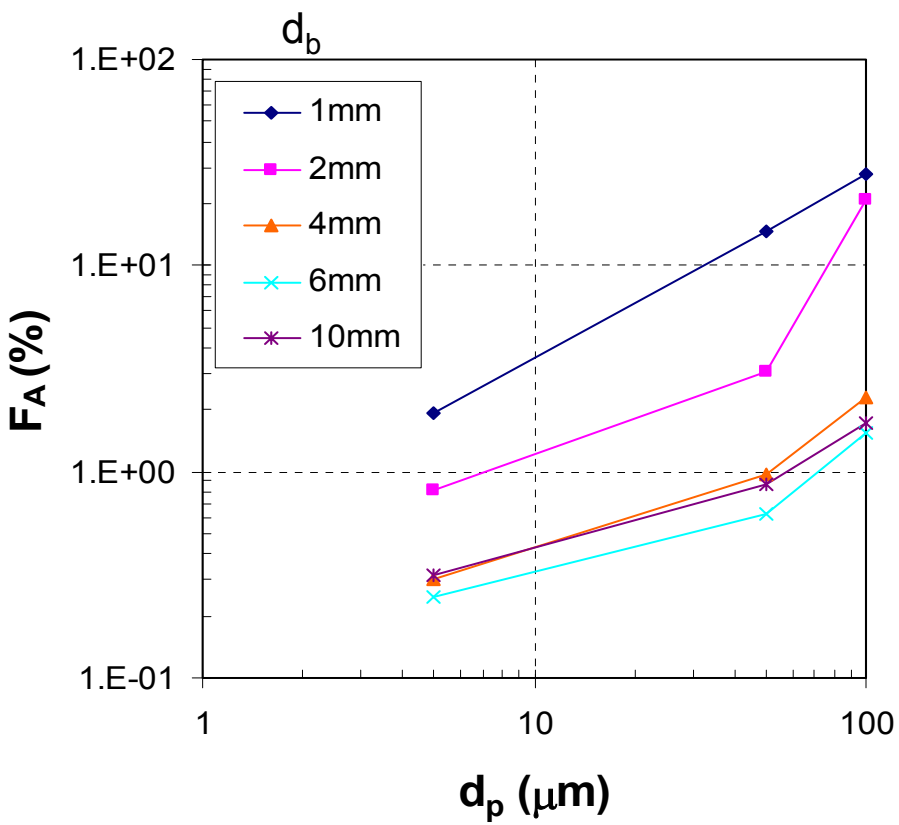


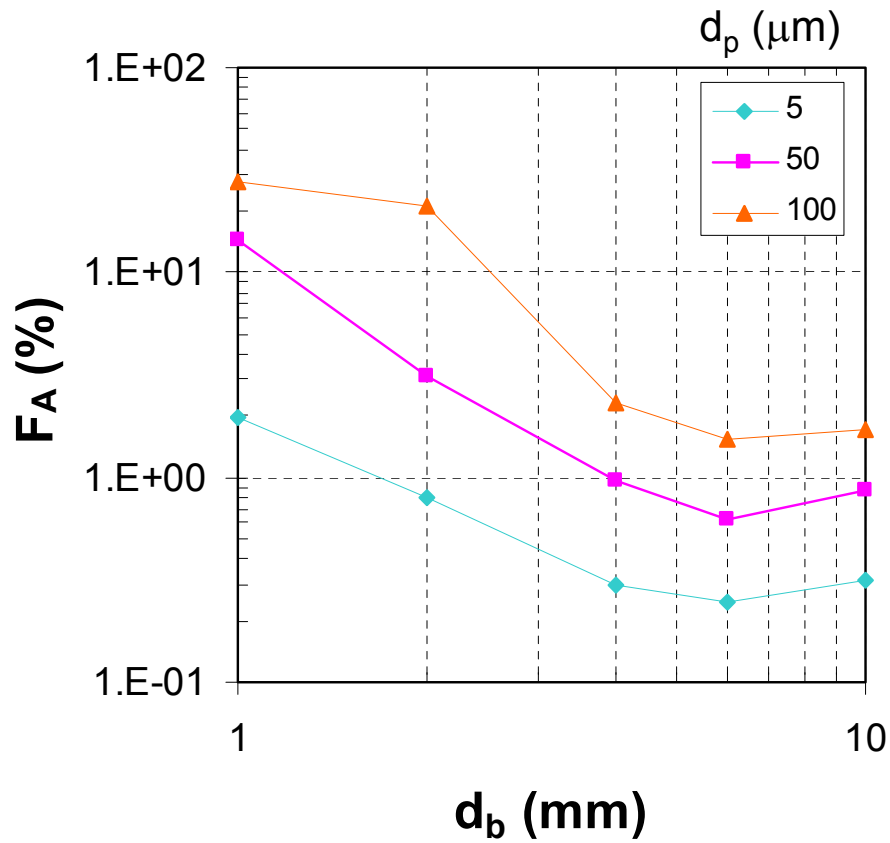
$$N = C_p S_C L = C_p S F_A L$$

$$R_A = C_p S_c = \pi \left(d_b + d_p\right)^2 C_p F_A$$

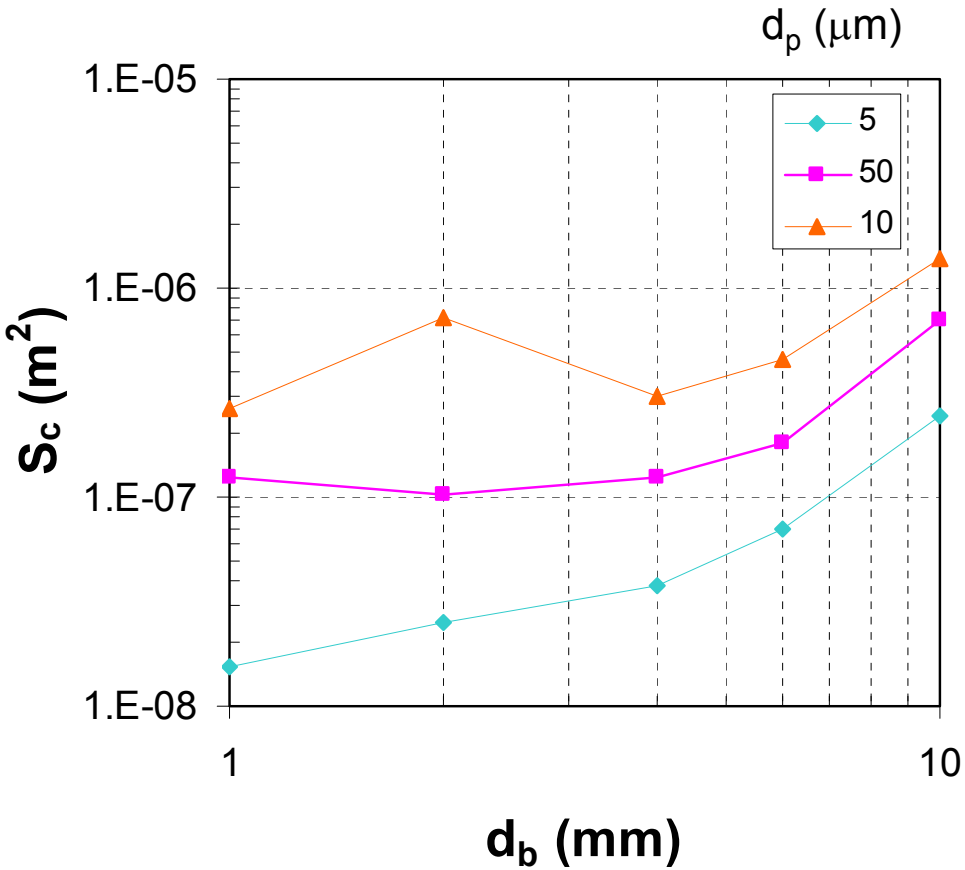
N : Number of particle attached to bubble
Cp : Particle concentration (m^{-3})
S_C : The area within that particles will attach to the bubble (m^2)
S : The area that the bubble sweeps (m^2)
F_A : Attachment area fraction ($=S_C/S$)
R_A : Particle attachment rate (m^{-1})

Attachment Area Fraction (Time-averaged Turbulent Model)





Particle Attachment Area (Time-averaged Turbulent Model)



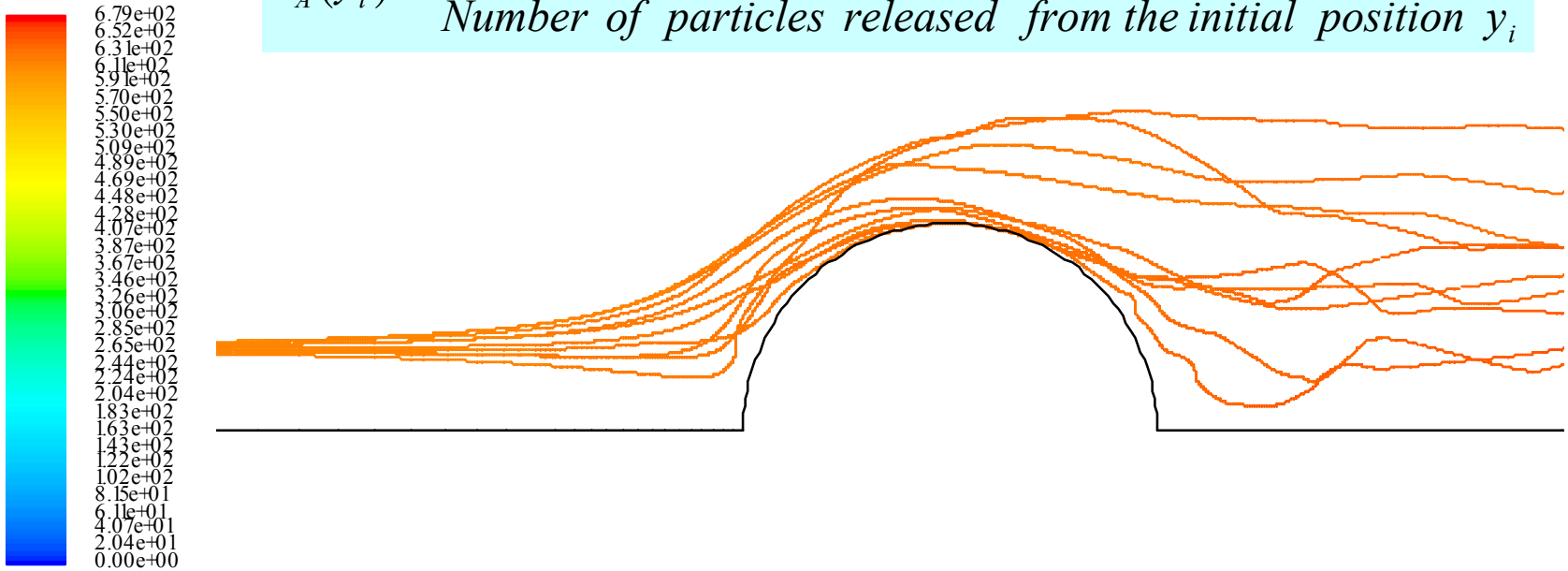
$$R_A = C_p S_c$$

→ Obtain Particle Attachment Rate

Particle Trajectory in Turbulent Flow
Applied Stochastic Random Walk Model

Attachment Probability P_A :

$$P_A(y_i) = \frac{\text{Number of particles attached to the bubble}}{\text{Number of particles released from the initial position } y_i}$$



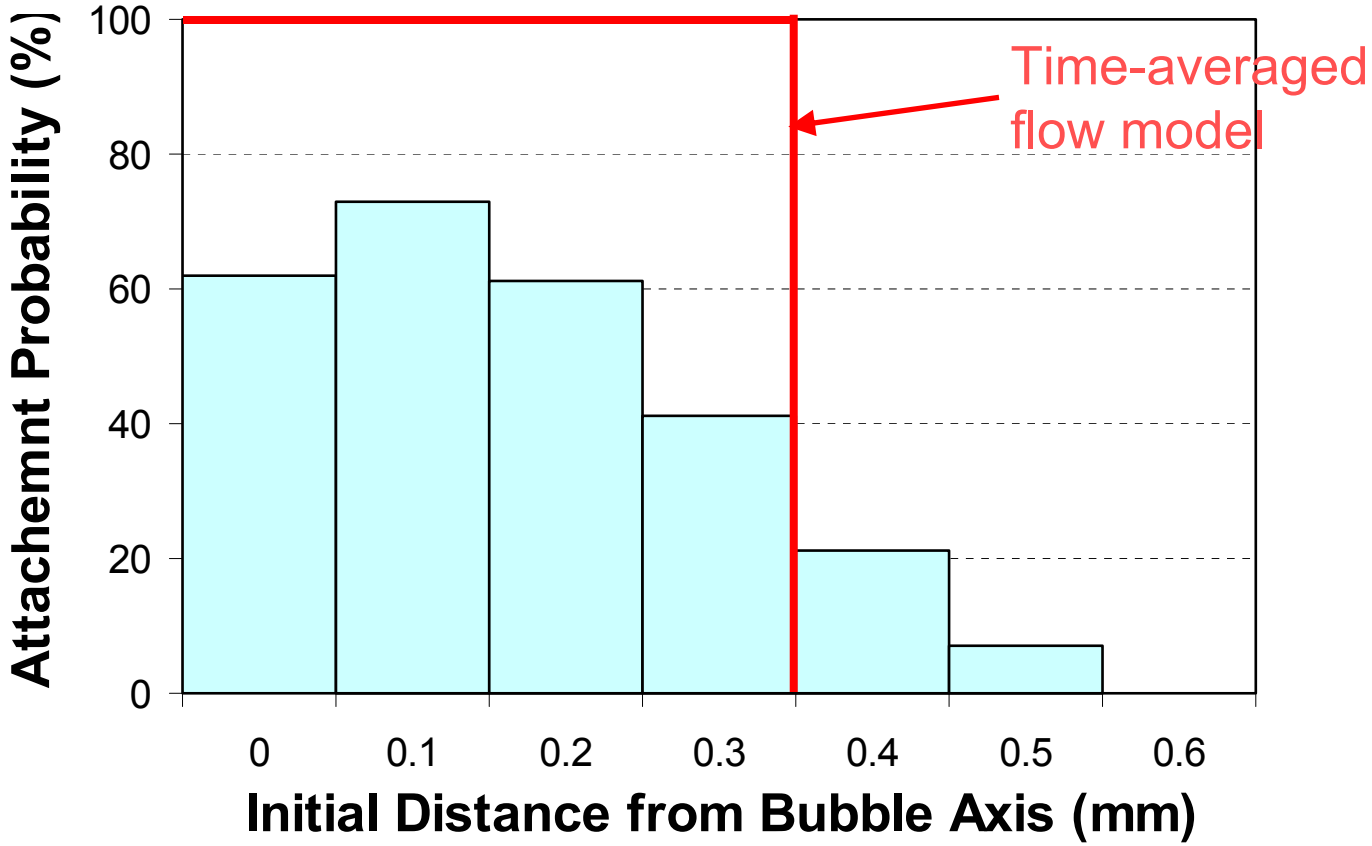
Particle Traces Colored by Particle Residence Time (ms)

May 01, 2004
FLUENT 6.1 (axi, dp, segregated, ske)

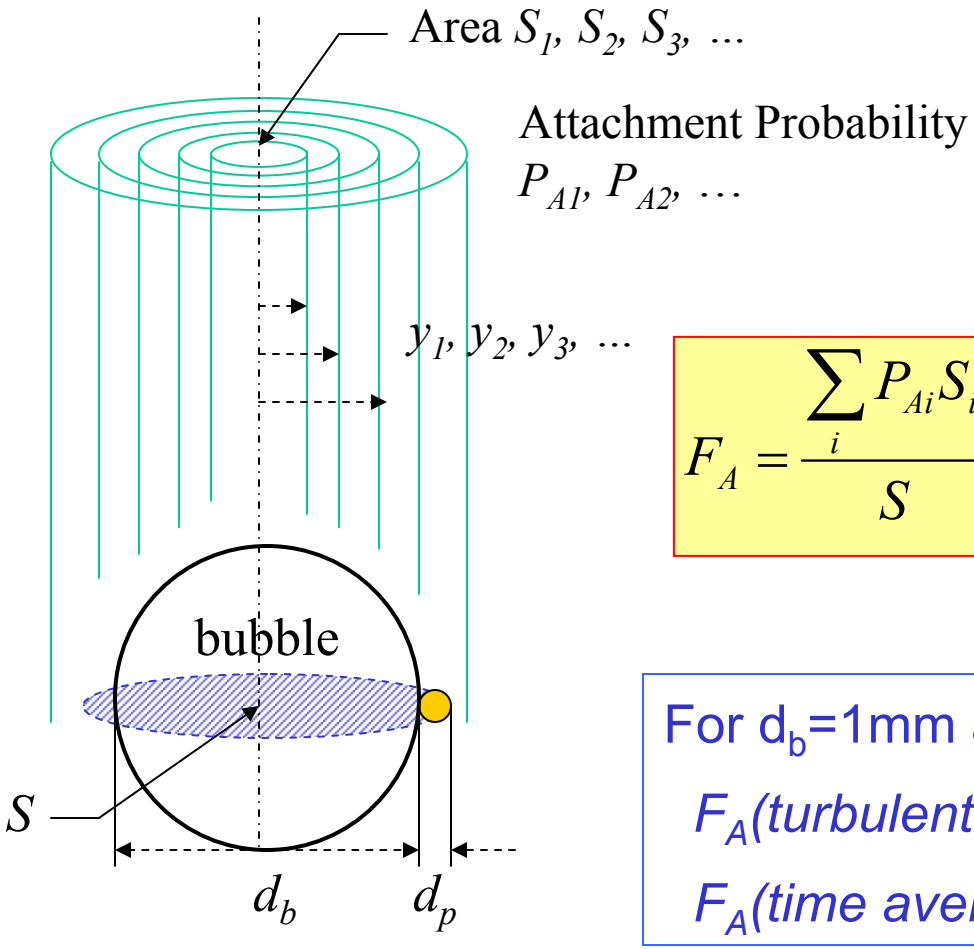
100μm silica inclusion trajectory toward 1mm Ar bubble with stochastic motion by turbulent flow

Attachment Probability in Turbulence

d_p=100μm,d_B=1mm
7 sets of 100 particles each



Calculation of F_A considering Attachment Probability in Turbulence



$$F_A = \frac{\sum_i P_{Ai} S_i}{S} = \frac{4\sum_i P_{Ai}\left(y_i^2 - y_{i-1}^2\right)}{\left(d_b + d_p\right)^2}$$

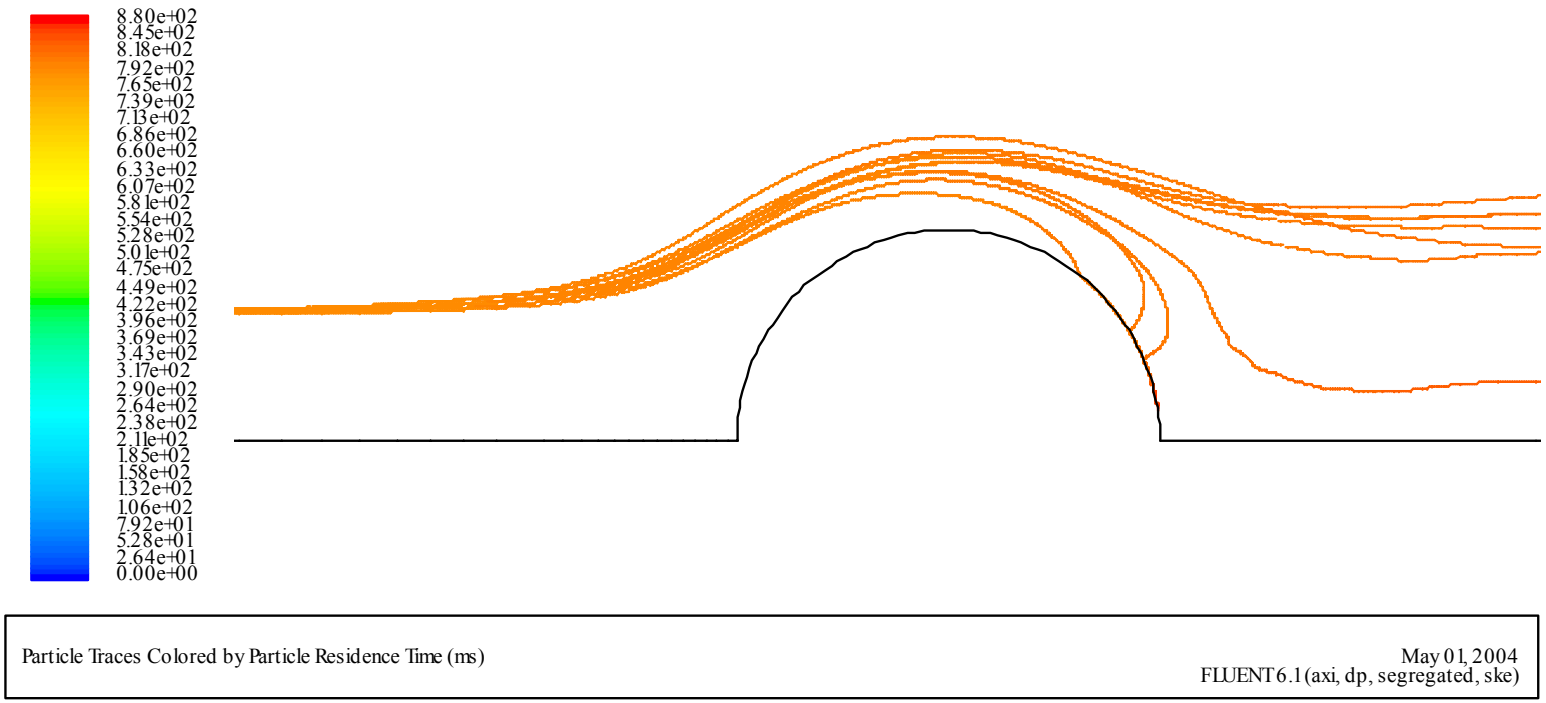
For d_b=1mm and d_p=100μm,

F_A(turbulent motion) = 29.4%

F_A(time averaged trajectory) = 27.8%

Backside 'Attraction'

(Important for large particle attachment)



500μm silica inclusion trajectory toward 1mm Ar bubble with stochastic motion by turbulent flow

Summary

- Inclusion attachment behavior to bubble is studied for 1mm-10mm bubbles with spheroid shape.
- The shape change of bubble may affect the attachment probability.
- Considering turbulent flow, statistical analysis is needed to predict attachment probability in realistic ladle refinement.

Future Work

- Further validation with measurement.
- Further statistical analysis of inclusion attachment probability in turbulent flow
- Incorporate to the Big 3D Multiphase flow model, to produce better ladle refining simulation.