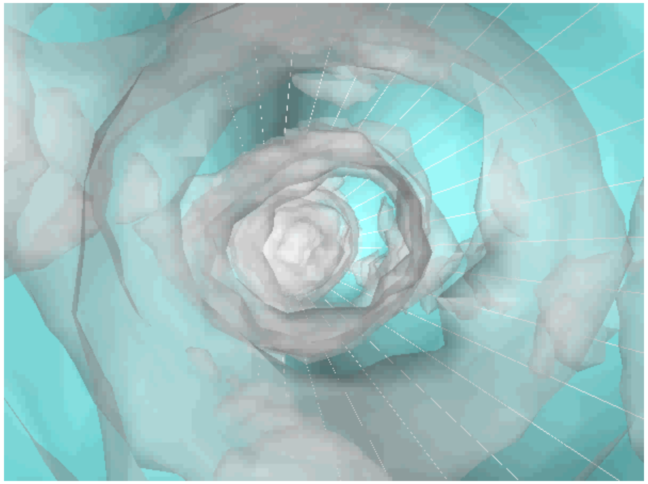
混相流における
プロセス･トモグラフィー計測

Chiba University
Laboratory on Multiphase
Flow and Visualization



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人工システム科学専攻　機械系コース
武居　昌宏

CONTENTS

トモグラフィーとは

Wikipediaより

tomo-【連結】切断{せつだん}、切開{せっかい}、部分{ぶぶん}

graphy 【連結】記述法{きじゅつほう}、書法{しょほう}、画法{がほう}

トモグラフィー

逆解析技術(逆問題: 結果から原因を見つける問題) で、対象領域を取り囲む形でセンサ（線源(ソース)と検出器）を配置し、内部の物性（電気的な物性、機械的な物性など）の分布を調べる技術。

CT　コンピューティッド・トモグラフィー

PT　プロセス・トモグラフィー

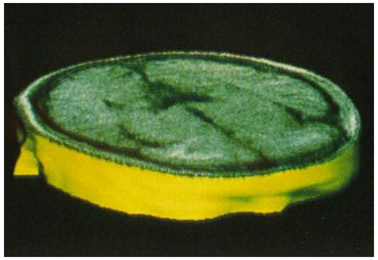
医療用トモグラフィーとプロセス･トモグラフィー

医療用トモグラフィー

X-ray or NMR

静止した人体内部
高空間解像度
低時間解像度

日立メディコWebより



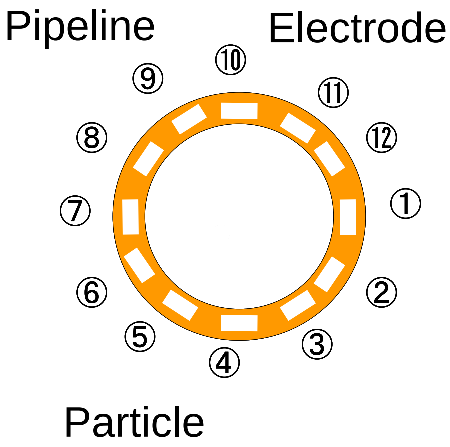
ウィキペディアWebより

Fig. Tomographic image of inside head by medical CT

混相流への応用

プロセス･トモグラフィー
低空間解像度
高時間解像度

PTLのWebより



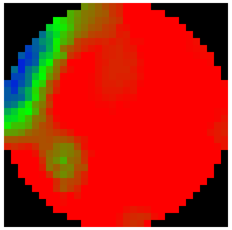
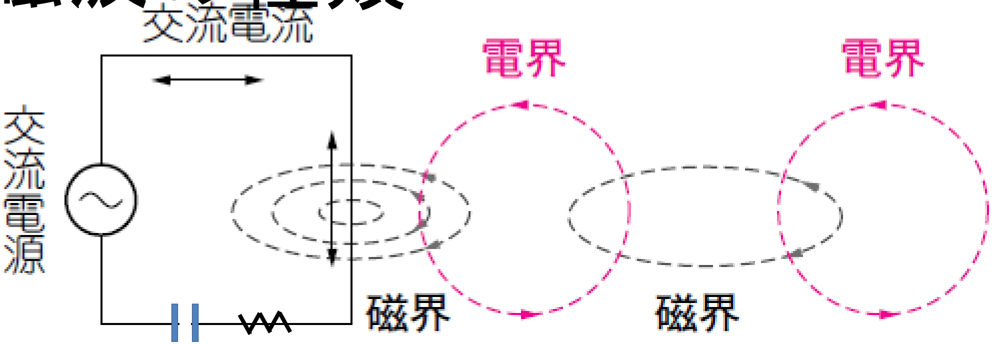


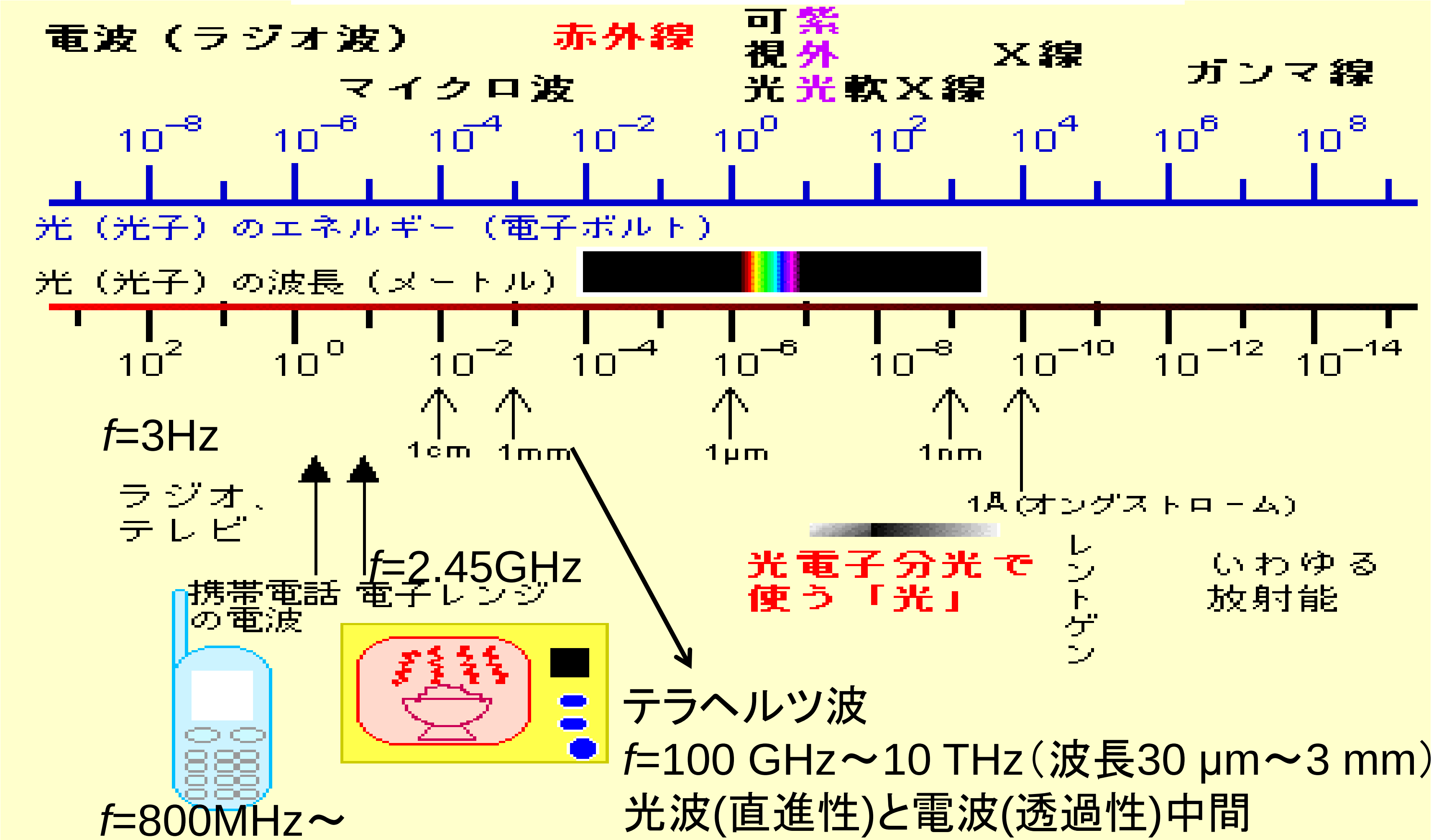
Fig. Overview of PT for particle flow

交流電流と電磁波の種類

ソフトフィード:
交流電流で混相流の抵抗やキャパシタンスを計測



ハードフィード
電磁波で混相流の透過、屈折、反射度を計測



f=3Hz

f=2.45GHz

f=800MHz～

テラヘルツ波
f=100 GHz～10 THz（波長30 μm～3 mm）
光波(直進性)と電波(透過性)中間

ハードフィールド・トモグラフィーにおける線の分類

●電磁波(Electromagnetic wave)

空間の電場と磁場の変化によって形成された横波となって伝播する波動。
波長の長い方から、電波・赤外線・可視光線・紫外線・X線・ γ線など

●粒子線(Particle beam）

イオン化された原子や分子などの粒子が束状になって進んでいくビーム。
例えば、電子線、陽子線（Proton,水素原子核）、α線(ヘリウム4原子核(陽子2個と中性子2個))、β線(原子核（中性子）がβ崩壊する際に放出される電子または陽電子)、中性子線など。

●放射線（Ionizing radiation）

電離性を有する高いエネルギーを持った電磁波や粒子線（ビーム）
強い電離作用（軌道電子をはじき飛ばすことによって、原子を陽イオンと電子に分離する作用）や蛍光作用を有する。
例えば、α線、β線、γ線、中性子線、X線

●放射線の透過能力

α線　紙1枚程度

β線　厚さ数mmのアルミニウム板

γ線　透過力が強く、コンクリートで50cm程度、鉛で10cm程度。

中性子線　最も透過力が強く水やコンクリートの厚い壁に含まれる水素原子によって遮断される。

ハードフィールドPTの歴史

●ヨハン・ラドン(Johan Radon) オーストリアの数学者　1917年　ラドンの画像再構成則
¨Uber die Bestimmung von Funktionen durch ihre Integralwerte l¨ angs gewisser Mannigfaltigkeiten *Math.-Phys.Kl*., 69, 262 267
三次元物体はその投影データ(Projection data)の無限集合から一意的に再生できる

Fig. Godfrey Hounsfield
日本放射線技術学会雑誌
Vol58No1より転写

●アラン・コーマック（Allan MacLeod Cormack) アメリカの物理学者。コンピュータ断層撮影 (CT) 技術の開発により、1979年にノーベル生理学・医学賞を受賞。Journal of applied physics (1963,1964)CT理論の論文を発表

Fig.最初の臨床画像
(Atkinson Moley病院の
J.Ambrose医師とともに)

●ゴッドフリー・ハウンズフィールド（Godfrey Hounsfield)
イギリスの電子技術者。コーマックCT理論を用いて1972年にCT装置開発に成功
ノーベル生理学・医学賞(1979)にアラン・コーマックとともに受賞。

ハードフィールド・トモグラフィーの基礎原理

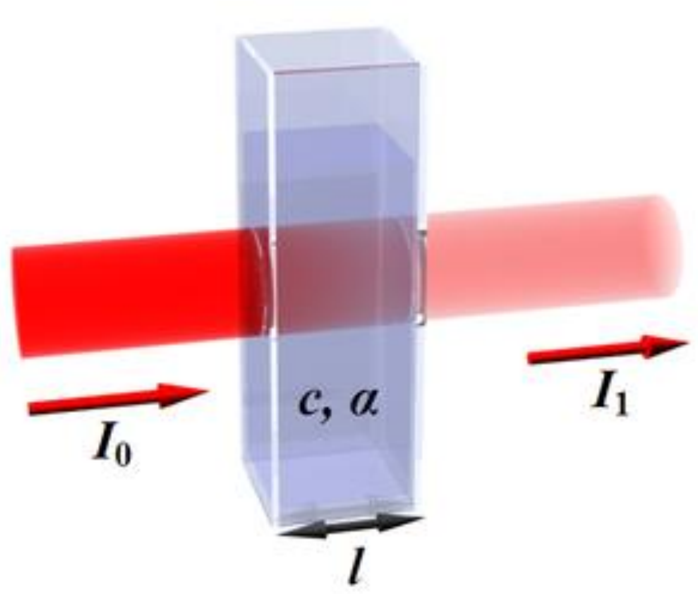
Hard Field Sensorはソースから
の走査線が対象内を直進する。
Soft Field Sensorは直進しない。

ランベルト・ベールの法則　Lambert-Beer law

媒質に入射する前の光の放射照度をI_0、媒質中を距離L移動したときの光の強度をI_1としたとき

$$\log_{10}\left(\frac{I_1}{I_0}\right) = -\alpha L = -\epsilon c l$$

ここでαは吸収係数
α ∝　分散相の濃度
光吸収透過CT，光干渉CT



ハードフィールド・トモグラフィー画像再構成の原理

●ランベルト・ベールの法則 $\int_s f(x,y)ds = \ln\frac{I_i}{I_0}$

f(*x*,*y*) : 断面吸収係数分布　I_i : 入射側の強度、
I_0 : 透過強度　*ds* : 走査線に沿った線素

x-*y*座標系から角度θ回転した*r*-*s*座標系
p(*r*,*θ*) : 投影データ

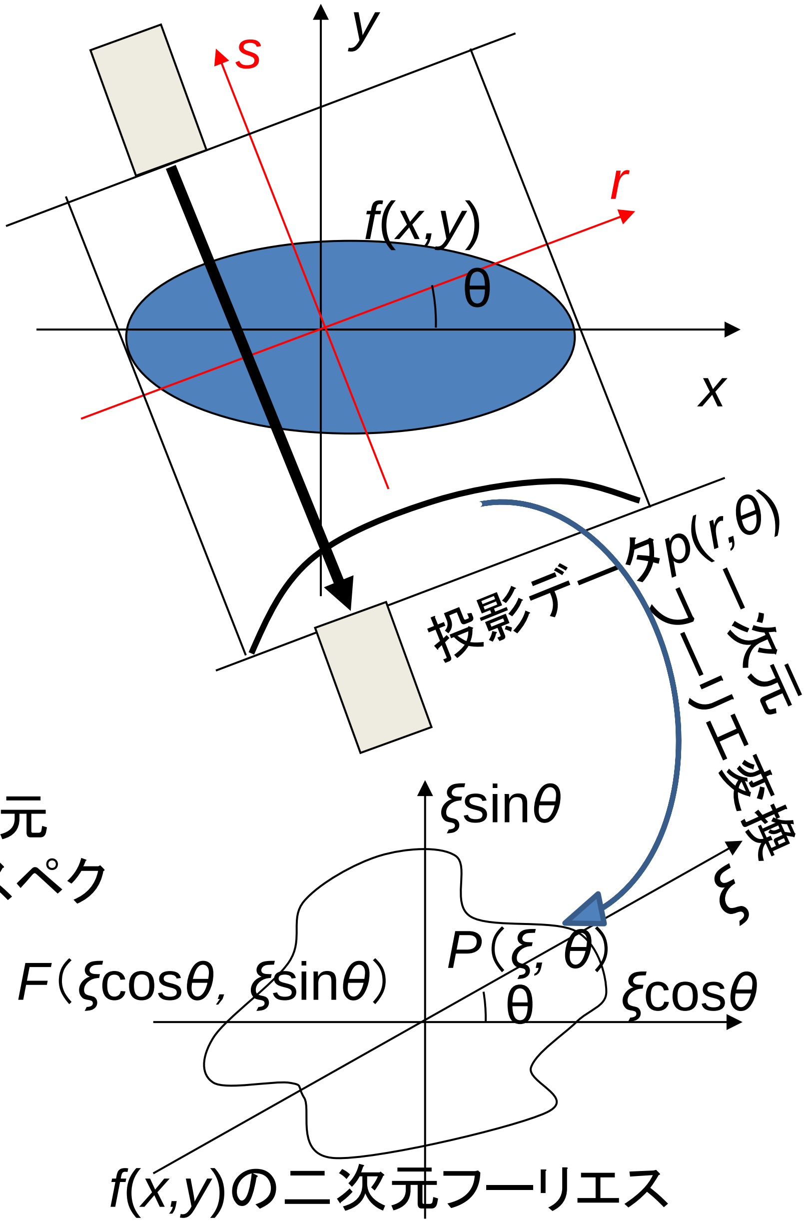
●ラドン変換

$$p(r,\vartheta)=\int_{-\infty}^{\infty} f(r\cos\theta - s\sin\theta, r\sin\theta + s\cos\theta)ds$$

●投影切断面定理： *θ*方向の投影データの一次元フーリエスペクトラムは、*f*(*x*,*y*)の二次元フーリエスペクトラムの*θ*方向の切断面に等しい

$$F(\xi\cos\theta,\xi\sin\theta)=\int_{-\infty}^{\infty} p(r,\theta)\exp(-j\xi)rdr$$

ξ: フーリエ級数の波数*ξ*



f(*x*,*y*)の二次元フーリエスペクトラム*F*(*ξ*cos*θ*, *ξ*sin*θ*)

フィルタ補正逆投影(FBP)法

$f(x,y)$: 断面吸収係数分布　$|\xi|$:波数ξの絶対値のフィルタ補正

$$f(x,y)=\int_{0}^{\pi}\left[\underline{\int_{-\infty}^{\infty}P(\xi,\theta)}\,|\xi|\,\underline{\exp(j\xi)rd\xi}\right]d\theta$$

逆フーリエ変換

$P(\xi)$: 角度θのときの投影データ$p(r,\theta)$のξ(波数)における一次元フーリエスペクトラム

$$P(\xi,\theta)=\int_{-\infty}^{\infty}p(r,\theta)\underline{\exp(-j\xi)}rdr$$

フーリエ変換

CONTENTS

- PTの概要　ソフトフィールドとハードフィールド
- ソフトフィールドPT
    - 電気PTの原理
    - プラントへの展開
    - 血流への展開
    - マイクロ流路への展開
- ハードフィールドPT
    - Optical CT
    - X ray CT
    - γ ray CT
    - Neutron Radiography
    - Ultrasound CT
    - MRI
    - Positron Emission Tomography (PET)
- まとめ

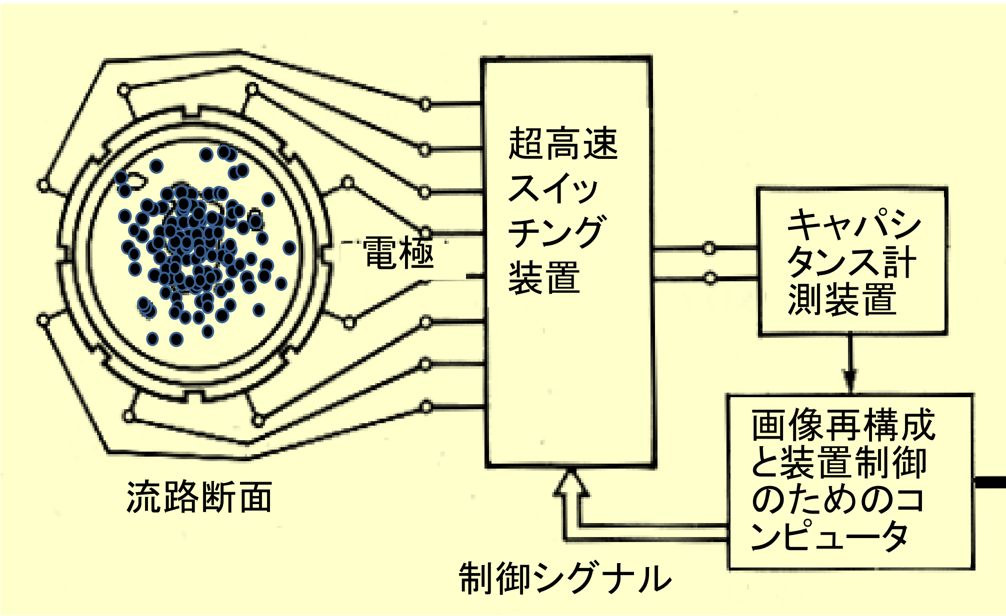
ソフトフィールド･トモグラフィー

走査線が対象内を直進しない

拡散光トモグラフィー

名称	対象となる二相流		測定と求める物理量	
	連続相	拡散相	測定物理量	求める物理量
キャパシタンス･トモグラフィ (ECT)	非導電性物質(空気)	誘電性物質(粒子)	キャパシタンス	誘電率分布 Permittivity ε
抵抗トモグラフィ (ERT)(EIT)	高導電性物質(水)	抵抗物質(粒子)	電流流したときの電位	導電率分布 Conductivity σ
磁気インダクタンス･トモグラフィ (EMT)	非透磁性物質(空気)	透磁性物質(磁性粒子)	渦電流によるコイル内の電流変化	透磁率分布 Permeability μ

ソフトフィールド・トモグラフィーのハードウェア



微粒子濃度分布画像

Fig. PT(ECT)法のシステム

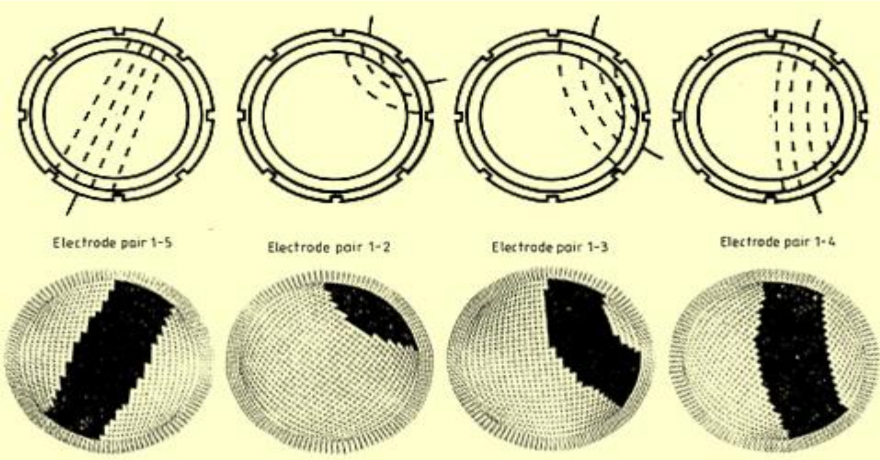
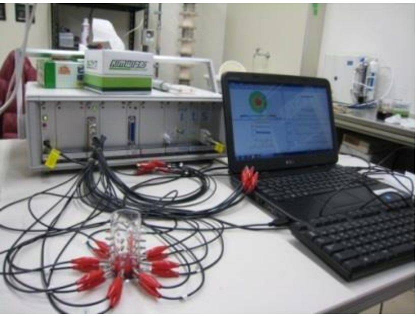
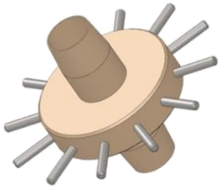
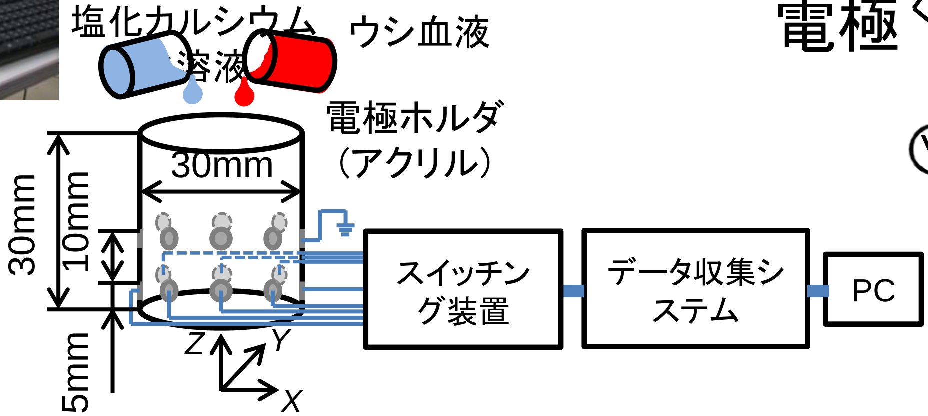


Fig. アクティブな領域

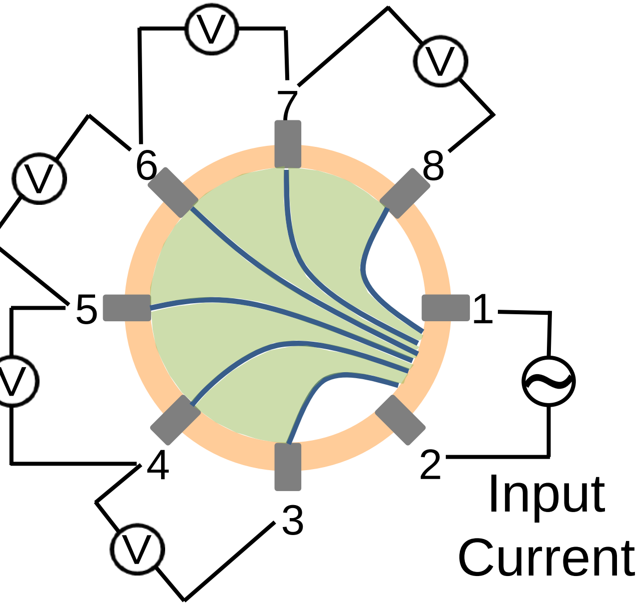




PTセンサ



電極



PTセンサ断面図

ECTセンサ

M.Takei,et al. *International Journal of Applied Electromagnetics and Mechanics, IOS Press*, (2002)
M.Takei et al., *Particulate Science and Technology, Taylor & Francis*, (2002)

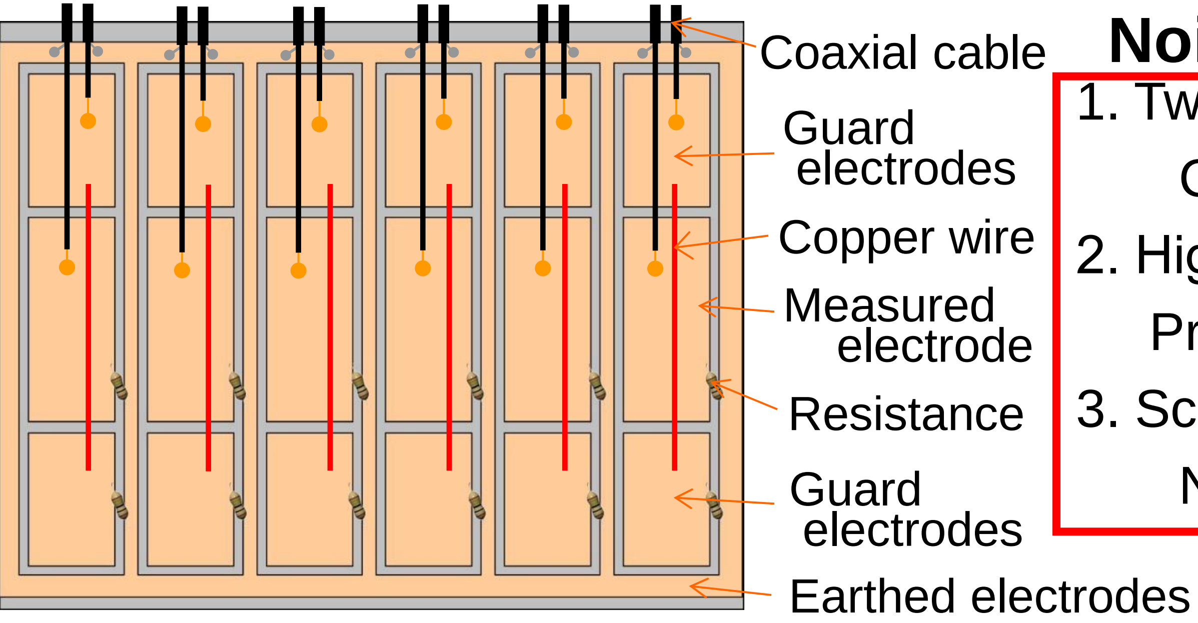


Fig. CT sensor

Noise protection method

1. Two guard electrodes
   Concentration of electrical line
2. High Ω Resistance
   Protection of stray capacitance
3. Screen electrodes
   Noise Absorption

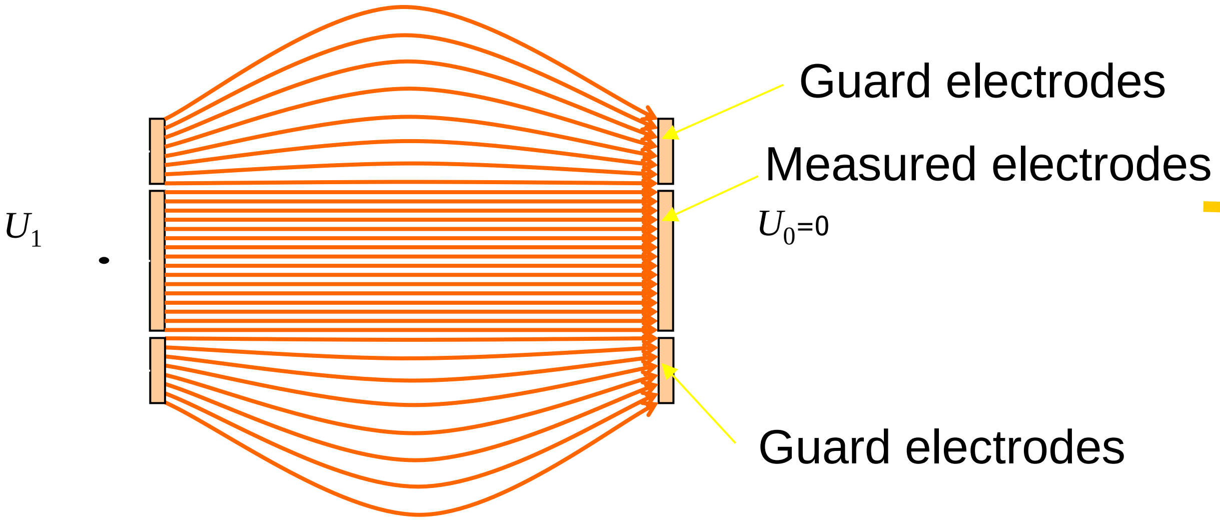


Fig. Guard electrodes

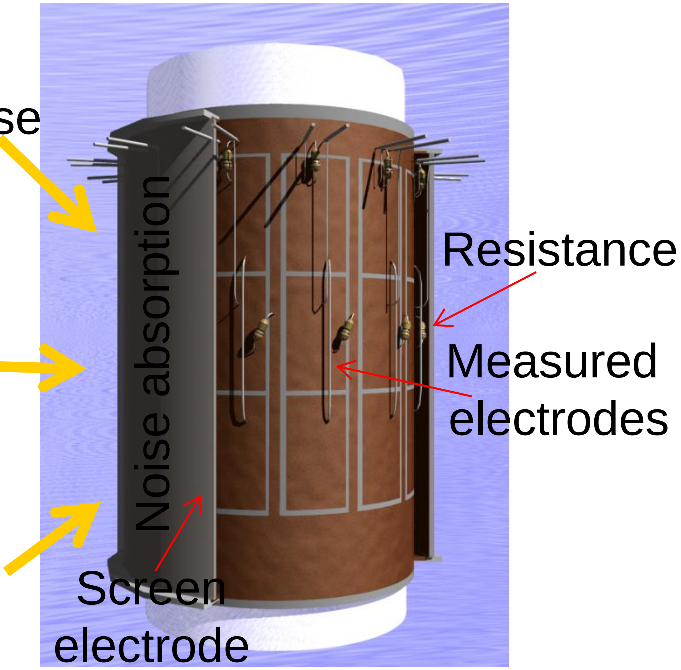


Fig. Screen electrode

ERT基礎式#1

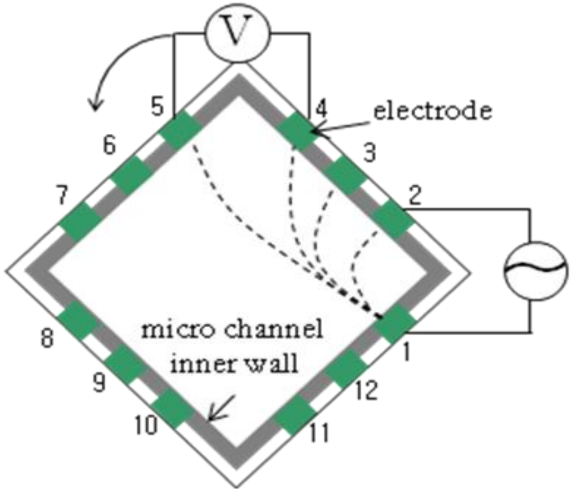


Fig. Neighboring method

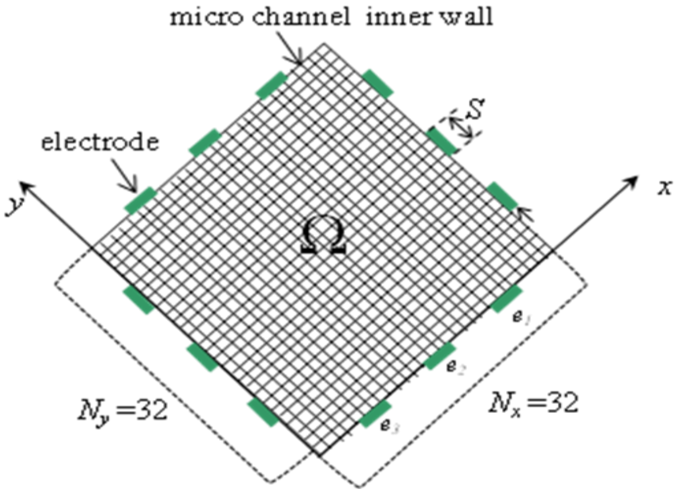


Fig. 空間解像度

$$\mathbf{U} = \mathbf{J}\boldsymbol{\rho}$$

$U(\rho)$: 電極上の電位

ρ : 抵抗率分布

J: ヤコビ行列(感度関数)
順問題で求める

未知数(空間解像度) < 式数

逆問題で求める

$$J = \begin{pmatrix} \dfrac{\partial U_1^1}{\partial \rho_1} & \cdots & \dfrac{\partial U_1^1}{\partial \rho_N} \\ \dfrac{\partial U_2^1}{\partial \rho_1} & \cdots & \dfrac{\partial U_2^1}{\partial \rho_N} \\ \vdots & \ddots & \vdots \\ \dfrac{\partial U_1^K}{\partial \rho_1} & \cdots & \dfrac{\partial U_1^K}{\partial \rho_N} \\ \vdots & \ddots & \vdots \\ \dfrac{\partial U_L^K}{\partial \rho_1} & \cdots & \dfrac{\partial U_L^K}{\partial \rho_N} \end{pmatrix}$$

N:空間要素
L:電圧測定パターン
K:電流印加パターン

基礎式#2と境界条件

Laplace 方程式

$$\nabla\cdot\left(\frac{1}{\rho}\nabla u\right)=0,\quad \text{on } x\in\Omega$$

j: 電流密度[A/m^2], ρ :抵抗率[Ω･m] u : 電位 [V]

境界条件

1) Summation of current density on electrodes is currency on electrodes:

$$\int_{e_l}\frac{1}{\rho}\frac{\partial u}{\partial\upsilon}dS=I_l,\, x\in e_l,\, l=1,2,\cdots,L$$

2) Current is zero except for the current electrode pair:

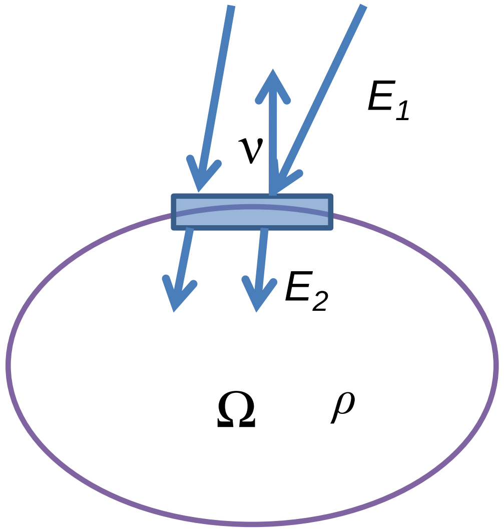
$$\frac{1}{\rho}\frac{\partial u}{\partial\upsilon}=0,\, x\in\partial\Omega\setminus\bigcup_{l=1}^{L}e_l$$

3) Contact impedance is considered on the electrodes

$$u+z_l\frac{1}{\rho}\frac{\partial u}{\partial\upsilon}=U_l,\, x\in e_l,\, l=1,2,\cdots,L$$

4) All current and voltage on all electrodes are zero

$$\sum_{l=1}^{L}I_l=0,\sum_{l=1}^{L}U_l=0$$

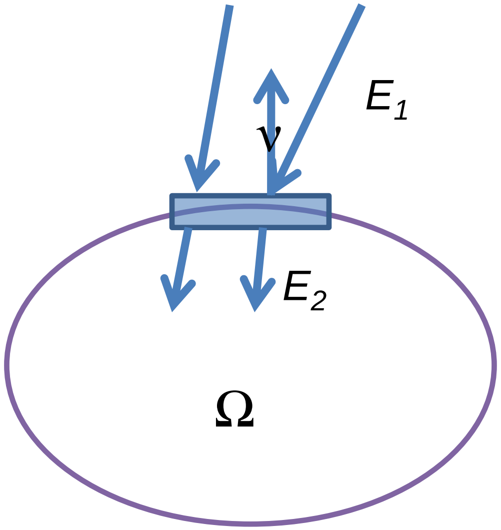


ρ: Resistivity distribution on Ω I: Current on electrodes u: Potential distribution on Ω U: Voltage on electrodes e_l : Surface on *lth* electrode ν :outward directed normal vector S: Electrode boundary L: electrode number z : Contact impedance

境界条件(complete electrode models)

1) Summation of current density on electrodes is currency on electrodes:

$$\int_{e_l} \frac{1}{\rho}\frac{\partial u}{\partial \upsilon} dS = I_l, x \in e_l, l = 1,2,\cdots, L$$



2) Current is zero except for the current electrode pair:

$$\frac{1}{\rho}\frac{\partial u}{\partial \upsilon} = 0, x \in \partial\Omega \setminus \bigcup_{l=1}^{L} e_l$$

3) Contact impedance is considered on the electrodes

$$u + z_l \frac{1}{\rho}\frac{\partial u}{\partial \upsilon} = U_l, x \in e_l, l = 1,2,\cdots, L$$

4) All current and voltage on all electrodes are zero

$$\sum_{l=1}^{L} I_l = 0, \sum_{l=1}^{L} U_l = 0$$

ρ: Resistivity distribution on Ω I: Current on electrodes u: Potential distribution on Ω U: Voltage on electrodes e_l : Surface on *lth* electrode ν :outward directed normal vector S: Electrode boundary L: electrode number z : Contact impedance

ECTの基礎式

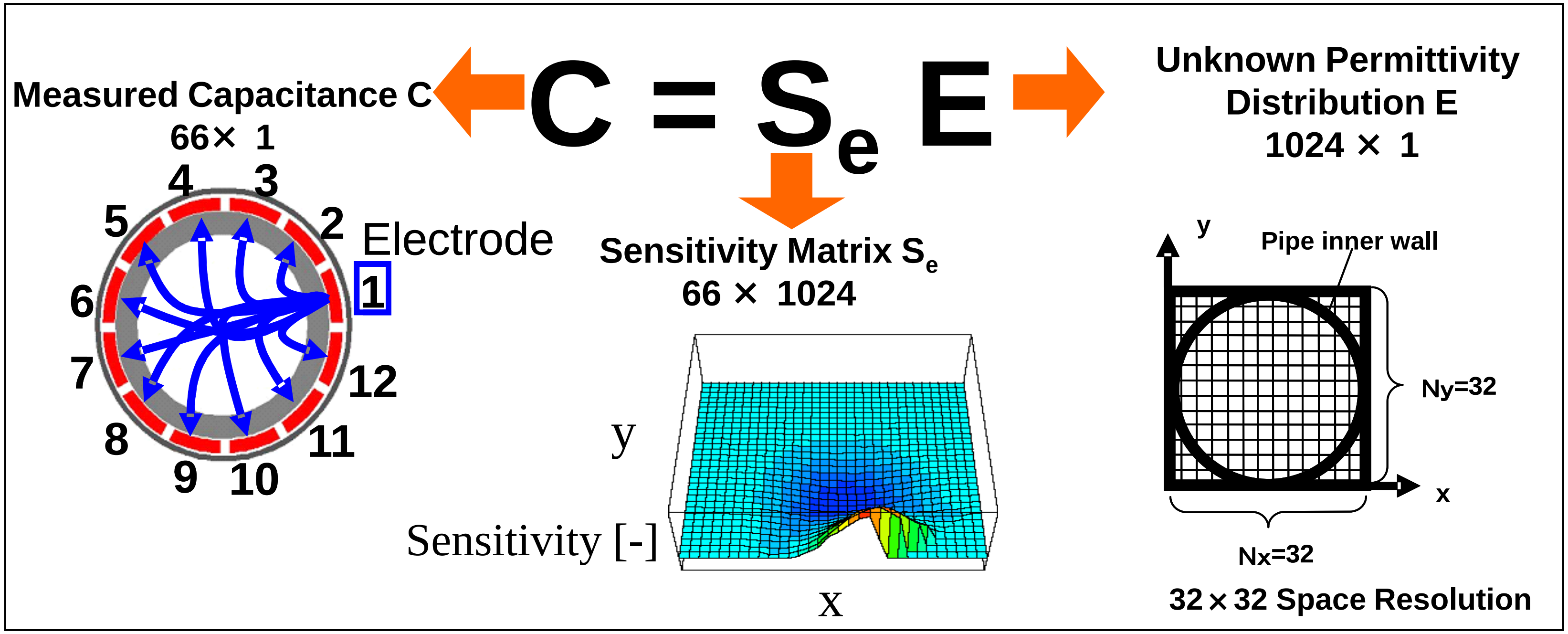
M. Takei et al. *Measurement Science and Technology* (2004, 2006)

Governing Equation in the Electrostatic Field

$$C_{i,j} = -\frac{\varepsilon_0}{V_c}\oint_{r\subseteq\Gamma_j} \varepsilon(\mathbf{r})\nabla V_i(\mathbf{r})\cdot d\mathbf{r} \qquad \nabla\cdot[\varepsilon(\mathbf{r})\nabla V(\mathbf{r})]=0$$

$$(i=1,2,\cdots,11;\ \ j=i+1,\cdots,12)$$

$C_{i,,j}$:Capacitance between *i* and *j* electrodes, ε $_0$:Vacuum permittivity, V_C : Electrode voltage , r : Position vector, ε : Relative permittivity, V_i : Potential in cross section, Γ_i: Area covered with electric force line



Measured Capacitance C
66× 1

C = S_e E

Unknown Permittivity Distribution E
1024 × 1

Sensitivity Matrix S_e
66 × 1024

32×32 Space Resolution

Ill posed Inverse Problem
Unknown Number > Expression Number

→

Image Reconstruction
Approximate Permittivity E

通常の逆問題の解法

Isaksen,O. 1996 *Meas. Sci. Technol.*
Yang,W.Q. 2003, *Meas. Sci. Technol.*

Linear Back Projection (LBP) Method

Blurred Image

Landweber (LW) method

Necessary Artificial Gain Value

$$\mathbf{E}^{(0)} = \mathbf{Se}^{\mathrm{T}}\,\mathbf{C}^{(0)}$$

▼

$$\mathbf{C}^{(1)} = \mathbf{Se}\,\mathbf{E}^{(0)}$$

▼

$$\Delta\mathbf{C}^{(1)} = (\mathbf{C}^{(1)} - \mathbf{C}^{(0)})$$

▼

$$\Delta\mathbf{C_G}^{(1)} = g \times \Delta\mathbf{C}^{(1)}$$

▼

$$\Delta\mathbf{E}^{(1)} = \mathbf{Se}^{\mathrm{T}}\,\Delta\mathbf{C_G}^{(1)}$$

▼

$$\mathbf{E}^{(1)} = (\mathbf{E}^{(0)} - \Delta\mathbf{E}^{(1)})$$

$$\mathbf{E}^{(k)} = \mathbf{E}^{(k-1)} + \Delta\mathbf{E}^{(k-1)}$$
$$= \mathbf{S}_{\mathbf{e}}{}^{\mathrm{T}}\mathbf{C}^{(0)} + g\left(\mathbf{I}_m - \mathbf{S}_{\mathbf{e}}{}^{\mathrm{T}}\mathbf{S}_{\mathbf{e}}\right)\mathbf{E}^{(k-1)}$$

Iterative Tikhonov Regularization (ITR) method

$$\mathbf{E}^{*(k)} = \mathbf{E}^{*(k-1)} - \left(\mathbf{S}_{\mathbf{e}}{}^{\mathrm{T}}\mathbf{S}_{\mathbf{e}} + \gamma\mathbf{I}\right)^{-1}\mathbf{S}_{\mathbf{e}}{}^{\mathrm{T}}\left(\mathbf{S}_{\mathbf{e}}{}^{\mathrm{T}}\mathbf{E}^{*(k-1)} - \mathbf{C}^{*(0)}\right)$$

CHARACTERISTICS OF GVSPM METHOD

Takei, M. et. al 2004 & 2006 *Meas. Sci. & Technol.*

Normalization by Norm

$$\mathrm{C} = \mathrm{S_e E} = \sum_{i=1}^{m} (\mathrm{S}_{\mathrm{e}_i} e_i)$$

Space resolution
***m*=1024**

Normalization

$$\mathrm{C'} = \frac{\mathrm{C}}{|\mathrm{C}|} \qquad \mathrm{S}_{\mathrm{e}_i}{}' = \frac{\mathrm{S}_{\mathrm{e}_i}}{|\mathrm{S}_{\mathrm{e}_i}|} \qquad e_i{}' = e_i \frac{|\mathrm{S}_{\mathrm{e}_i}|}{|\mathrm{C}|}$$

$$|\mathrm{C}| = \sqrt{c_1{}^2 + c_2{}^2 + \ldots + c_n{}^2}$$

$$|\mathrm{S}_{\mathrm{e}_i}| = \sqrt{S_{ei_1}{}^2 + S_{ei_2}{}^2 + \ldots + S_{ei_n}{}^2}$$

Total pair number of electrodes *n*=66

$$\mathrm{C'} = \sum_{i=1}^{m} (\mathrm{S}_{\mathrm{e}_i}{}' e_i{}') = \mathrm{S_e' E'}$$

Evaluation Function

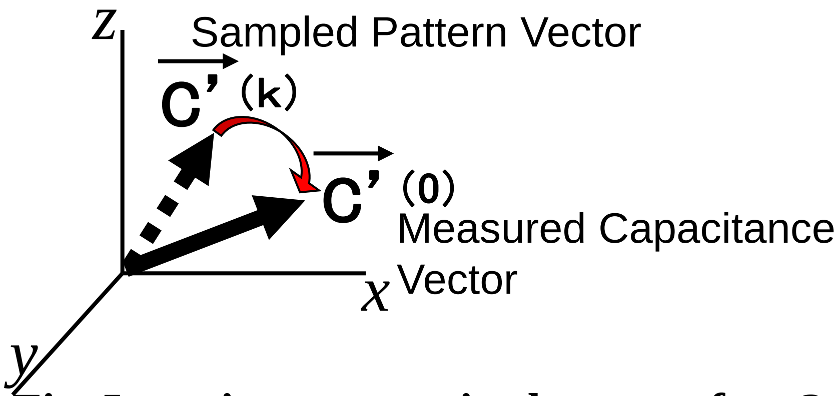


Fig. Iteration process in the case of *n*=3

$$\mathbf{f}(\mathrm{E'}^{(k)}) = \mathrm{C'}^{(\mathbf{0})} \mathrm{C'}^{(k)} \rightarrow 1.0$$

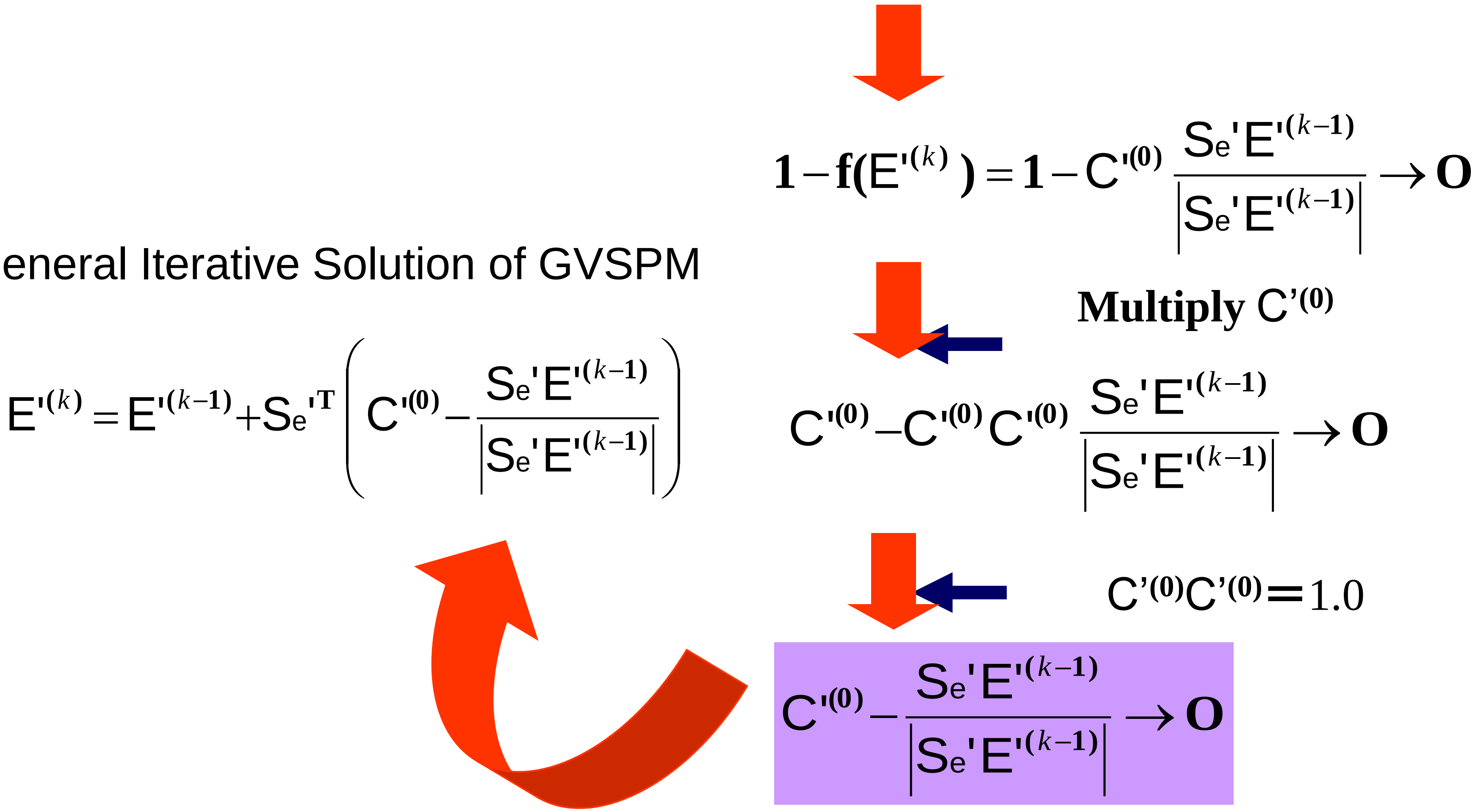
$\mathrm{E}'^{(k)}$: **k^{th} iterative solution of SPM**
$\mathrm{C}'^{(k)}$: **Capacitance from** $\mathrm{E}'^{(k)}$
$\mathrm{C}'^{(\mathbf{0})}$: **Measured capacitance**

Iterative Solution

Accurate Images

No Artificial Gain Value

INCLUSION OF EVALUATION FUNCTION IN ITERATIVE SOLUTION



Evaluation Function

$$\mathbf{f}(E'^{(k)}) = C'^{(0)}\,C'^{(k)} \rightarrow 1.0$$

$$\mathbf{1} - \mathbf{f}(E'^{(k)}) = \mathbf{1} - C'^{(0)} \frac{S_e'E'^{(k-1)}}{\left|S_e'E'^{(k-1)}\right|} \rightarrow \mathbf{O}$$

Multiply $C'^{(0)}$

$$C'^{(0)} - C'^{(0)}C'^{(0)} \frac{S_e'E'^{(k-1)}}{\left|S_e'E'^{(k-1)}\right|} \rightarrow \mathbf{O}$$

$$C'^{(0)}C'^{(0)} = 1.0$$

$$\boxed{C'^{(0)} - \frac{S_e'E'^{(k-1)}}{\left|S_e'E'^{(k-1)}\right|} \rightarrow \mathbf{O}}$$

General Iterative Solution of GVSPM

$$E'^{(k)} = E'^{(k-1)} + S_e'^{T}\left(C'^{(0)} - \frac{S_e'E'^{(k-1)}}{\left|S_e'E'^{(k-1)}\right|} \right)$$

RECONSTRUCTION OF PSEUDO IMAGES

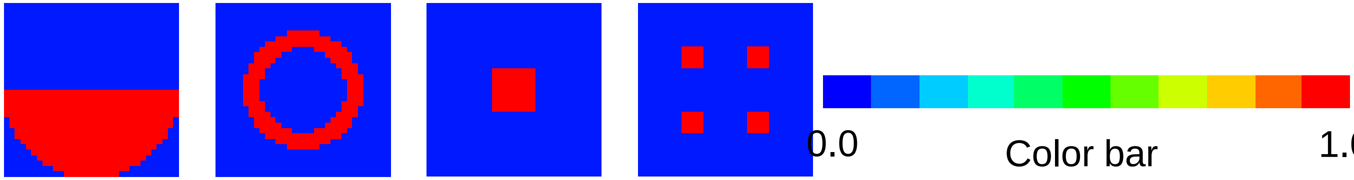
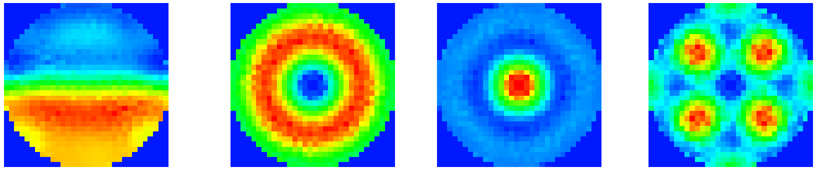
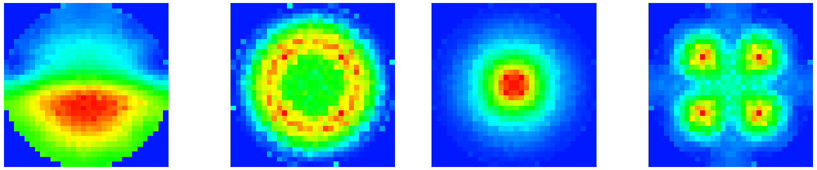


Fig. Pseudo particle images



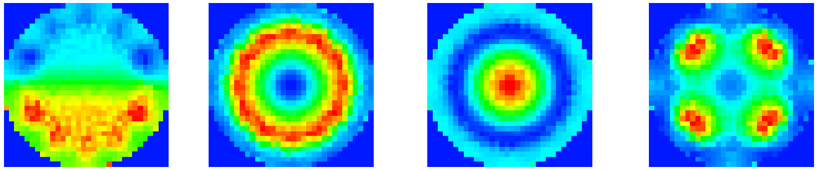
(a-1)Bottom(a-2)Annular(a-3)Center(a-4)Four-bulk

(a) Reconstructed image by Landweber



(b-1)Bottom(b-2)Annular(b-3)Center(b-4)Four-bulk

(b) Reconstructed image by Iterative Tikhonov

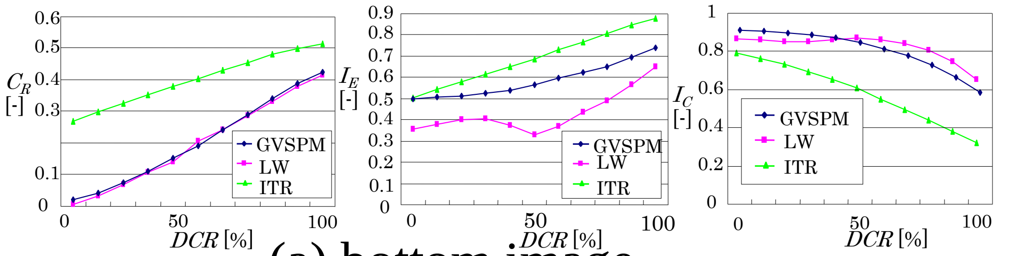


(c-1)Bottom(c-2)Annular(c-3)Center(c-4)Four-bulk

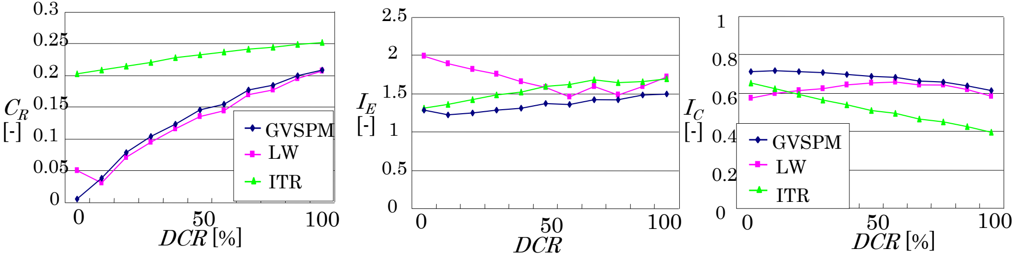
(c) Reconstructed image by GVSPM

Fig. Reconstructed images of pseudo particle images

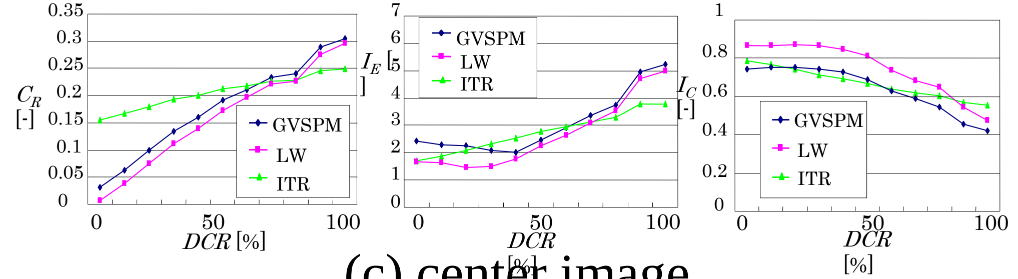
EVALUATION OF RECONSTRUCTION



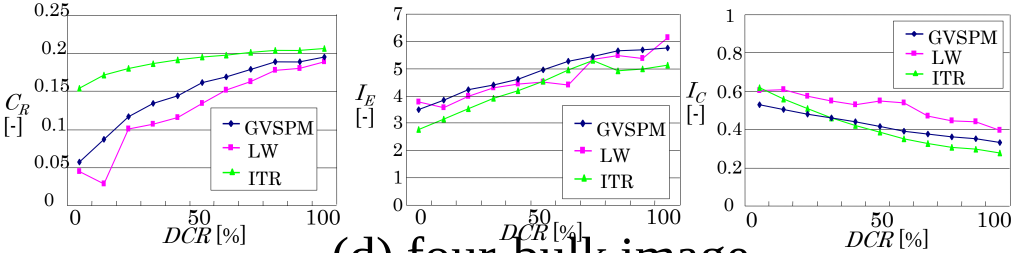
(a) bottom image



(b) annular image



(c) center image



(d) four-bulk image

C_R I_E I_C

Evaluation Method

Residual Capacitance C_R

$$C_R = \frac{\sqrt{\sum_{i=1}^{n}\left(c_i^{(k)} - c_i^{(0)}\right)^2}}{\sqrt{\left(\overline{\mathbf{C}^{(0)}}\right)^2}}$$

Image Error I_E

$$I_E = \frac{\sqrt{\sum_{i=1}^{m}\left(e_i^{(k)} - e_i^{original}\right)^2}}{\sqrt{\left(\overline{\mathbf{E}^{original}}\right)^2}}$$

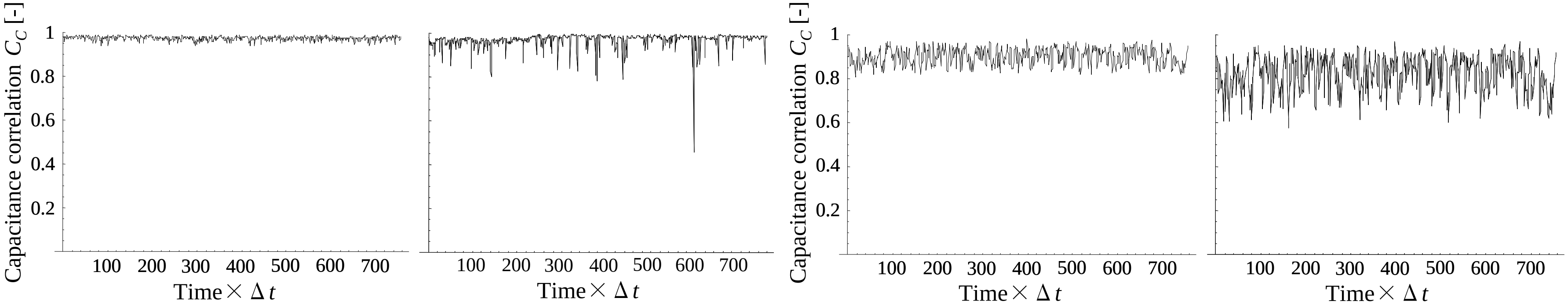
Image Correlation I_C

$$I_C = \frac{\sum_{i=1}^{m}\left[\left(e_i^{(k)} - \overline{\mathbf{E}^{(k)}}\right)\left(e_i^{original} - \overline{\mathbf{E}^{original}}\right)\right]}{\sum_{i=1}^{m}\sqrt{\left(e_i^{(k)} - \overline{\mathbf{E}^{(k)}}\right)^2}\sum_{i=1}^{m}\sqrt{\left(e_i^{original} - \overline{\mathbf{E}^{original}}\right)^2}}$$

High accuracy reconstructed images

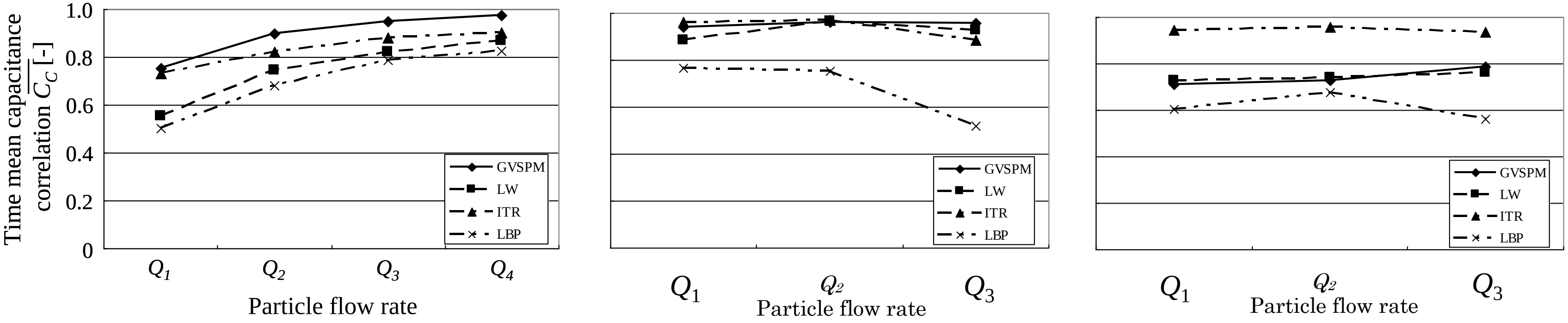
low C_R low I_E high I_C

CORRELATION OF CAPACITANCE



GVSPM **LW** **ITR** **LBP**

Fig. Correlation of capacitance for polyethylene pellet (Particle flow rate: Q_4)



(a) Polyethylene Pellet (PP) **(b)** Silica Particle (SP) **(c)** Polyvinyl Chloride (PVC)

Fig. Time mean correlation of capacitance

STATIC ACCURACY TEST

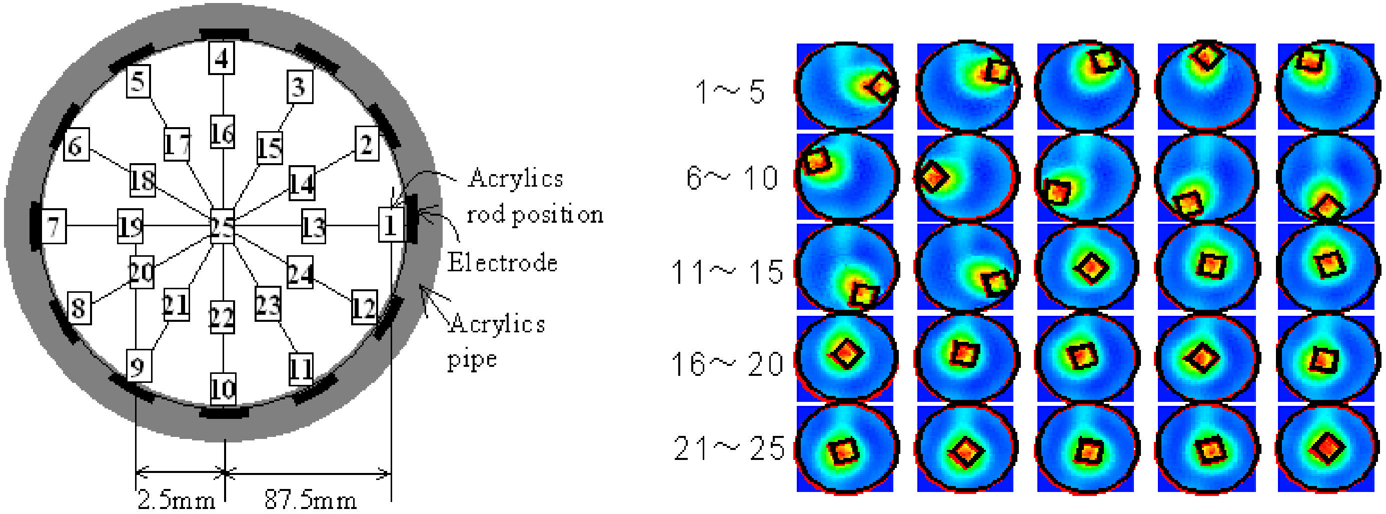
M.Takei et al.,*Powder Technology, Elsevier,* (2004)

Test Rod: Acrylic rod 500mm (L) × 60mm (W) × 60mm (H)

Permittivity : 2.8

Experiment: PTL300E Electrical capacitance tomography system
Process Tomography Ltd.

Input voltage: 15V (1.25 MHz)



(a) Positions of test rod (b) Reconstructed images by LBP

Fig. Static accuracy of CT sensor

CONTENTS

- PTの概要　ソフトフィールドとハードフィールド
- ソフトフィールドPT
  - 電気PTの原理
  - プラントへの展開
  - 血流への展開
  - マイクロ流路への展開
- ハードフィールドPT
  - Optical CT
  - X ray CT
  - γ ray CT
  - Neutron Radiography
  - Ultrasound CT
  - MRI
  - Positron Emission Tomography (PET)
- まとめ

①ECTの例　②ERTの例
③温度分布計測の例

Circulating Fluidized Bed (Downer)

High demand of sulfur free & high-octane gasoline

FCC (fluid catalytic cracking) gasoline

Residual oil + FCC catalysts in CFB
(Circulating Fluidized Bed)

Key factor of high quality
Uniform concentration of FCC powder in CFB

Fig. FCC catalysts

1-2 μm zeolites dispersed on an amorphous silica-alumina forming 60 μm powders

Nondestructive visualization technique in pipe cross section

Comparison with Previous Study

H. Zhang et al., *Chemical Engineering Science*, 1999

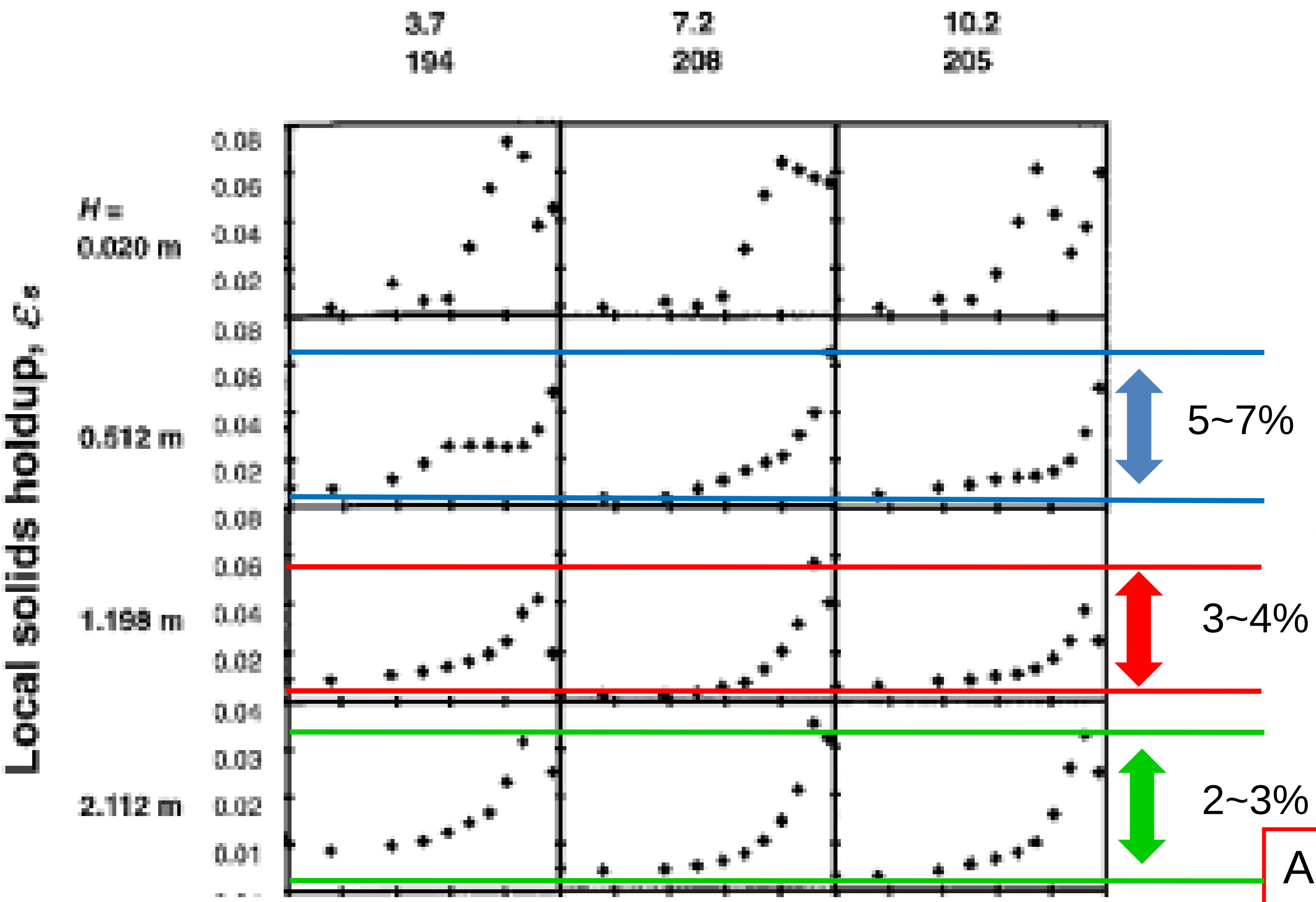
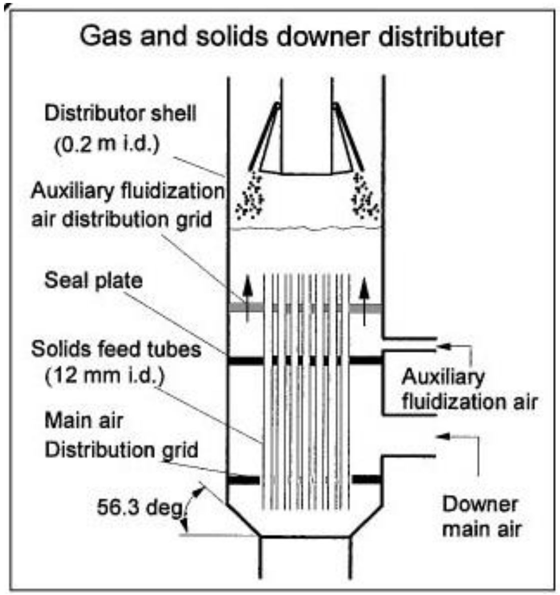


Fig. Radial solids holdup profiles along the downer



A non-uniform distribution is clearly seen near the entrance of the CFB in conventional distributor.

Experimental Setup

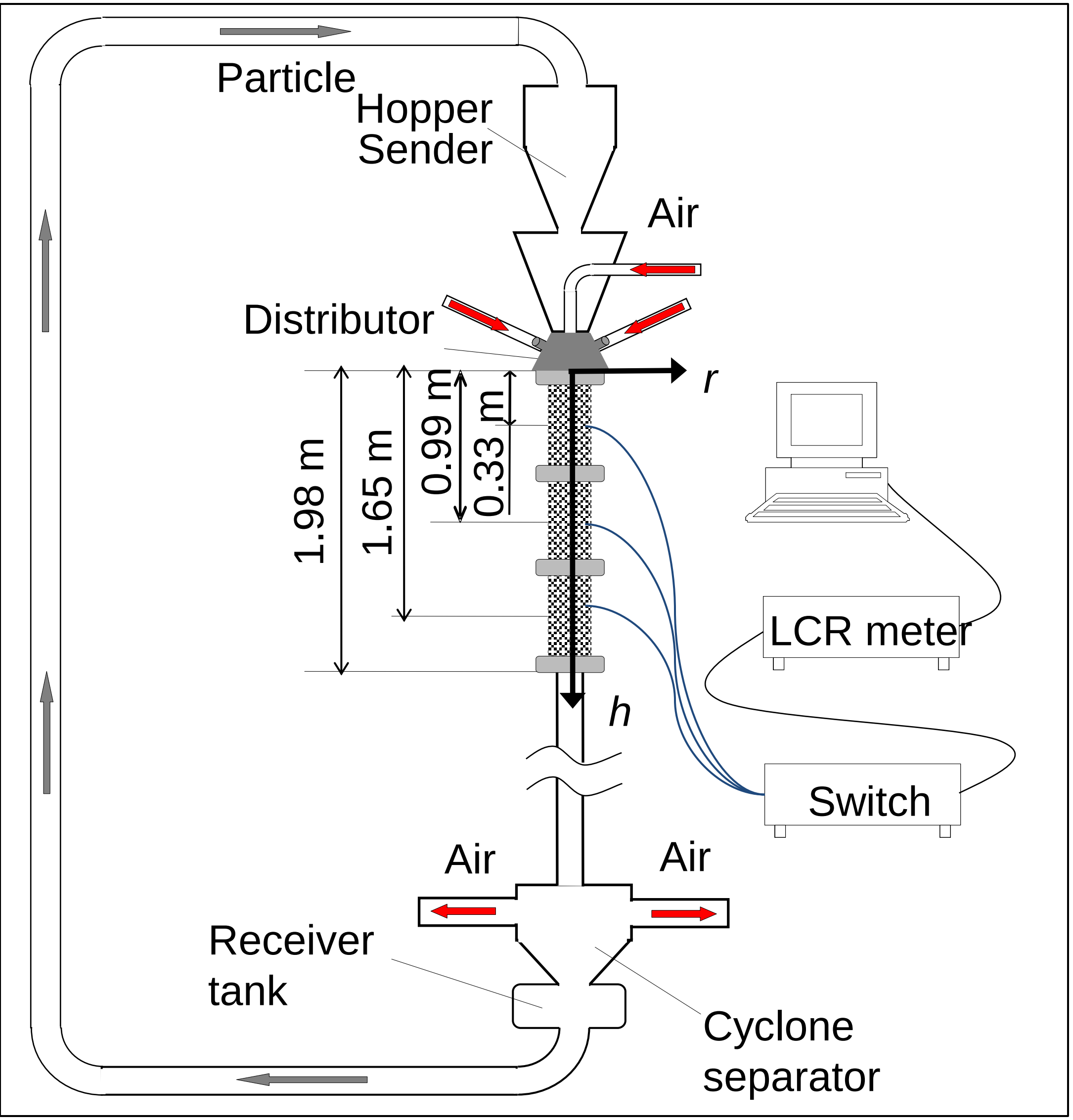


Fig. Experimental Setup

Pipe I.D:	270mm
Total Height:	5.3m
Sensor length :	660mm
Particle:	MFI-type zeolite
Particle Density:	1200 [kg/m^3]
Particle diameter:	69.6 μm
Sampling time:	10ms/one frame

PT(ECT)による循環流動層濃度分布可視化計測

M.Takei et al. *Powder Technology* (2009)
M.Takei, et al., *Experiments in Fluids, Springer,* (2008)

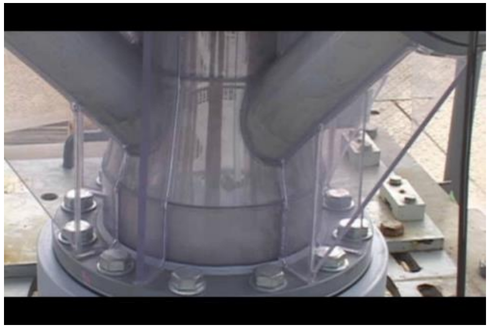
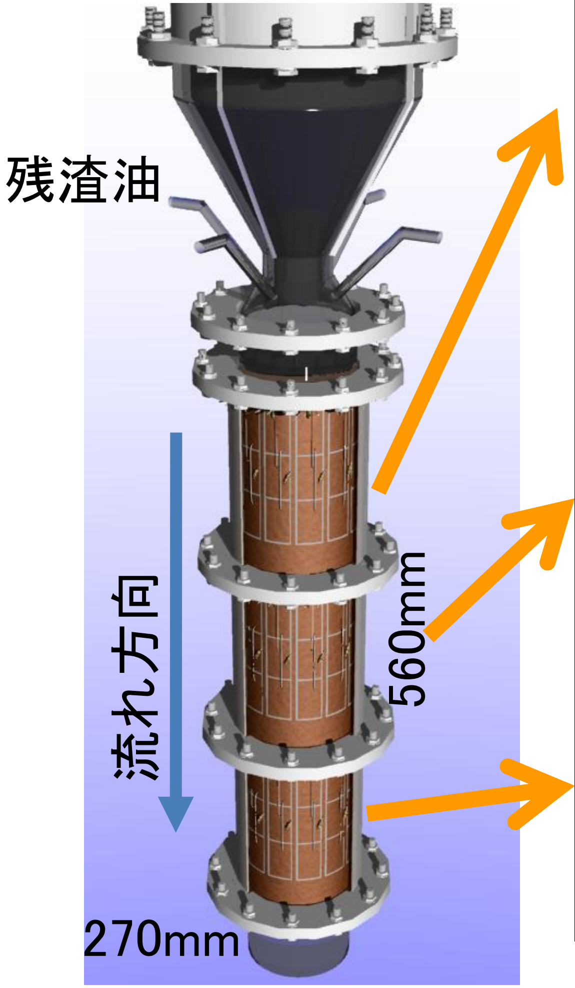
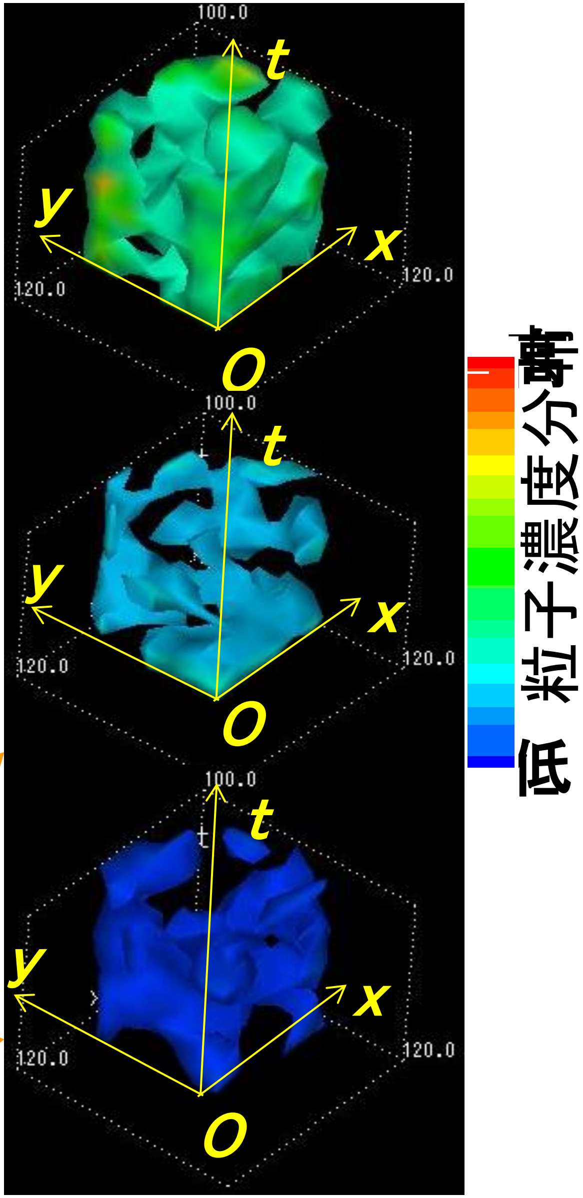


Fig. FCC 循環流動層テストプラント

FCC 触媒粒子



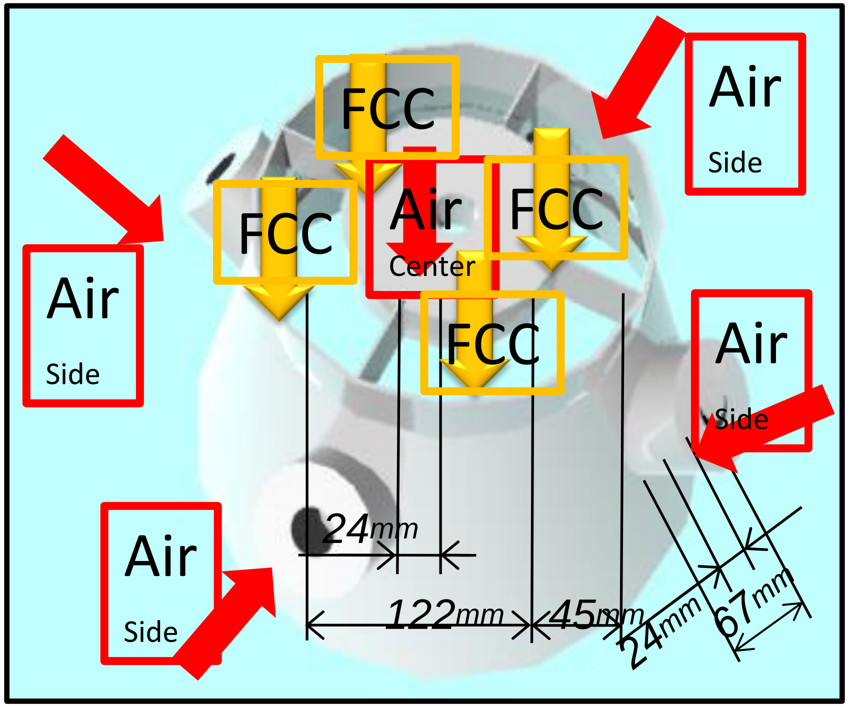
大口径のPTセンサ



粒子の3D拡散現象

New Designed Distributor & Experimental Conditions

T.Zhao, M.Takei, *Flow Measurement and Instrumentation*, 2007
Tong Zhao, Masahiro Takei, et al., *Powder Technology,* (2011)



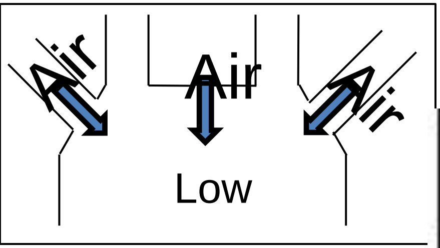
Center : Side = 1:4
(Ratio of Air flow rate)

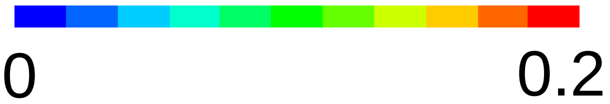
Fig. New designed distributor

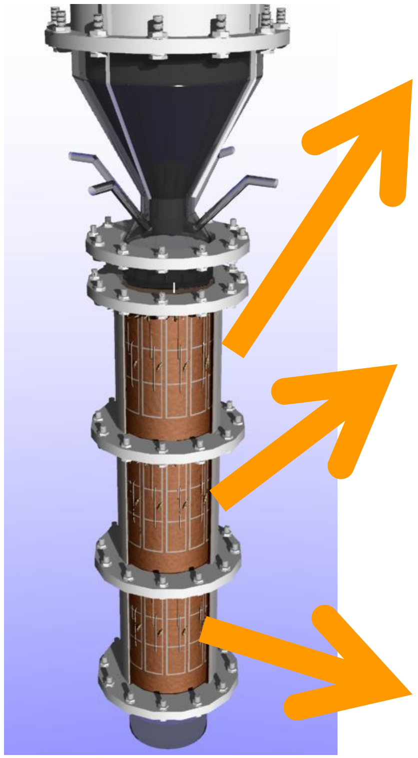
Table Experimental condition

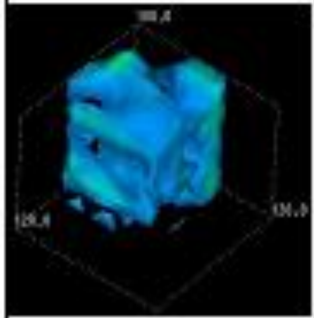
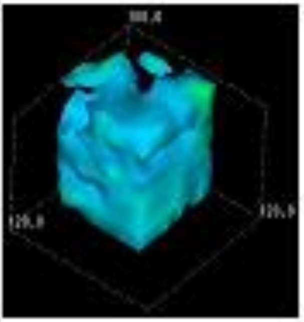
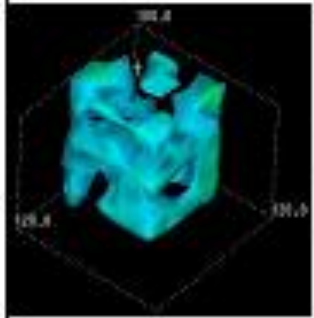
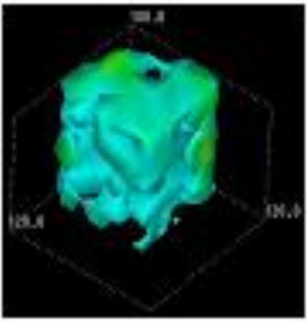
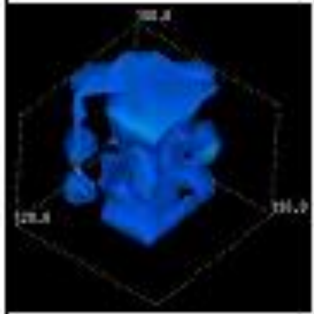
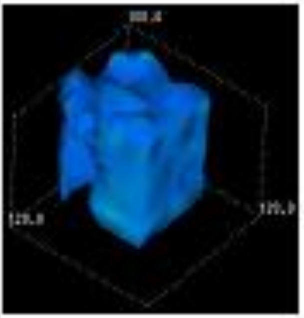
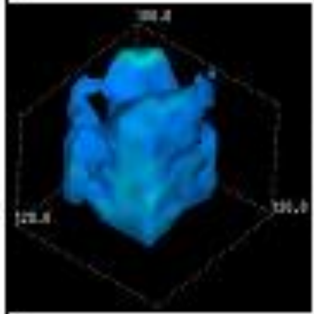
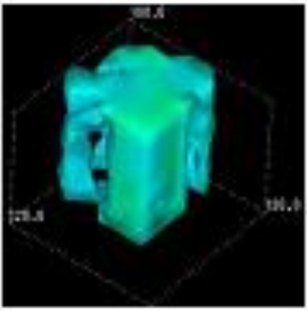
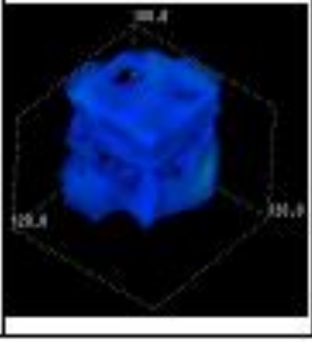
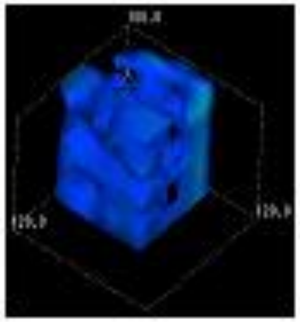
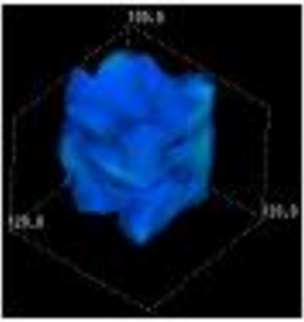
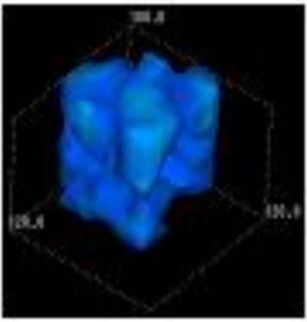
		Case 1.1	Case 1.2	Case 1.3	Case 1.4
Powder circulation rate (particle flow rate) G_s [kg/m^{2}s]		175	233	292	349
Center: Side 1:4	Air flow rate of center nozzle Q_{ac} [m^3/s]	0.094			
	Total air flow rate of side nozzle Q_{as} [m^3/s]	0.378			

Time Mean Reconstructed Images (Centre : Side =1:4)

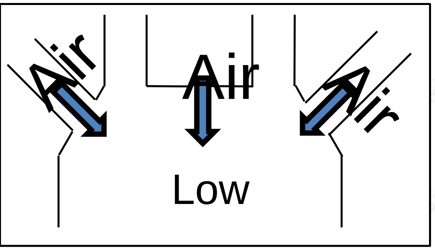


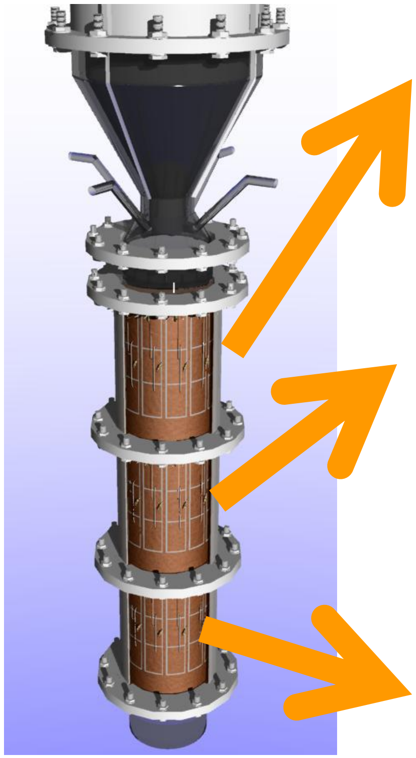


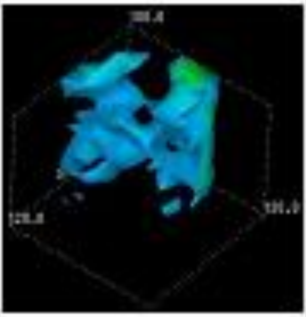
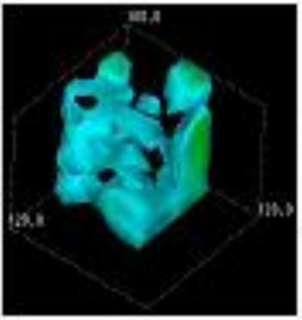
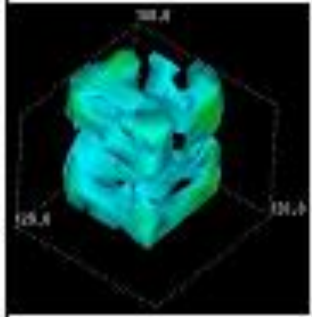
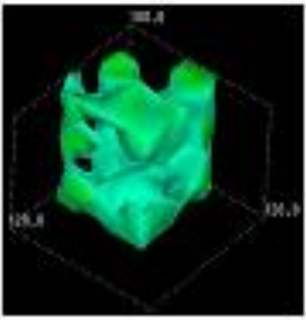
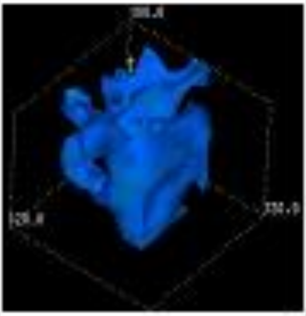
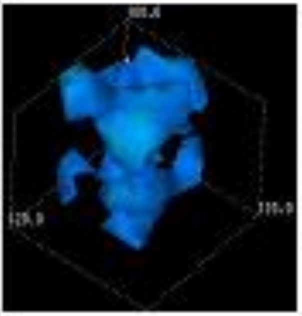
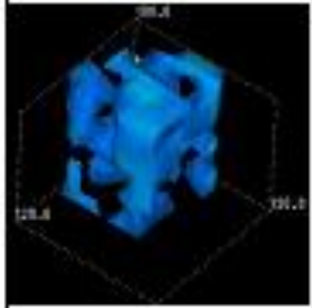
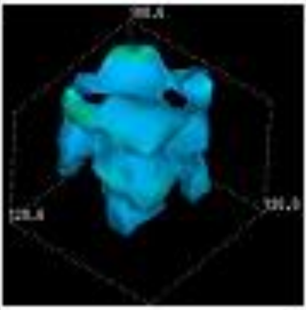
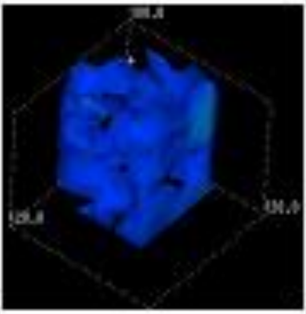
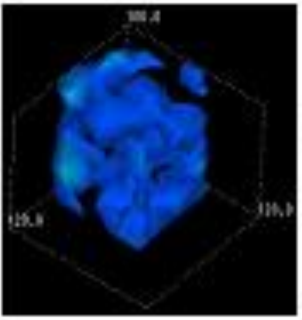
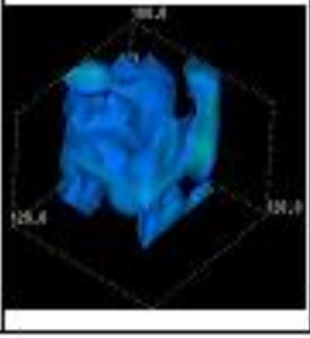
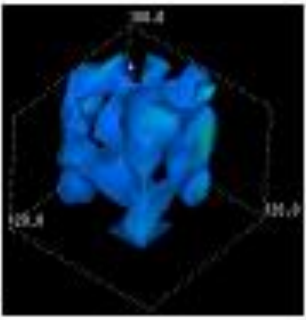


Sensor position	Case1.1	Case1.2	Case 1.3	Case 1.4
h=0.33m				
h=0.99m				
h=1.65m				

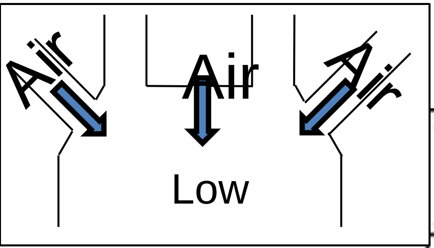
Time Mean Reconstructed Images (Centre : Side =1:2)

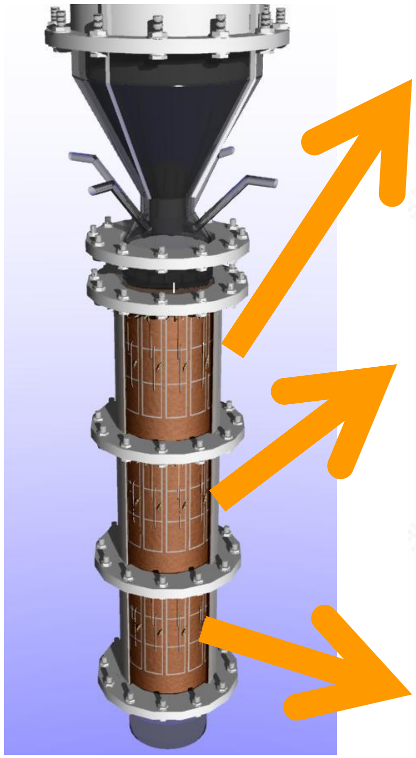


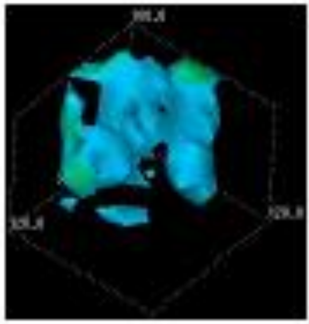
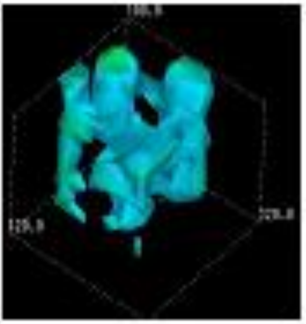
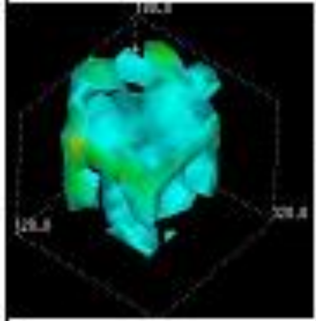
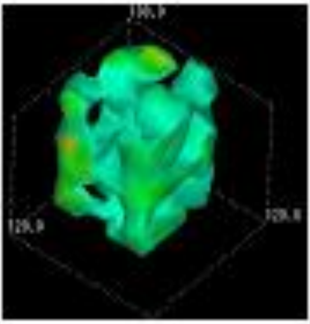
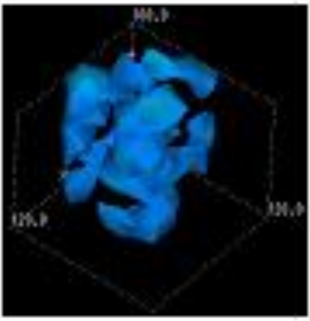
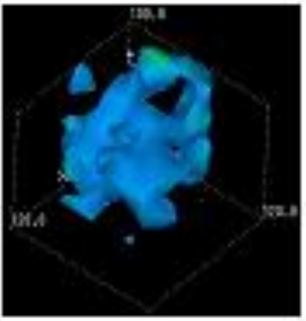
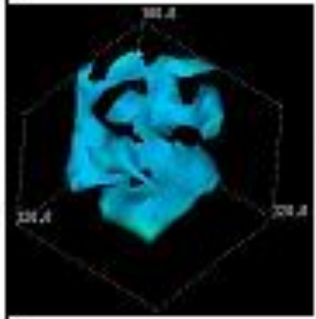
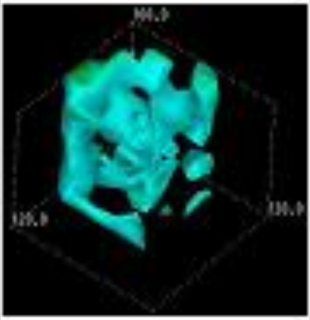
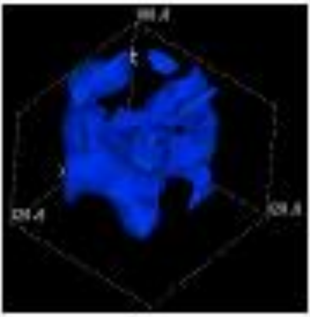
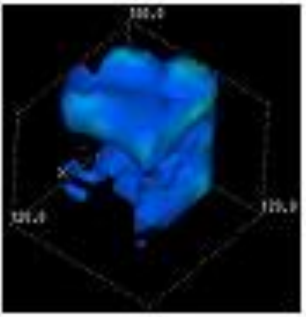
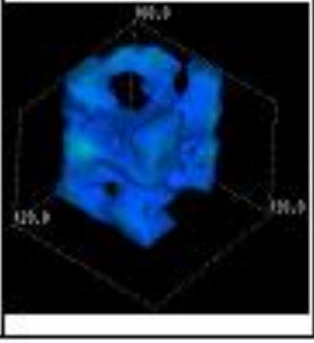
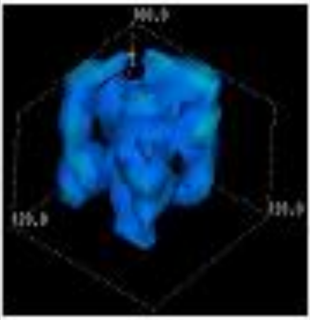


Sensor position	Case1.1 Case 1.4	Case1.2	Case 1.3	
h=0.33m				
h=0.99m				
h=1.65m				

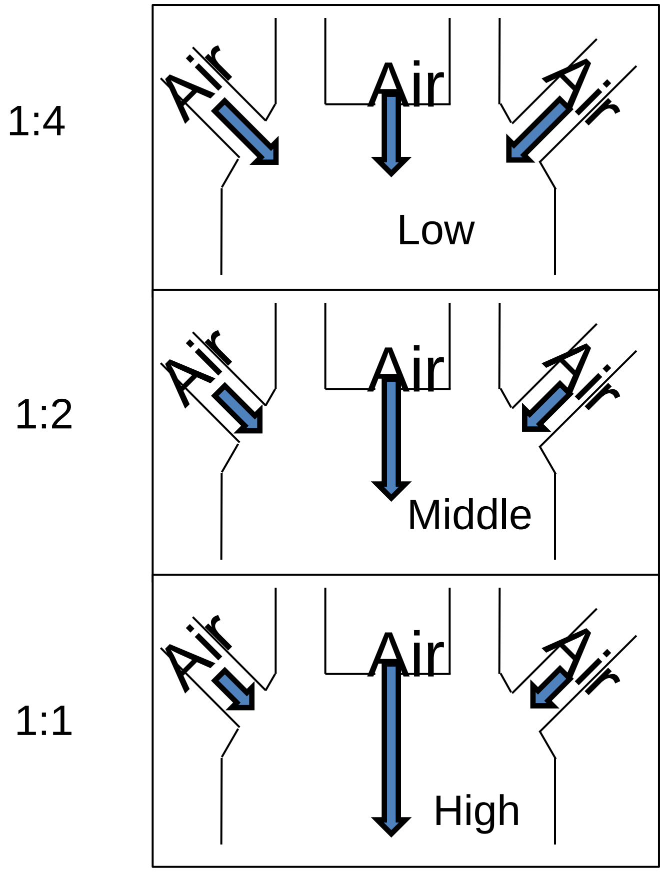
Time Mean Reconstructed Images (Centre : Side =1:1)

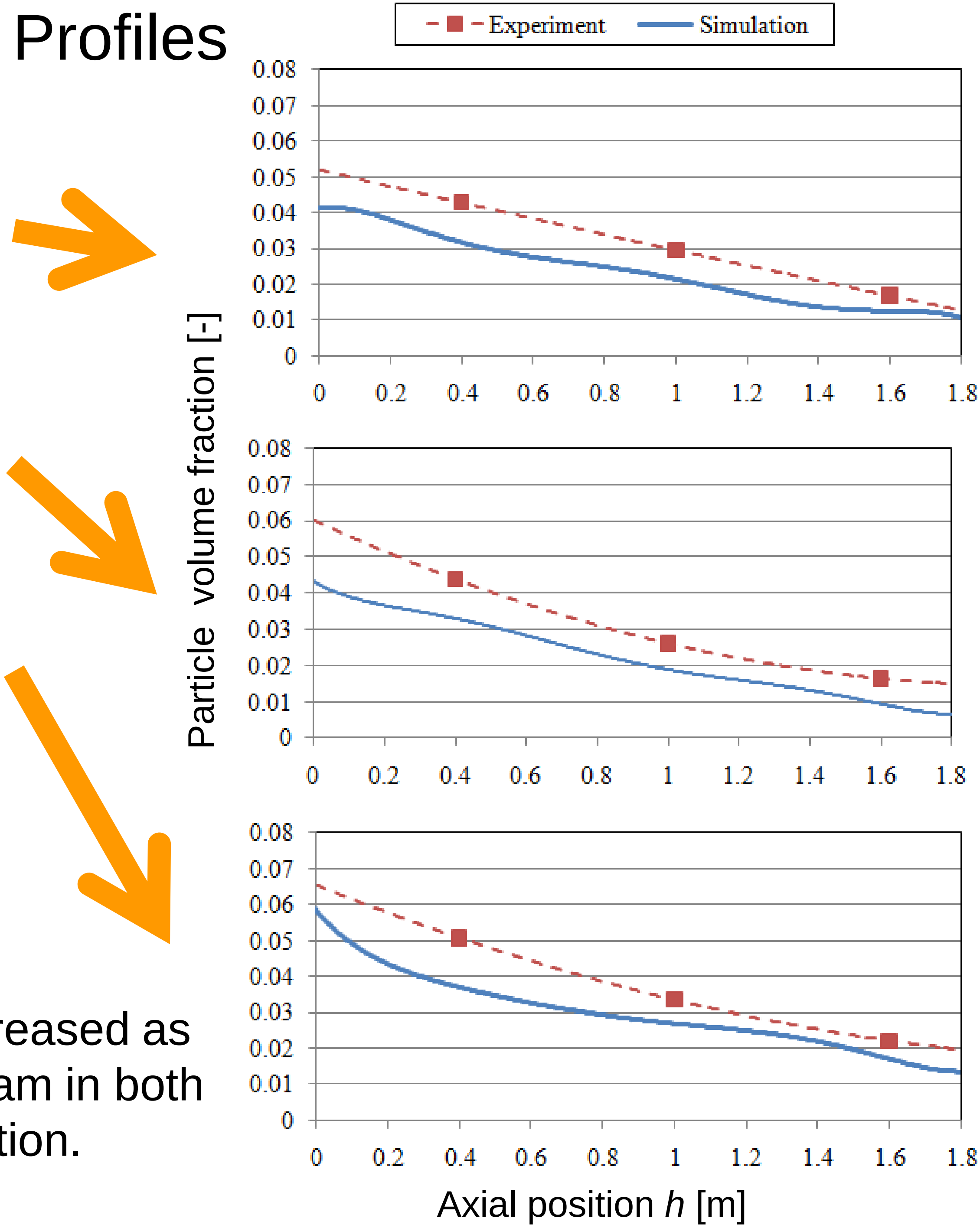




Sensor position	Case1.1	Case1.2	Case 1.3	Case 1.4
h=0.33m				
h=0.99m				
h=1.65m				

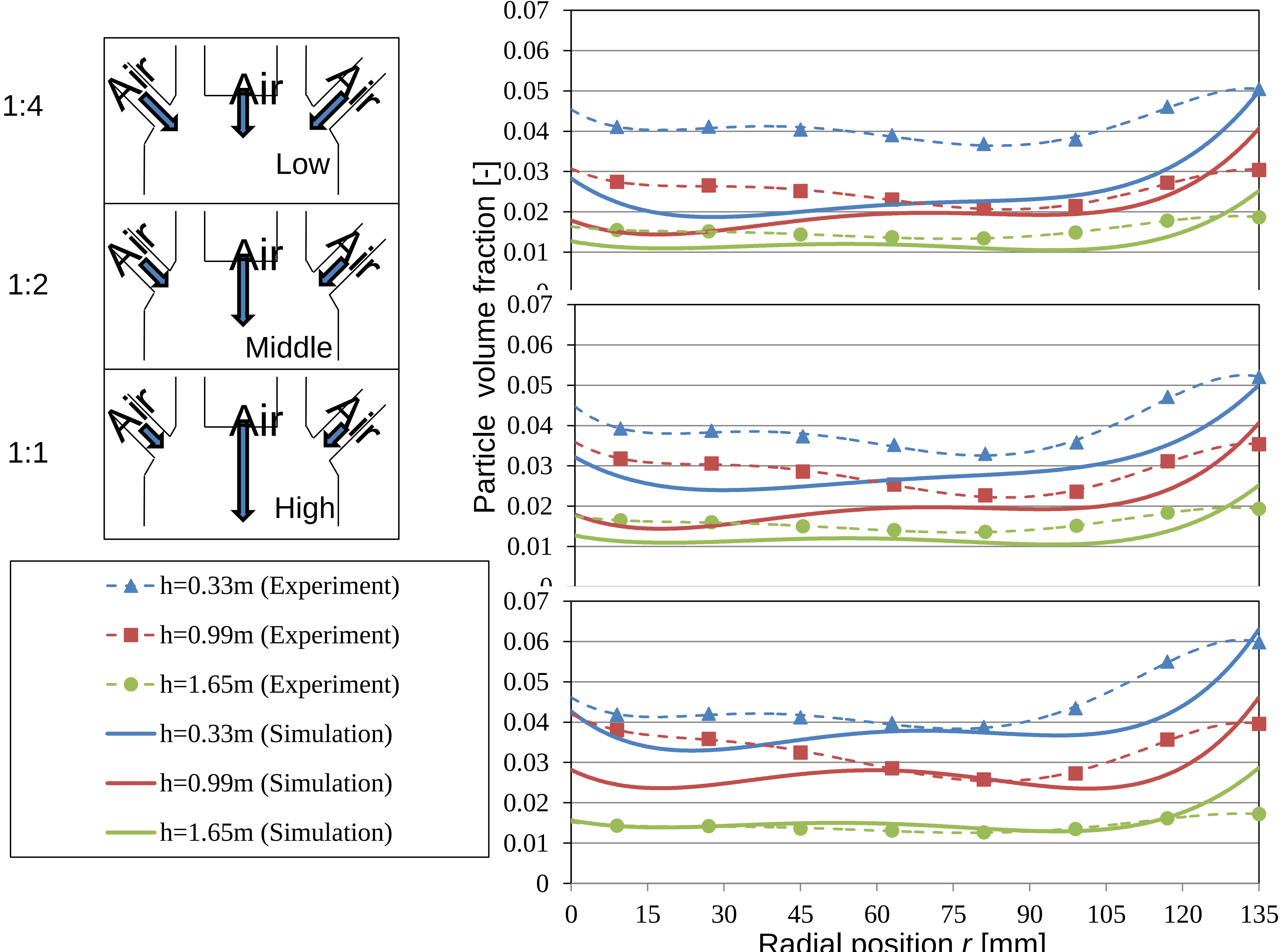
Axial Volume Fraction Profiles



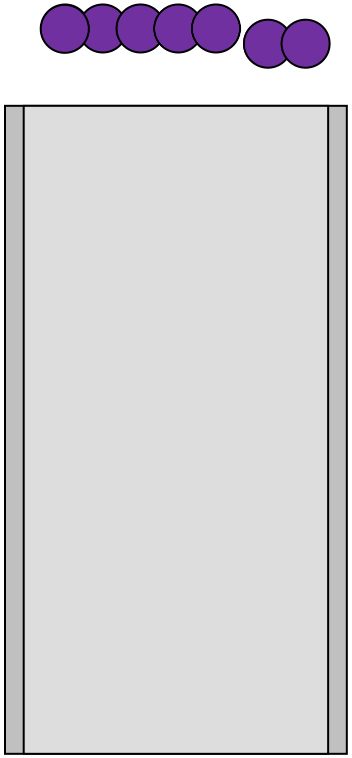


Particle volume fraction decreased as axial position goes downstream in both experiment and simulation.

Radial Volume Fraction Profiles



Discussion to Axial Profiles



First acceleration section ($V_p < V_a$)

Second acceleration Section ($V_p > V_a$)

Constant velocity section (V_p = constant)

Z. Wang et al. (1992)

$$Q_p = A \times V_p \times \alpha$$

$$Q_a = A \times V_a \times (1 - \alpha)$$

$$\frac{Q_p}{Q_p + Q_a} = \frac{\alpha\beta}{\alpha\beta + (1 - \alpha)} \qquad \left(\beta = \frac{V_p}{V_a}\right)$$

Particle volume fraction

$$\alpha = \frac{Q_p}{Q_p + \beta Q_a}$$

α is inversely proportional to β.

A : Sectional area of pipe

Q_p : Particle flow rate

V_p : Particle velocity

Q_a : Air flow rate

V_a : Air velocity

α : Particle volume fraction

β : Slip velocity

Governing Equations & Fluid Drag Force

Solid phase (Discrete phase)

$$m\frac{dv}{dt} = F_a + F_c + G$$

$$I\frac{d\omega}{dt} = T$$

Gas phase (Continuum phase)

$$\frac{\partial \varepsilon}{\partial t} + \nabla \cdot (\varepsilon u) = 0$$

$$\frac{\partial(\rho_g \varepsilon_g \mathbf{u})}{\partial t} + \nabla \cdot (\rho_g \varepsilon_g \mathbf{uu}) = -\varepsilon_g \nabla p + f_{a,i} + \varepsilon_g (\mu + \mu_e) \nabla^2 \mathbf{u}$$

Drag force

$$f_{a,i} = \frac{\beta}{\rho_g}(v_{pi} - u_i), \quad \mathrm{Re} = \frac{\left|\overrightarrow{v_p} - \vec{u}\right| \rho \varepsilon d_p}{\mu}$$

$$\beta = \begin{cases} \dfrac{\mu(1-\varepsilon)}{d_p^2 \varepsilon}\left[150(1-\varepsilon) + 1.75 R_e\right] & (\varepsilon \le 0.8) \\ \dfrac{3}{4} C_D \dfrac{\mu(1-\varepsilon)}{d_p^2} \varepsilon^{-2.7} R_e & (\varepsilon > 0.8) \end{cases}$$

Ergun's equation, 1952

Wen and Yu's equation, 1966

$$C_D = \begin{cases} 24(1 + 0.15\,\mathrm{Re}^{0.687}) \big/ \mathrm{Re} & (\mathrm{Re} \le 1000) \\ 0.43 & (\mathrm{Re} > 1000) \end{cases}$$

m : Mass of the particle, v : Translational velocity, ω : Rotational velocity, P : Pressure,
I : Moment of inertia, F_a : Force acting on particle exerted by surrounding air,
F_c : Contact force, G : Gravitational force, u : Velocity vector of air,
T : Torque caused by the contact force and the moment of inertia of particle,
ε : Volume fraction, ρ_g : Density of air, μ : Fluid viscosity, μ_e : Eddy viscosity ,
C_D : Drag coefficient for a single particle, d_p : Particle diameter, v_p : Particle velocity

Contact Force

Normal contact force

$$F_{cn} = k_n \Delta x_n - \eta_n \frac{dx_n}{dt}$$

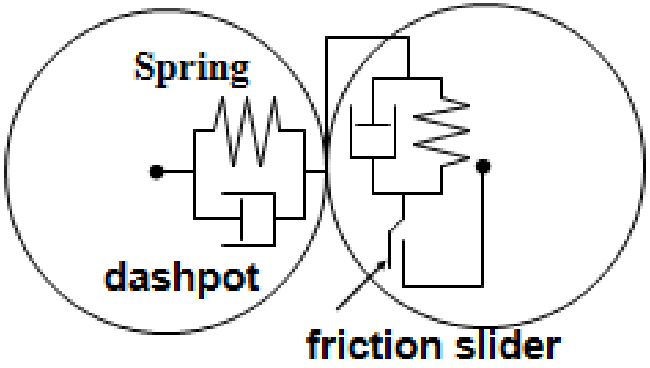


Fig. Models of contact force

Cundall and Strack 1979

Tangential contact force

$$F_{ct} = k_t \Delta x_t - \eta_t \frac{dx_t}{dt} \quad if \quad |F_{ct}| \le \mu_f |F_{cn}|$$

$$F_{ct} = \mu_f |F_{cn}| \frac{x_t}{|x_t|} \quad if \quad |F_{ct}| > \mu_f |F_{cn}|$$

k_n & k_t : Stiffness of the springs in the normal and tangential direction

η_n & η_t : Coefficient of viscous dissipation in the normal and tangential direction

x_n & x_t : Particle displacement in the normal and tangential direction

μ_f : Friction coefficient.

Turbulence Model —— Standard k-ε Model

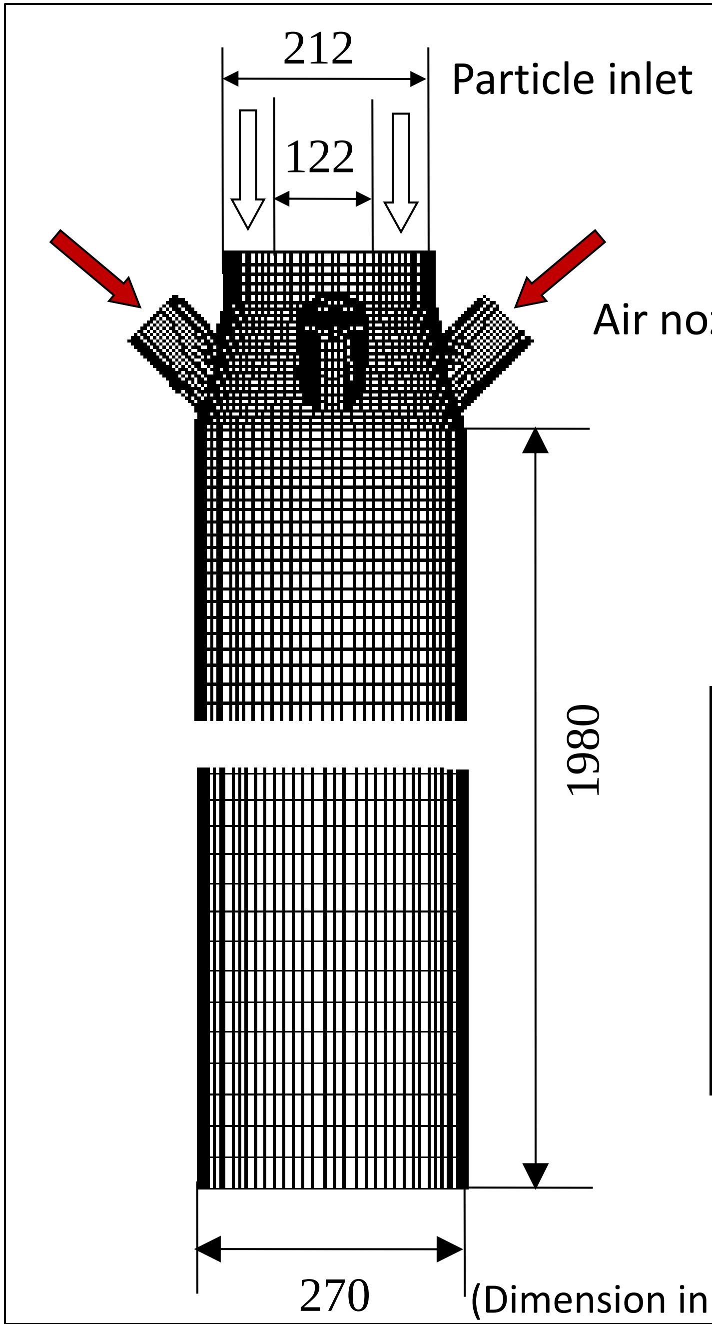
Simulation Conditions

T. Zhao and M.Takei, *Advanced Powder Technology, Elsevier,* (2008)
T.Zhao and M.Takei, *Powder Technology, Elsevier,* (2010)

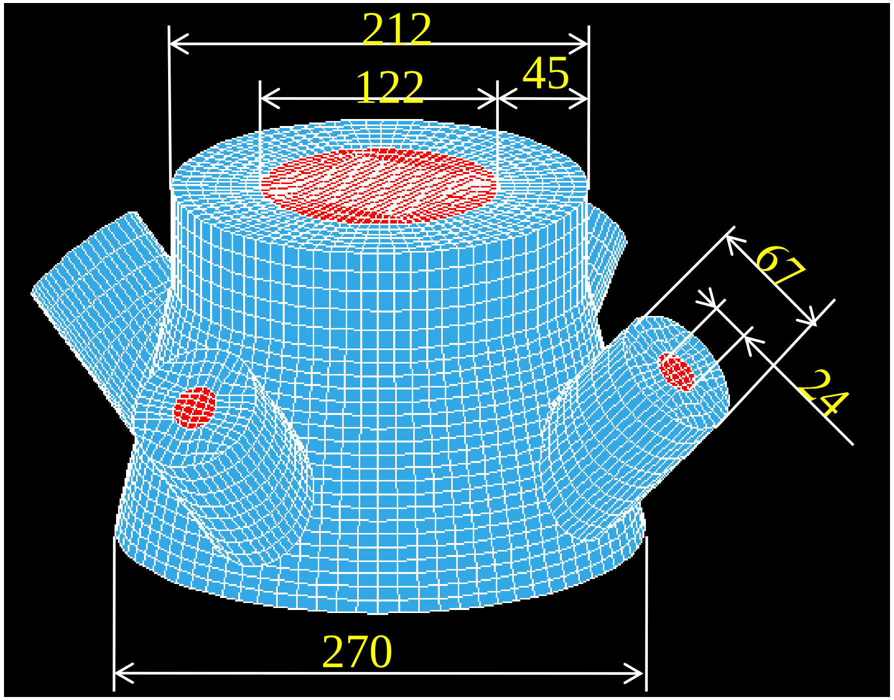
Gas phase		Particle phase	
Fluid type	Air	Particle shape	spherical
Density(kg/m^3)	1.2	Density(kg/m^3)	1200
Bed geometry(m)	0.27 (diameter)	Particle diameter(mm)	0.3
	1.98(height)	Number of particles	328400
Superficial velocity (m/s)	20	Spring constant (N/m)	800
Viscosity(kg/ms)	2.0×10^{-5}	Friction coefficient	0.3
Acceleration of gravity (m/s^2)	9.8	Time step (s)	10^{-4}

Time step
$$\Delta t = \frac{2}{5}\pi\sqrt{\frac{(\pi d_p)^3 \rho_p}{6k_n}}$$
(Y. Tsuji et al. 1992)

Calculation Domain and Calculation Results



(Dimension in mm)



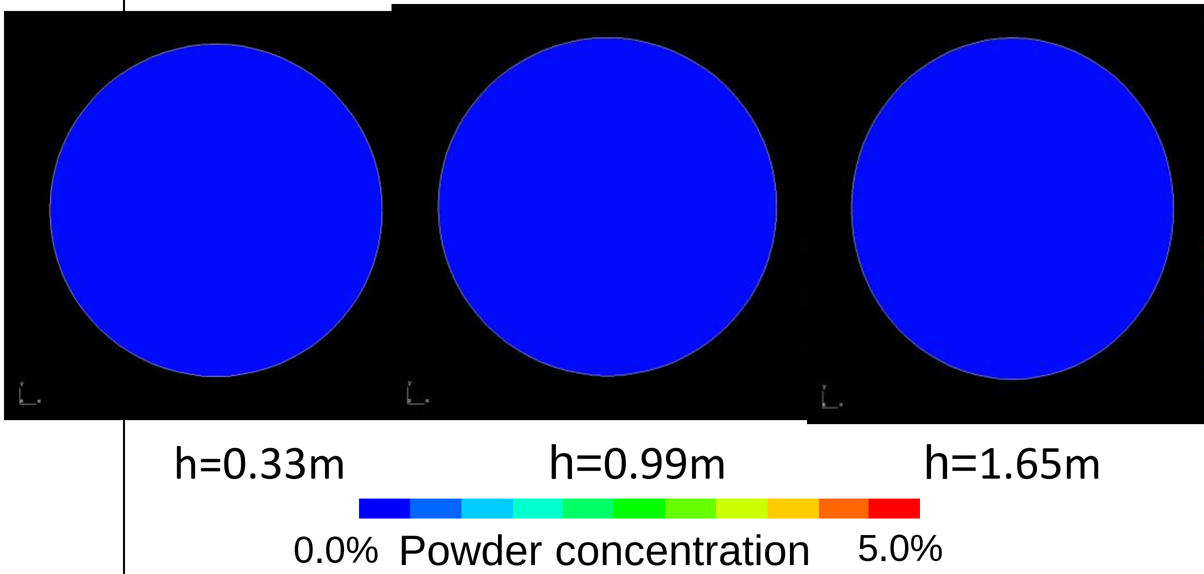
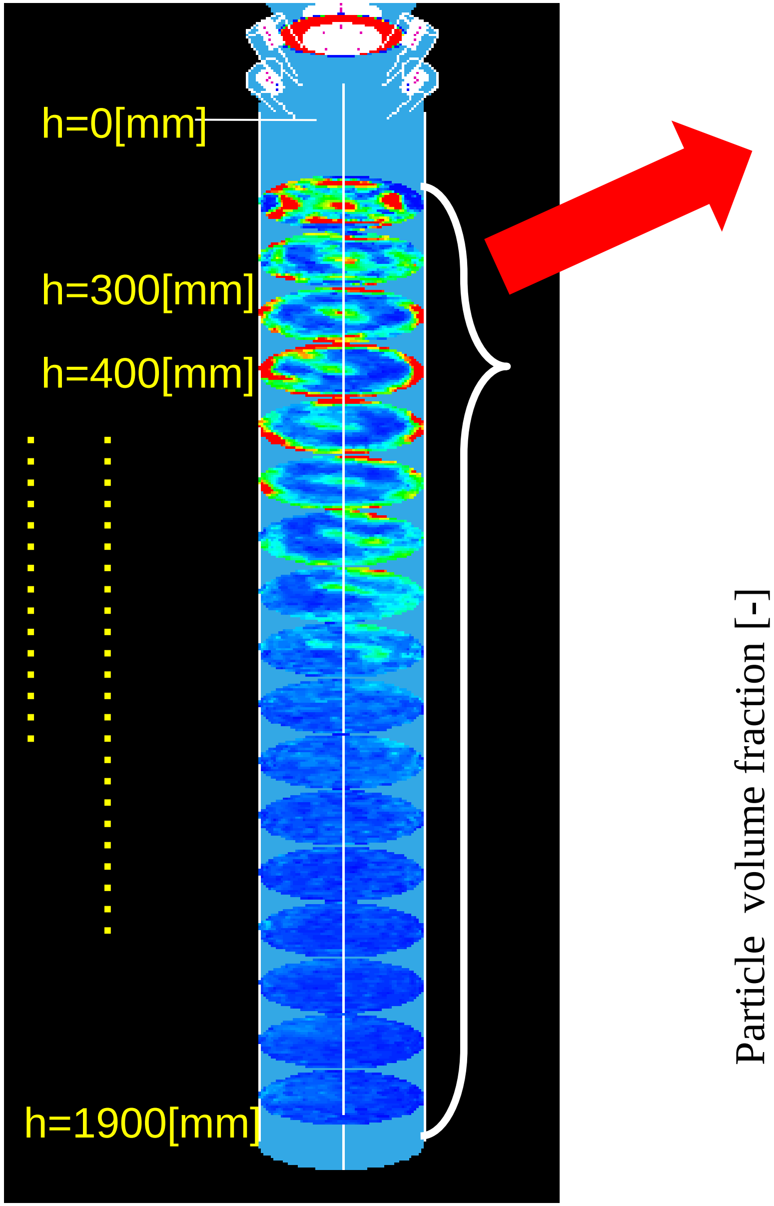


Fig. Simulation results of axial position

Calculated Profiles of Axial & Radial Volume Fraction

T.Zhao, M.Takei,. *Flow Measurement and Instrumentation,* (2010)

T.Zhao, and M.Takei et al., *Advanced Powder Technology, Elsevier,* (2010)



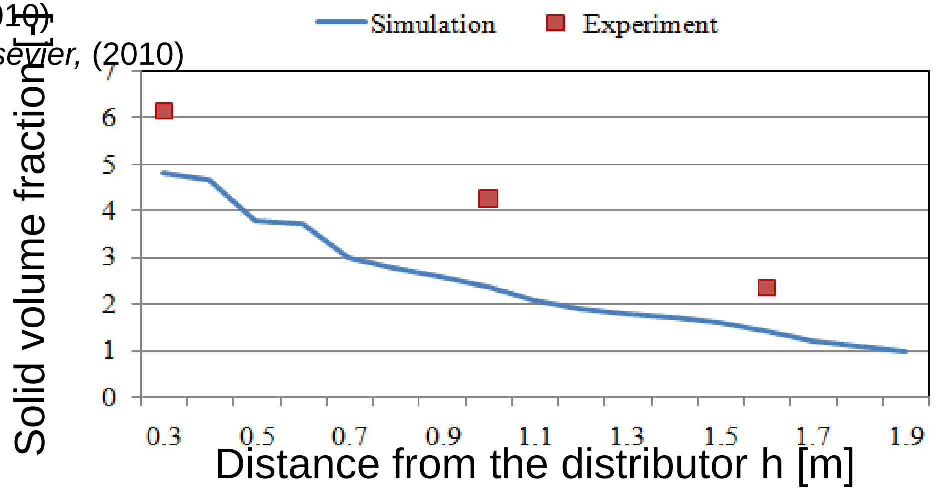


Fig. Profiles of axial volume fraction

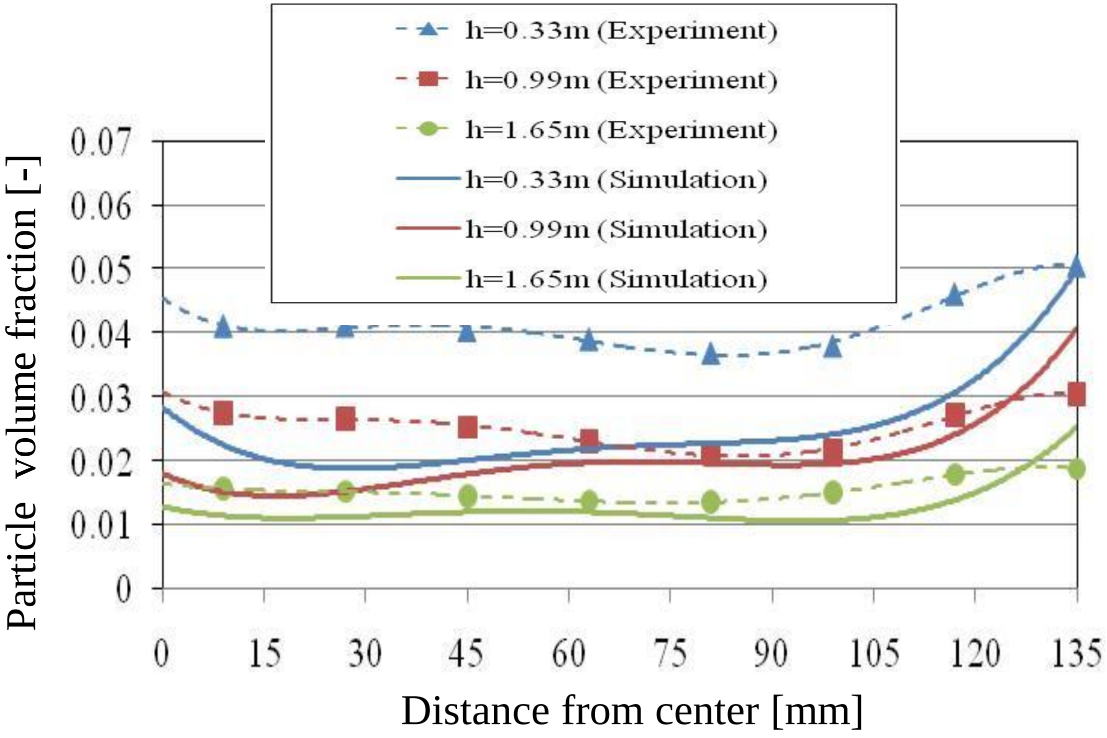


Fig. Profiles of radial volume fraction

COATING PROCESS IN DRUG PRODUCTION

Functional particle

Production by coating process

Nozzle spray of coating solvent to nucleus particles in fluidized bed

Dry of coating solvent around nucleus particles by hot air

Operational factors for uniform coating

Noninvasive monitoring technique to visualize the uniformity of particles fluidization during coating process

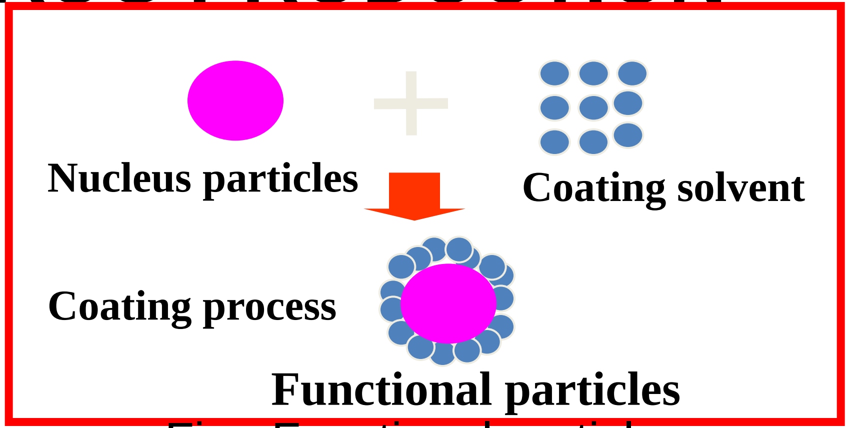


Fig. Functional particles

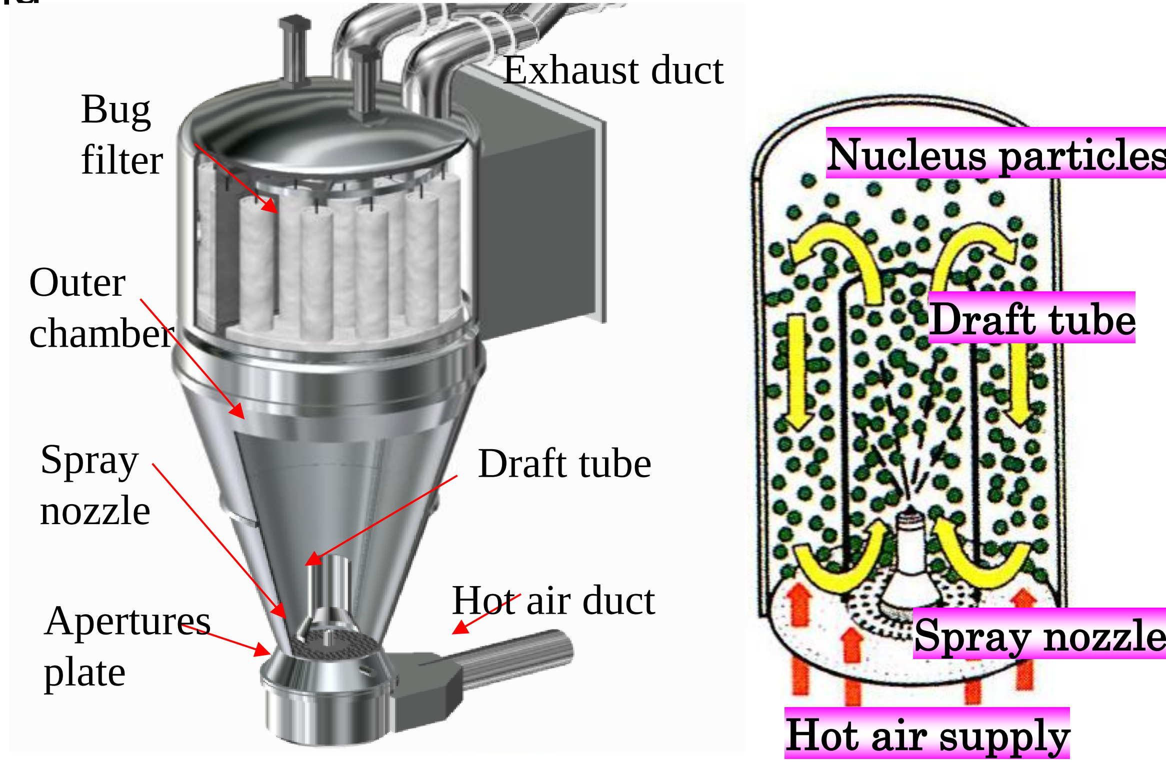
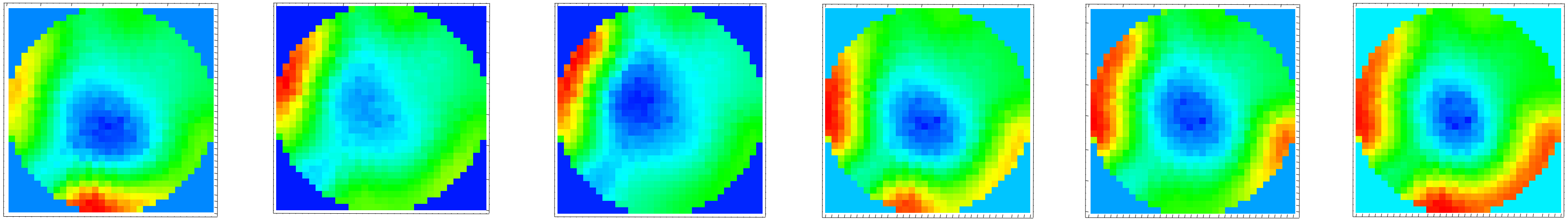


Fig. Coating process

INSTANTANEOUS CT IMAGES

Nucleus powder	Crystalline cellulose Asahi Kasei Corporation Celphia 203
Nucleus powder diameter	150μm
Density of powder	870 kg/m^3
Relative permittivity of Air	1.0006
Relative permittivity of Powder	2.1
Atomized coating liquid	HPC (Hydroxypropyl Cellulose) Shin-Etsu Chemical Co., Ltd.
Spray coating time	50 minutes
Sampling time	Every 5 minutes for several seconds



Spray time 0 min

Spray time 10 min

Spray time 20 min

Spray time 30 min

Spray time 40 min

Spray time 50 min

Fig. Instantaneous CT Images at each spray time

The high concentration particle distribution is located near the tube

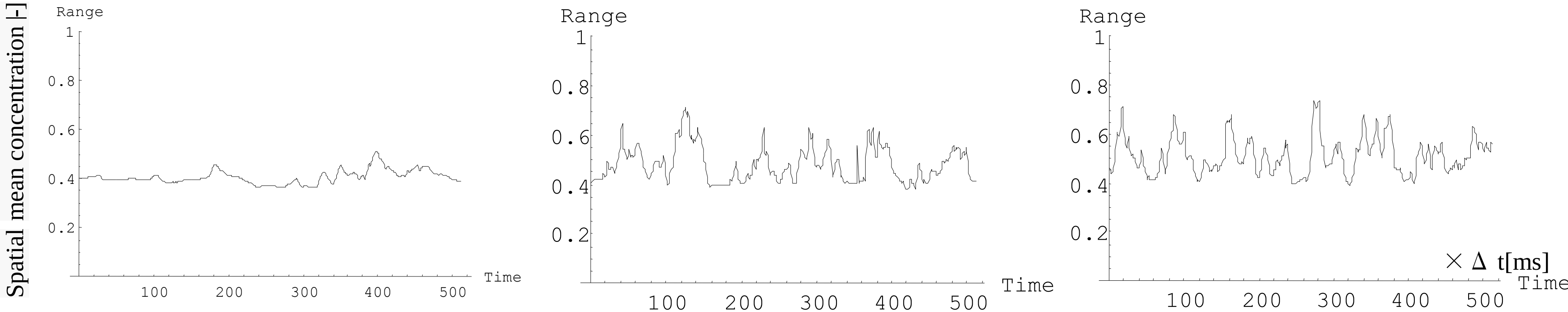
SPATIAL MEAN CONCENTRATION FROM IMAGE

M.Takei, et al.,*Powder Technology, Elsevier,* (2009)

The spatial mean particle concentration at a time point

$$\overline{D_p}(t)=\frac{1}{\left(N_x N_y - N_{out}\right)}\sum_{y=1}^{N_y}\sum_{x=1}^{N_x}\mathbf{E_{xyt}}$$

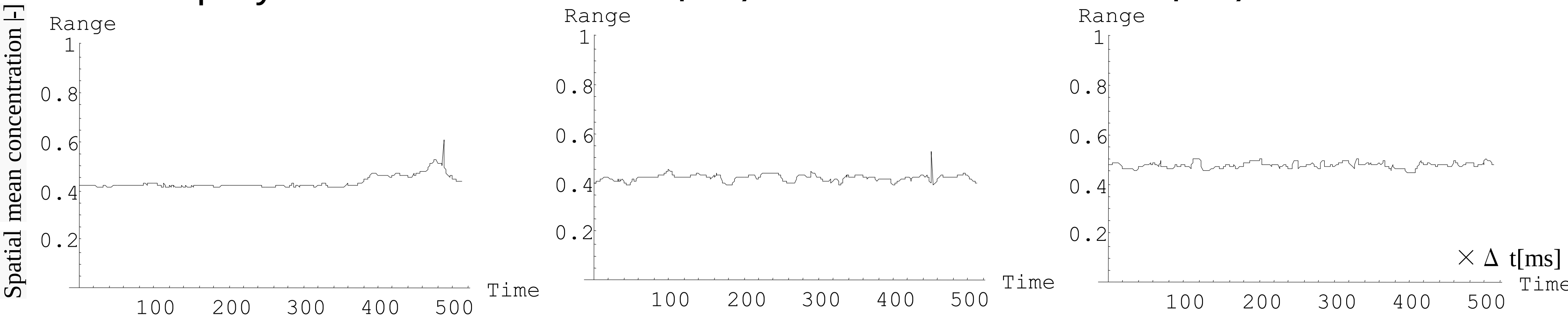
N_{out} : the pixel number outside the pipe



Spray time 0 min

Spray time 10 min

Spray time 20 min



Spray time 30 min

Spray time 40 min

Spray time 50 min

Fig. Spatial mean concentration from CT images.

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  - MRI
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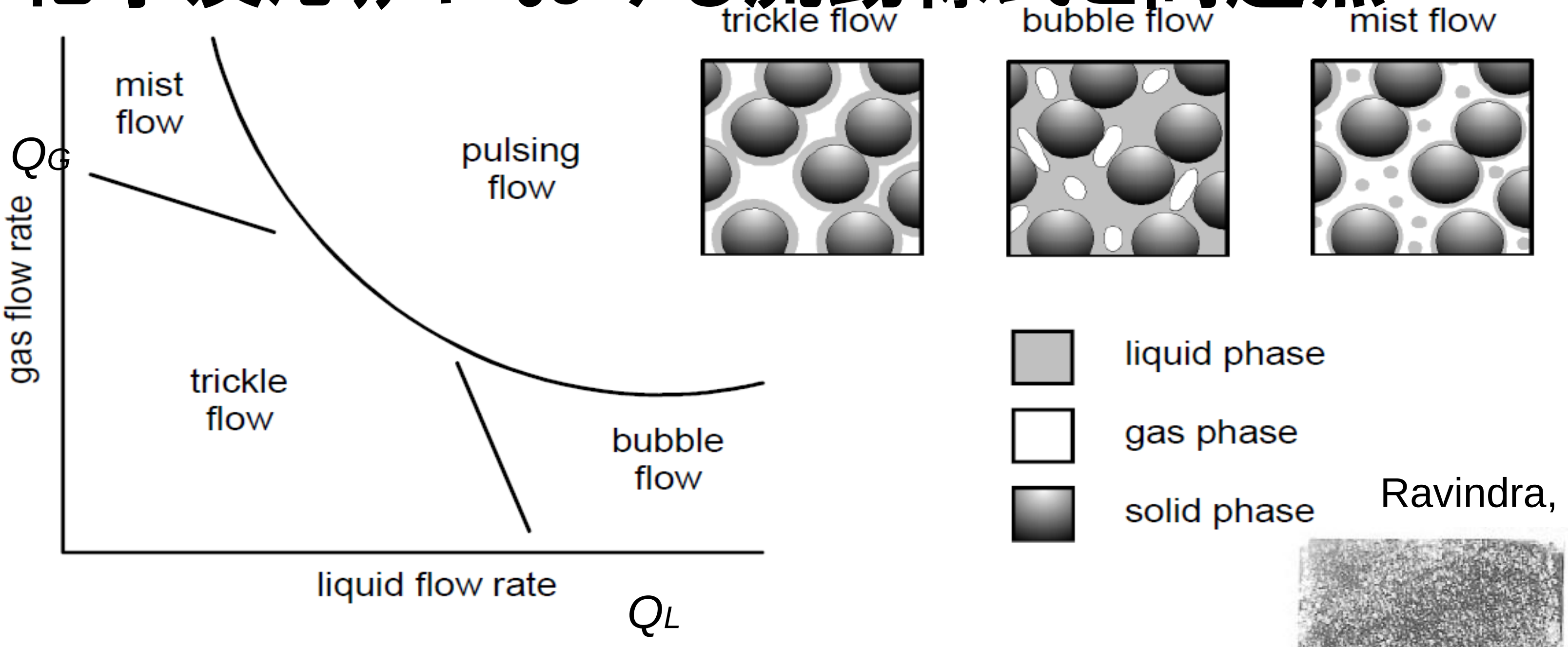
化学反応炉における流動様式と問題点



Ravindra, P.V. et al. (1997)

●問題点

液体の偏流（チャネリング）

- 反応効率の低下
- 反応熱の蓄積

Q_LとQ_Gに対する流動状態の把握が不十分

ー低パフォーマンス化

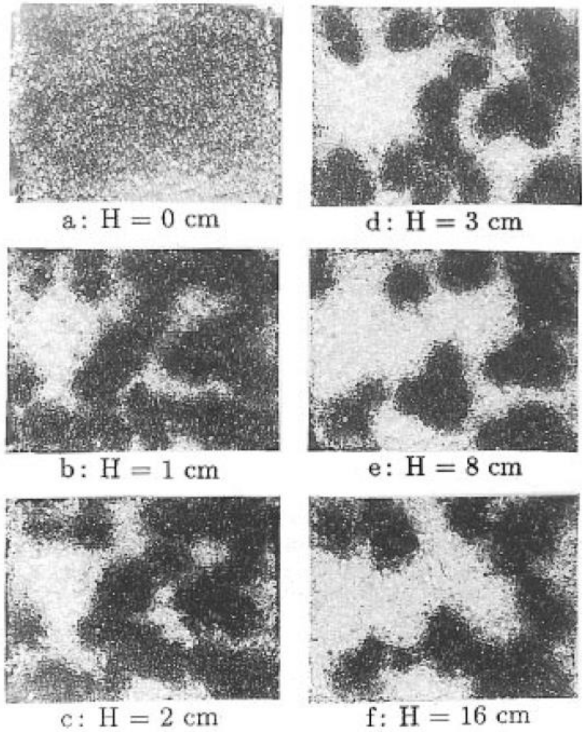
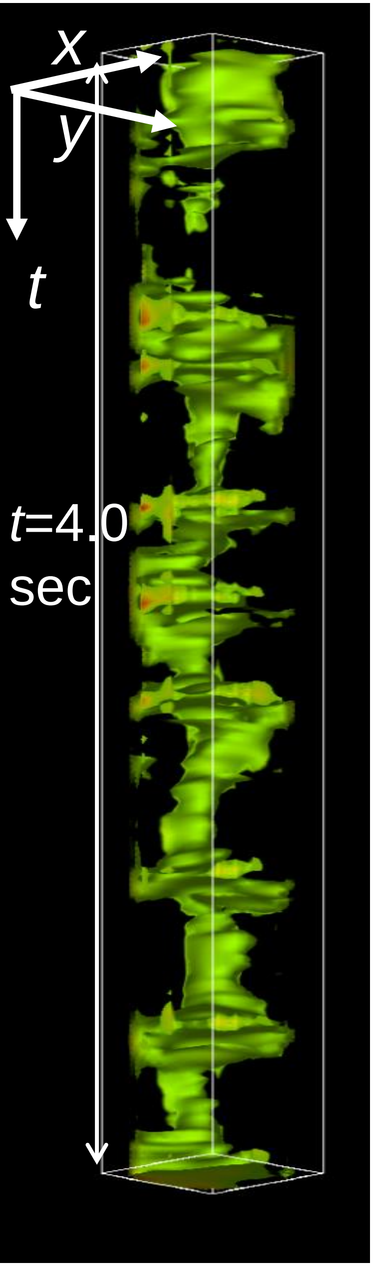


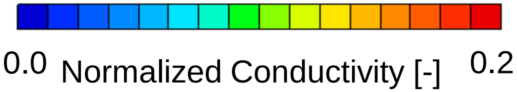
Fig.着色法による偏流の破壊可視化

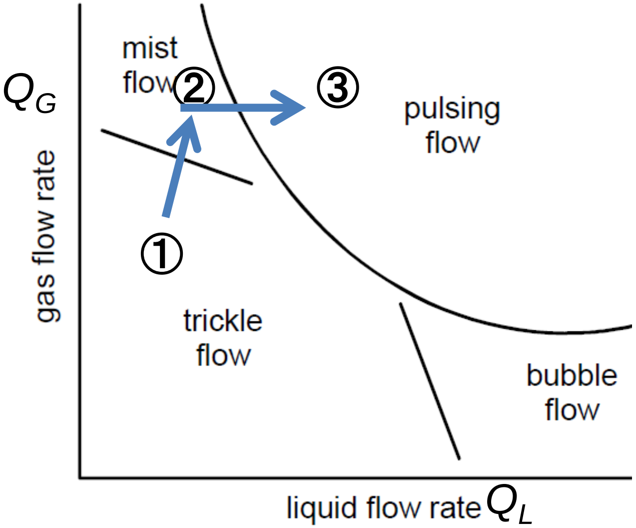
流動様式の比較



3D再構成例

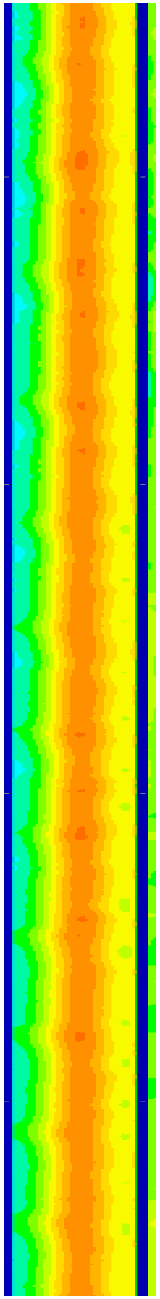
(Q_L, Q_G)= (13L/min, 70L/min)





z = 1020 mm,
d_p = 5 mm,

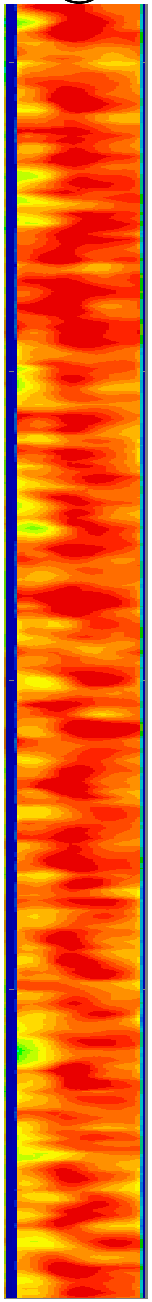
①



(Q_L, Q_G) =(6L/min, 10L/min)

トリクル流

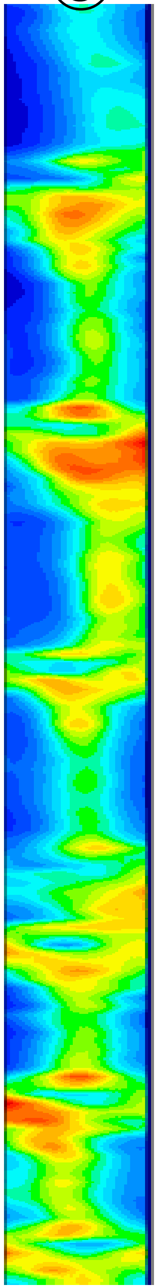
②



(Q_L, Q_G) =(13L/min, 15L/min)

気泡流

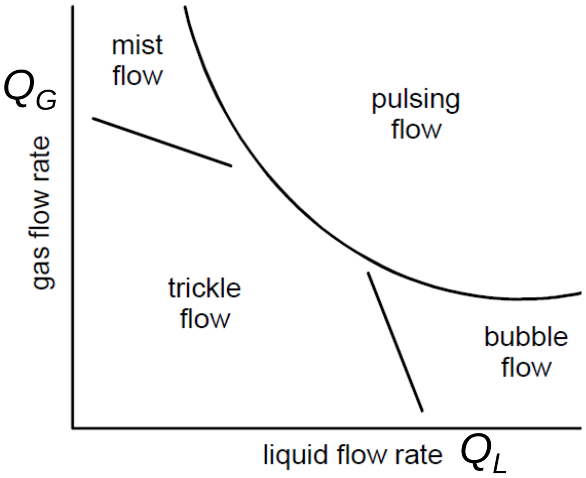
③

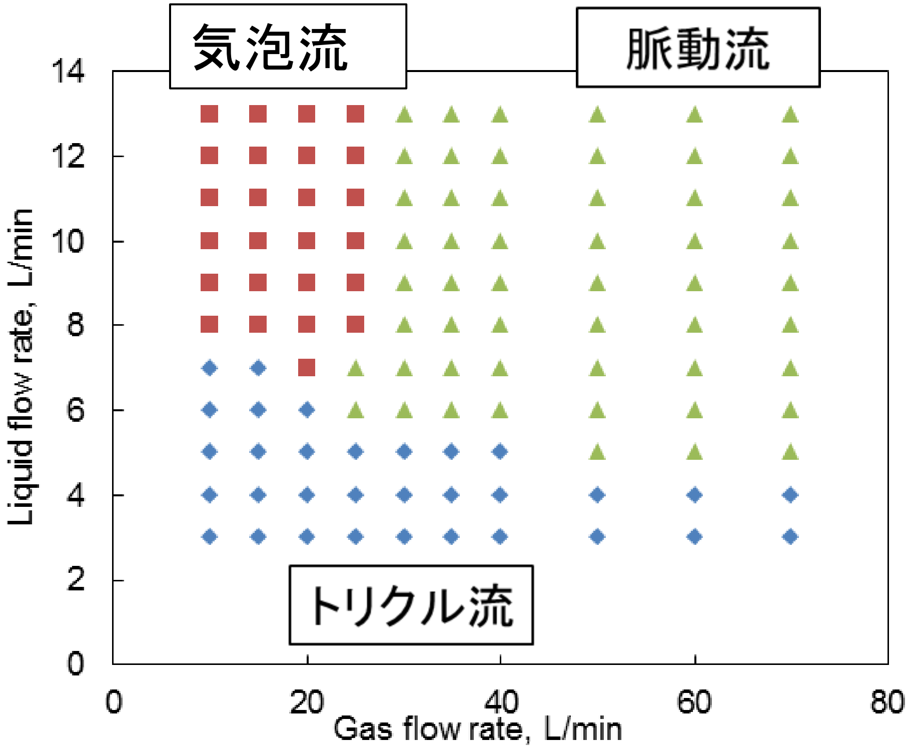


(Q_L, Q_G)= (13L/min, 70L/min)

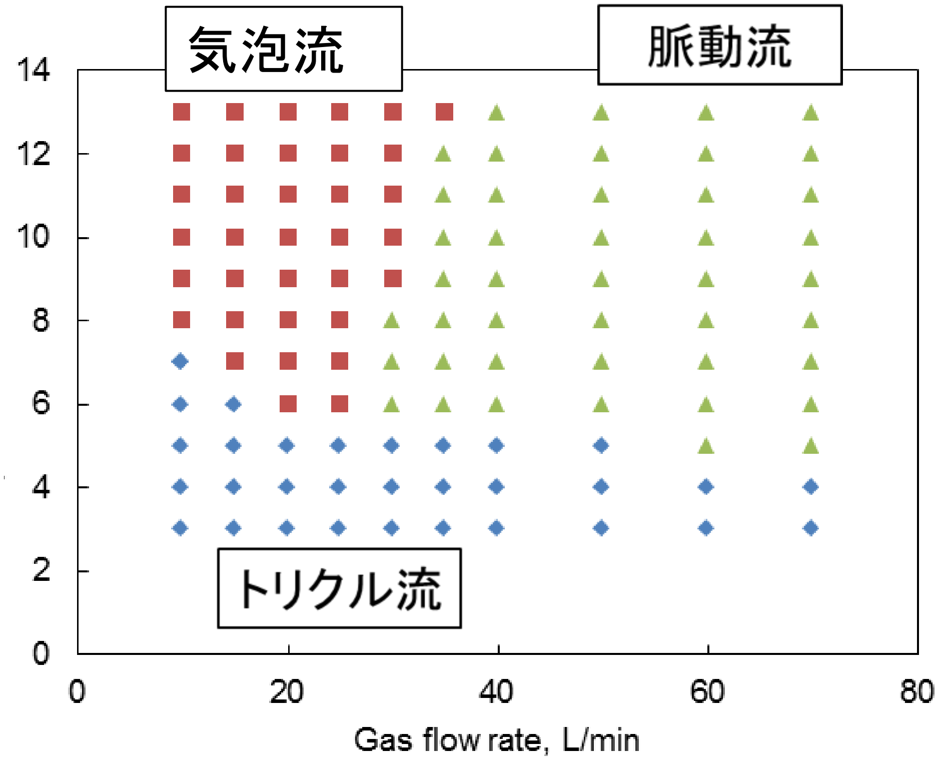
脈動流

状態図



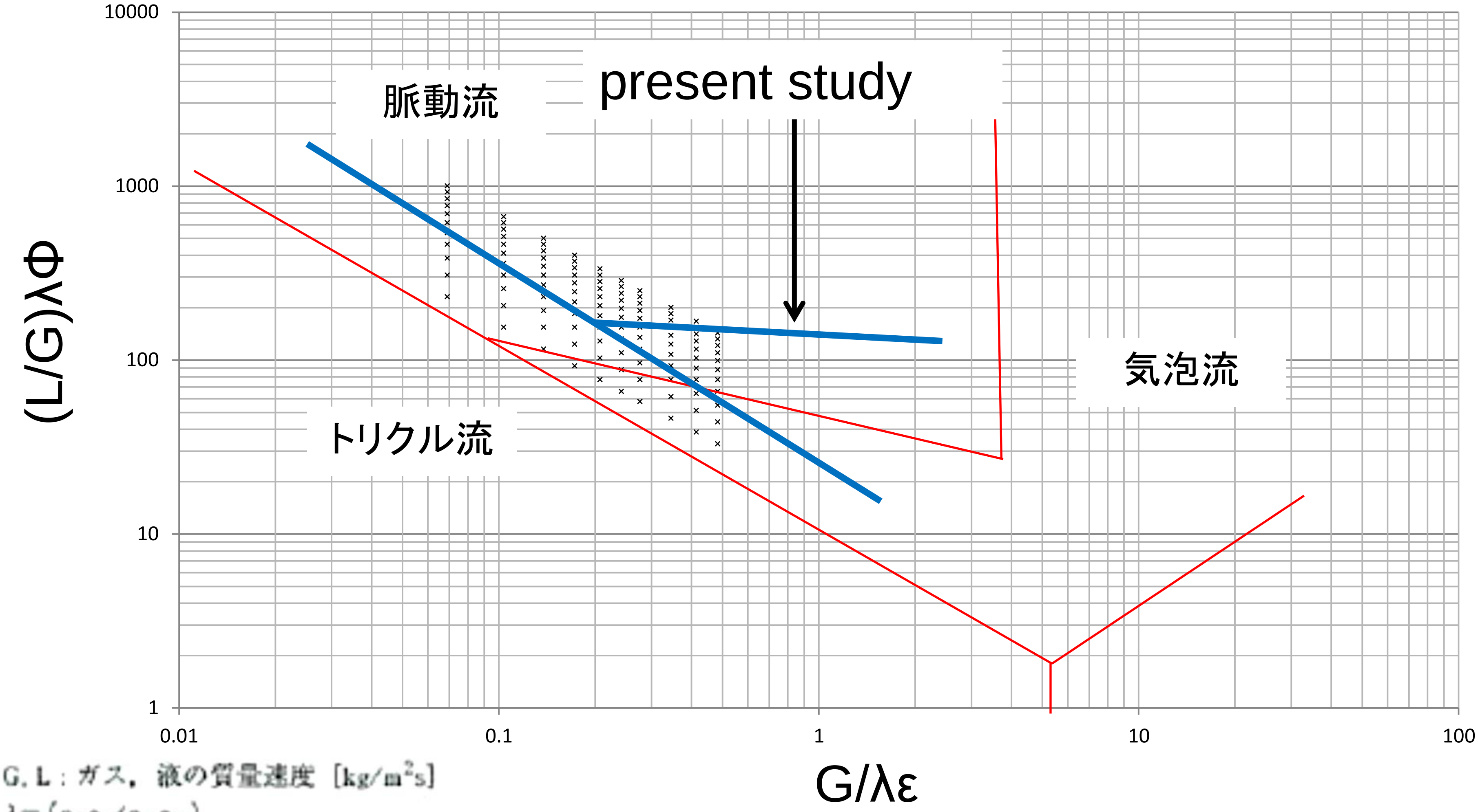


d_p = 3 mm



d_p = 5 mm

状態図の比較



A. Gianetto et al., AIChE J 24,(6)1087(1978)

G, L：ガス，液の質量速度 [kg/m²s]

$\lambda=(\rho_G\rho_L/\rho_A\rho_W)$

$\phi=(\sigma_W\sigma_L)\ [(\mu_L/\mu_W)\ (\sigma_W/\sigma_L)^2]^{1/3}$

ε：充填層の空隙率 [−]

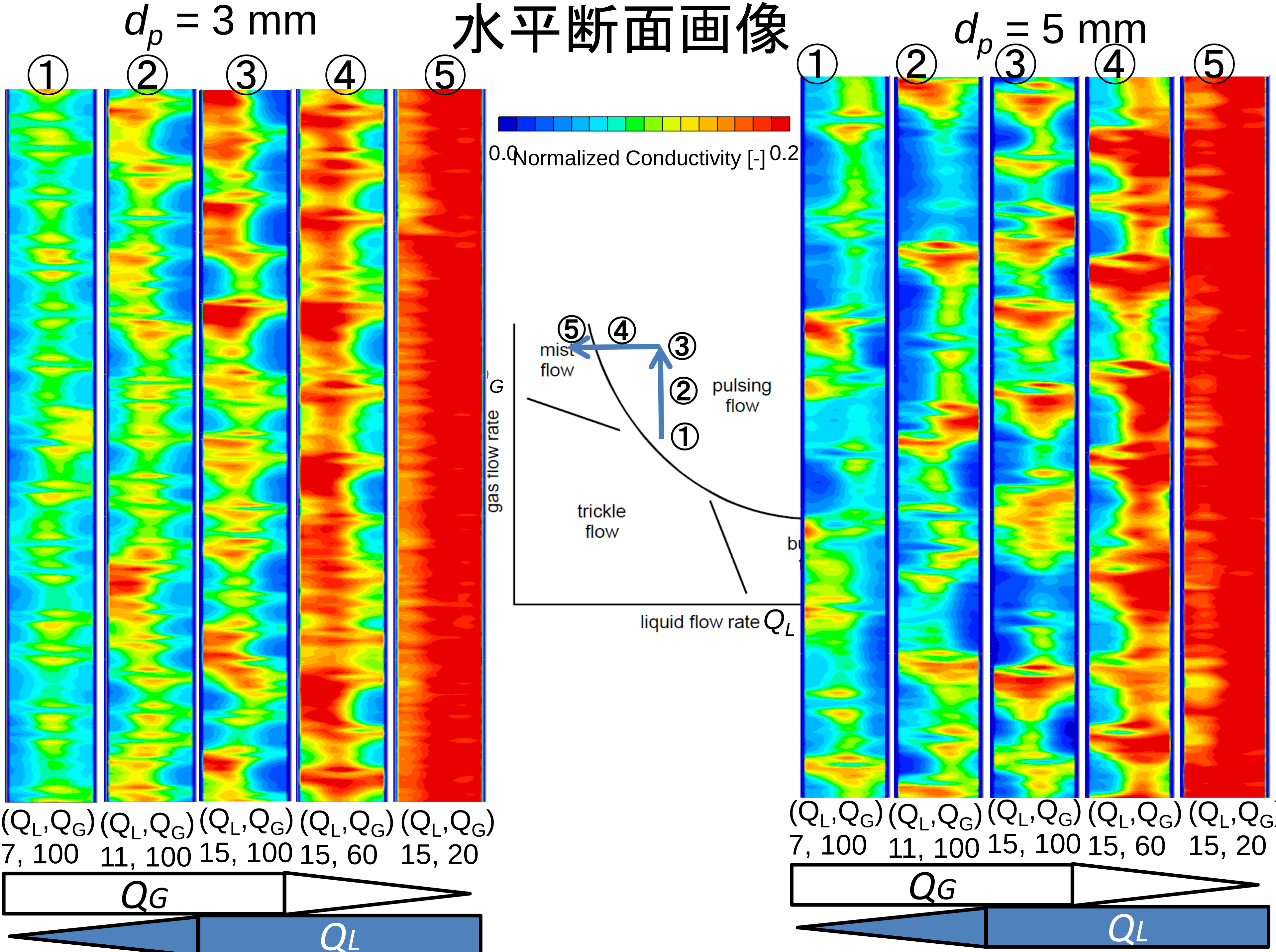
ρ_G，ρ_L：ガス，液の密度 [kg/m³]

ρ_A，ρ_W：空気，水の密度 [kg/m³]

μ_L：液の粘度 [kg/m・s]，μ_W：水の粘度 [kg/m・s]

σ_L：液の表面張力 [kg/m²]，σ_W：水の表面張力 [kg/m²]

水平断面画像


d_p = 3 mm
①
②
③
④
⑤
(Q$_L$,Q$_G$) 7, 100
(Q$_L$,Q$_G$) 11, 100
(Q$_L$,Q$_G$) 15, 100
(Q$_L$,Q$_G$) 15, 60
(Q$_L$,Q$_G$) 15, 20
Q_G
Q_L
0.0
Normalized Conductivity [-]
0.2
⑤
④
③
②
①
mist flow
pulsing flow
trickle flow
bu
gas flow rate Q_G
liquid flow rate Q_L
d_p = 5 mm
①
②
③
④
⑤
(Q$_L$,Q$_G$) 7, 100
(Q$_L$,Q$_G$) 11, 100
(Q$_L$,Q$_G$) 15, 100
(Q$_L$,Q$_G$) 15, 60
(Q$_L$,Q$_G$ 15, 20
Q_G
Q_L

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①ECTの例　②ERTの例
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PT法による濃度・温度分布の画像再構成

$$C_{i,j} = -\frac{\varepsilon_0}{V_c}\oint_{r\subseteq\Gamma_j}\varepsilon(\mathbf{r})\nabla V_i(\mathbf{r})\cdot d\mathbf{r} \qquad \nabla\cdot[\varepsilon(\mathbf{r})\nabla V(\mathbf{r})]=0$$

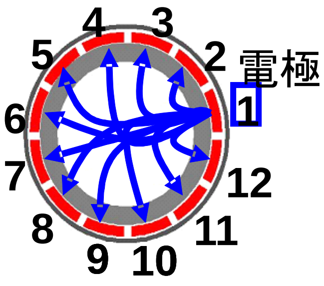
$$(i=1,2,\cdots,11;\quad j=i+1,\cdots,12)$$

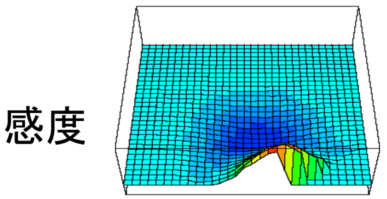
$C_{i,j}$: 電極iとj間のキャパシタンス, ε_0: 真空の誘電率, V_c: 電極にかける電圧, **r**: 位置ベクトル,
ε: 比誘電率, V(**r**): 位置**r**における電位, Γ: 電気力線がカバーする領域

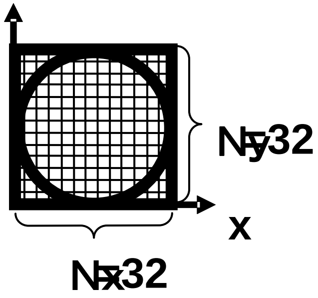
逆問題による比誘電率分布の計算

計測したキャパシタンス ← **C = S E** → **求める比誘電率分布**

感度行列
66×1024







不適切逆問題　未知数 > 式数

画像再構成アルゴリズム
近似的な比誘電率(濃度)分布

デバイ式による比誘電率から温度分布の計算

$$\frac{\varepsilon-1}{\varepsilon+2}=\frac{\rho N_A}{3\varepsilon_0 M}\left(\frac{\mu^2}{3k_B T}\right)$$

$$T=\left(\frac{\varepsilon\ \ +2}{\varepsilon\ \ -1}\right)\left(\frac{\rho\ N_A\mu^2}{3\ \varepsilon_o M\ 3\ k_B}\right)$$

$$T=f(\varepsilon\ )$$

ε_0 :真空の誘電率[F/m], M :モル質量[kg/mol],
ρ :密度[kg/m^3], N_A :アボガドロ定数[l/mol],
T :温度[K], k_B :ボルツマン定数[J/K],
μ :永久双極子モーメント[D], ε :比誘電率[-]

PT法による温度分布可視化計測

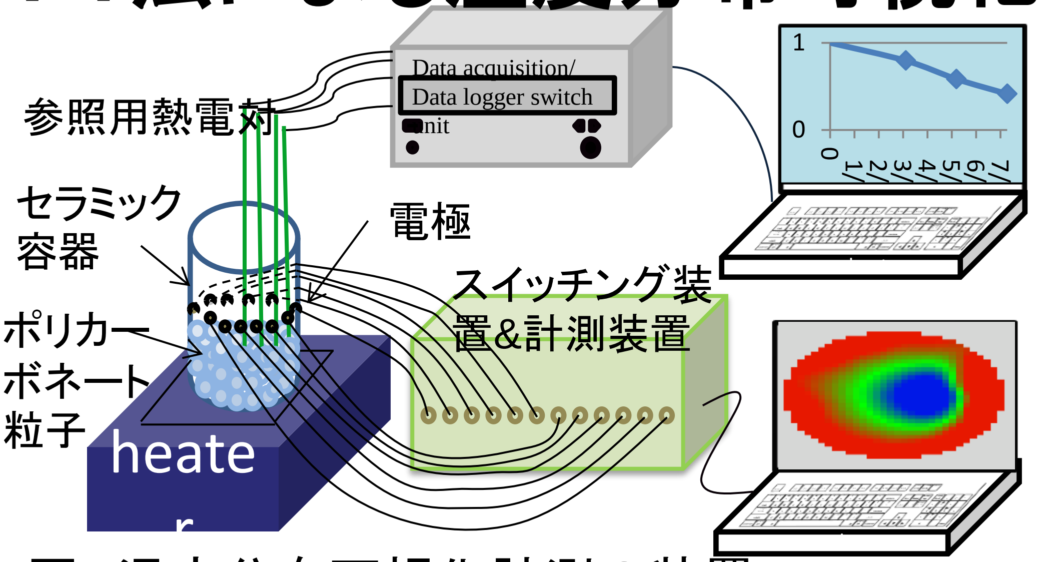
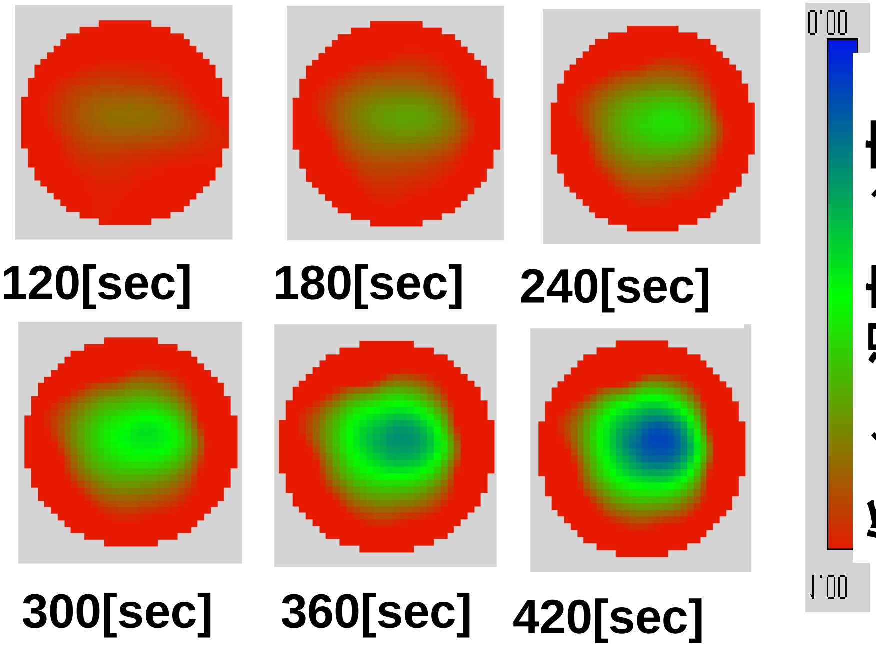


図　温度分布可視化計測の装置

- ●ポリカーボネート粒子のPTセンサ内充填+下部中心より加熱溶解
- ●デバイ式により誘電率分布から温度分布の画像再構成
- ●温度分布の3D(2D+時間)可視化計測に成功
- ●従来技術(熱電対)と比較して数 %の誤差



120[sec]　180[sec]　240[sec]

300[sec]　360[sec]　420[sec]

図　温度分布の時間変化画像

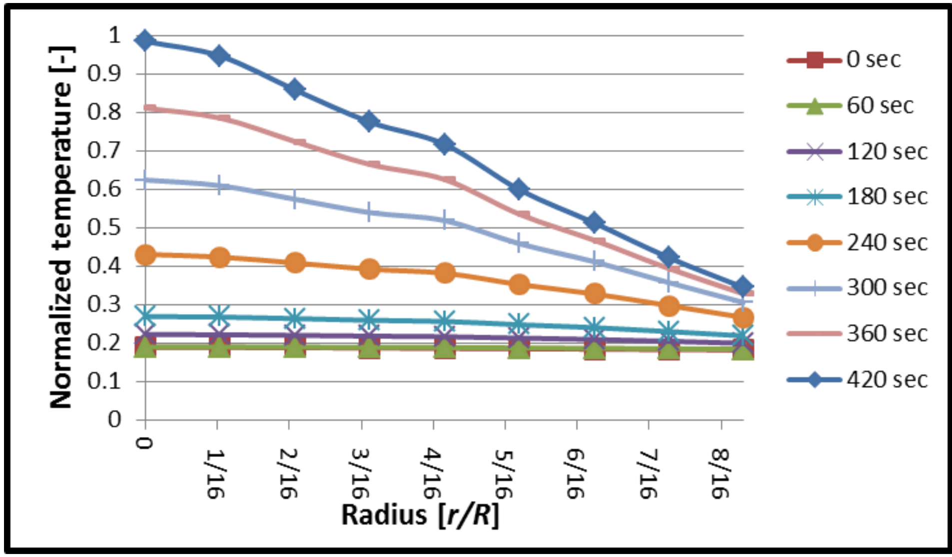


図 PT法による温度分布の時間変化

CONTENTS

背景と従来技術の問題点

日本人の死因:30% 循環器系疾患

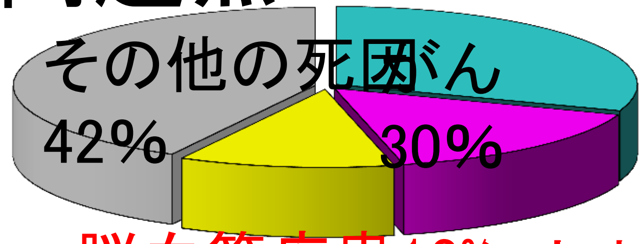


図 日本人の死因(厚生労働省:人口動態統計の概況より)

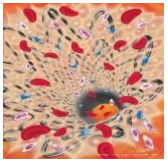
人工臓器の実用化

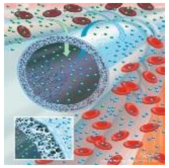
人工臓器による
血栓症リスクの増大

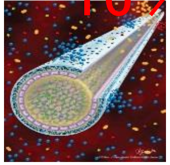

人工心臓


人工弁


人工血管


ステント


人工肺


人工腎臓


人工肝臓

大量の抗凝固剤投与
患者の血栓に対する不安

30万人 人工透析患者
在宅人工透析が進まない理由

血栓症の予測(いつ、どこで、どれだけの血栓)の可能性

しかしながら

1)血栓検出計測技術の未熟性

2)人工臓器と血液との界面マルチフィジックスが不明

血栓オンライン計測が不可能

血栓未来予測が不可能

補助人工心臓の例

体内植え込み型補助
人工心臓の薬事承認

2011年4月1日より発売
「EVAHEART」「DuraHeart」

補助人工心臓
を装着して自宅
療養・職場復帰

血栓が生じやすい
脳梗塞などの合併症

千葉大学病院でも
症例多数あり

そこで、私たちの提案!!

血栓症の未来予測技術の確立

トータルソリューションの研究開発

①血栓*Insitu*(その場)検出技術
②血栓*Insilico*(シミュレーション)予測技術
③血栓*Invitro*(精密制御体外実験)検証

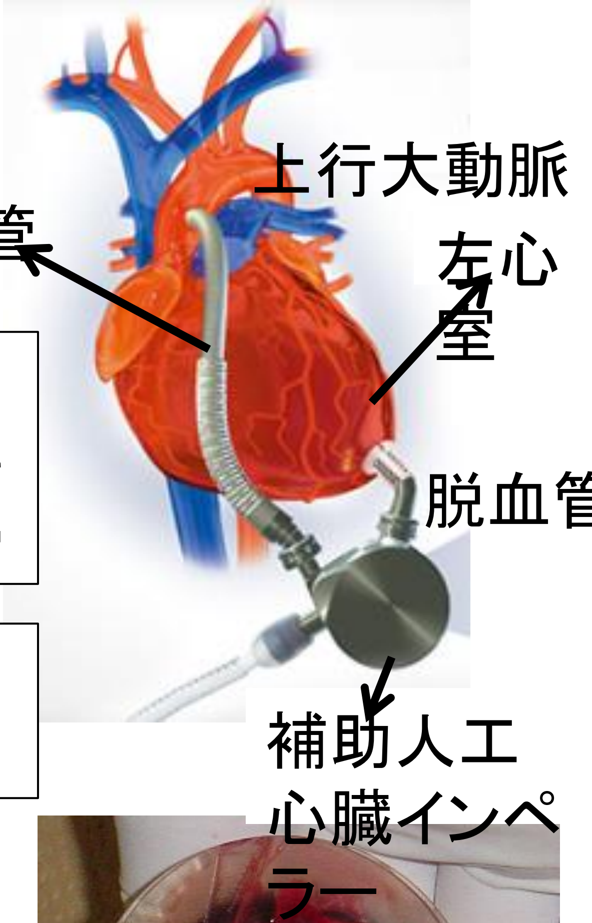
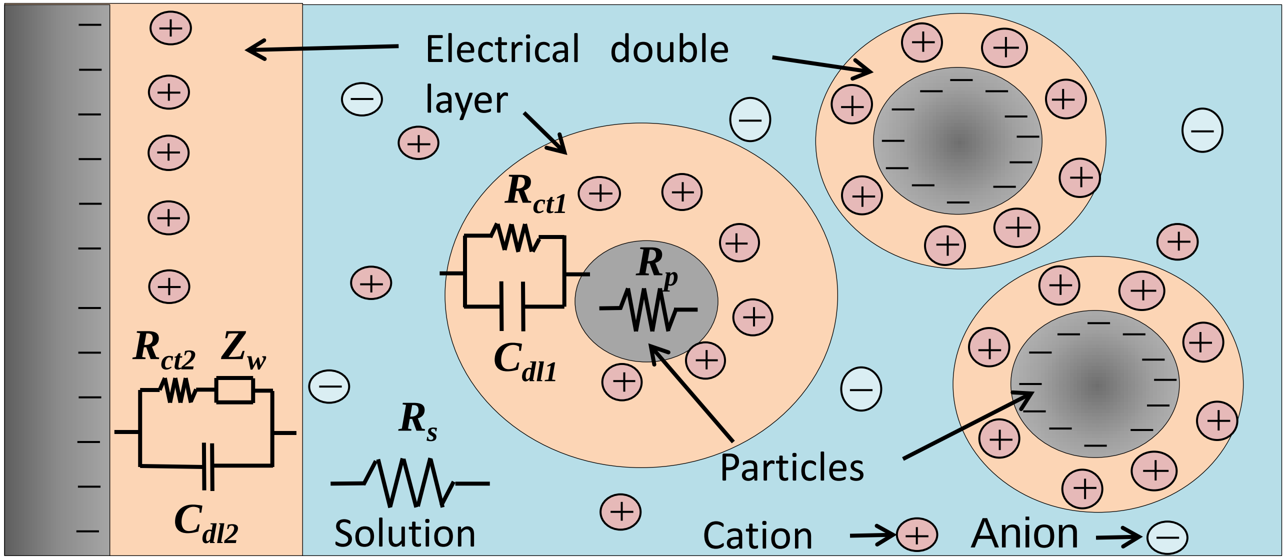


図　血栓が生じた人工心臓インペラー

血流におけるインピーダンス計測

電気二重層



R_{ct1}：粒子界面電気二重層電荷移動抵抗

C_{ct1}：粒子界面電気二重層容量

R_{ct2}：電極界面電気二重層電荷移動抵抗

C_{ct2}：電極界面電気二重層容量

R_p：粒子抵抗　R_s：溶液抵抗

Z_w：ワールブルグインピーダンス

電気二重層

溶液中の粒子は多くの場合帯電

↓

溶液中の対イオンが集まり、
界面にイオンの層が形成（電気二重層）

- コンデンサのような電気容量
- 緩和周波数

インピーダンストモグラフィー

- 単一周波数
- インピーダンス値のみ計測

↓

周波数をスイープして様々な電気成分を計測

誘電スペクトル

⇒電子分極

⇐配向分極⇒

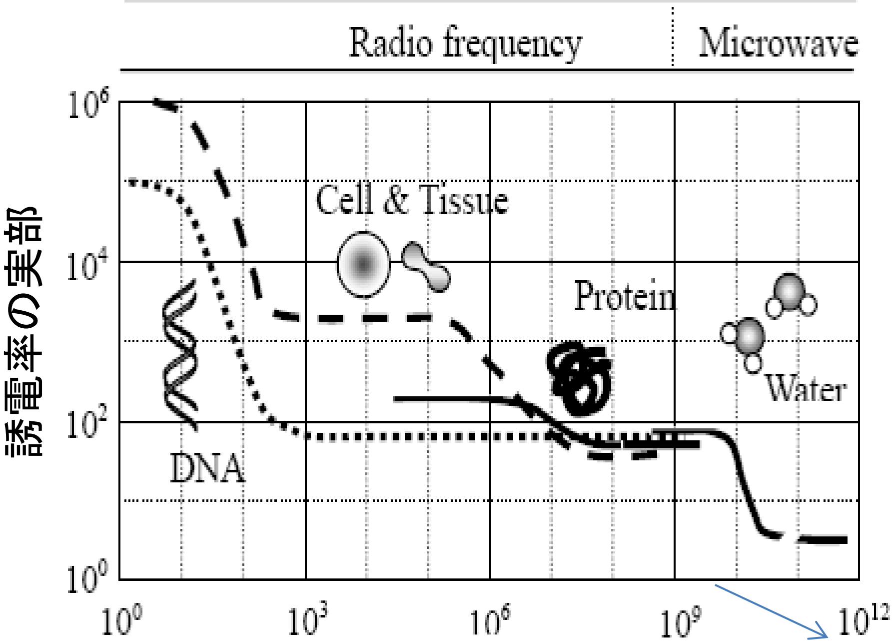
⇒イオン分極

- 電束密度と分極

$$\boldsymbol{D} = \varepsilon_0 \boldsymbol{E} + \boldsymbol{P}$$

$$\boldsymbol{P} = N\boldsymbol{m} = N\alpha \boldsymbol{F}$$

$\boldsymbol{D}$: 電束密度[C/m2], ε_0: 真空の誘電率[F/m] ,$\boldsymbol{E}$: 電場[V/m],$\boldsymbol{P}$: 分極[C/m2], N: 単位体積当たりの分子数[-], $\boldsymbol{m}$:誘起双極子モーメント[Cm], $\boldsymbol{F}$:有効電場[V/m], ε:誘電率[F/m], α :分子の分極率 [Cm2/V] , μ :永久双極子モーメント [Cm]



周波数 [Hz] 電子レンジf=2.45GHz

浅見耕司 http://www003.upp.so-net.ne.jp/asami/DS.pdfより

配向分極(極性分子）

Clausius-Mossotti式

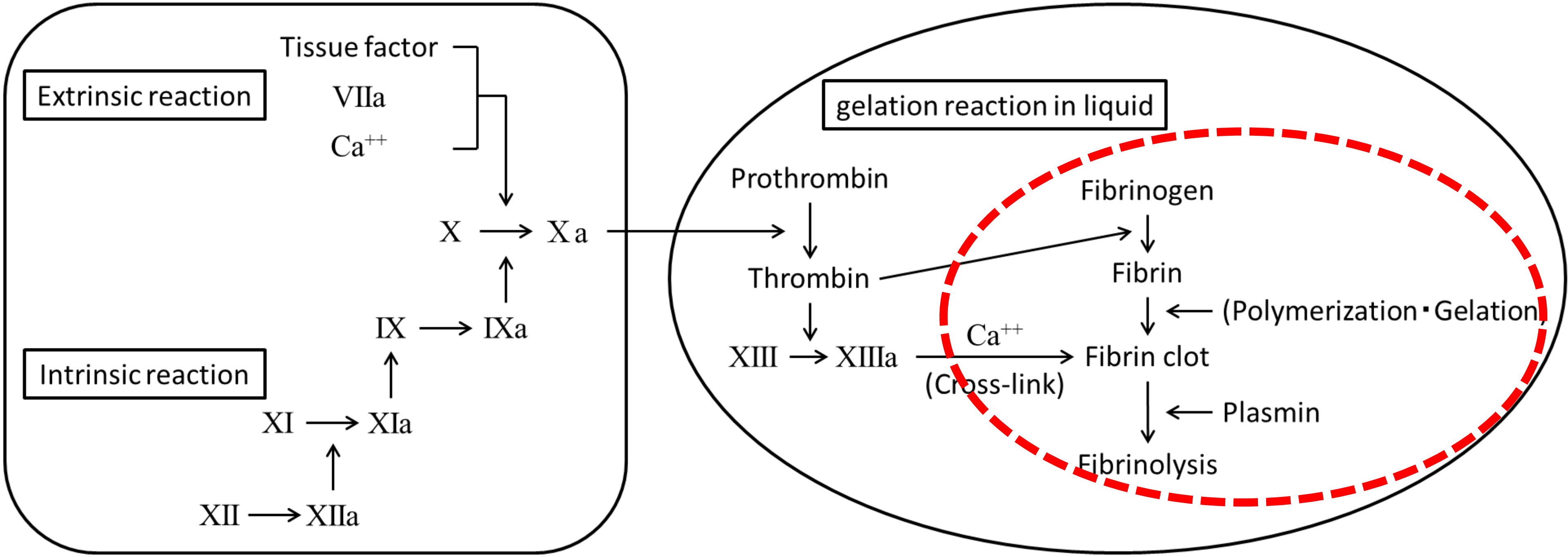
$$\frac{\varepsilon - 1}{\varepsilon + 2}\frac{M_W}{\rho} = \frac{N_A \alpha}{3\varepsilon_0}$$

Debye式

$$\frac{\varepsilon - 1}{\varepsilon + 2}\frac{M_W}{\rho} = \frac{N_A}{3\varepsilon_0}\left(\alpha_e + \frac{\mu^2}{3k_B T}\right)$$

M_w:分子量, N_A:Avogadro数, k_B:Boltzmann定数, T:絶対温度, ρ:密度

血液凝固過程と電気的特性


Extrinsic reaction
Tissue factor
VIIa
Ca^{++}
X → Xa
IX → IXa
Intrinsic reaction
XI → XIa
XII → XIIa
gelation reaction in liquid
Prothrombin
Thrombin
Fibrinogen
Fibrin
(Polymerization・Gelation)
XIII → XIIIa
Ca^{++}
(Cross-link)
Fibrin clot
Plasmin
Fibrinolysis

●低測定周波数 ⇒ **血漿の抵抗率変化**

#1.　フィブリン・クロット(フィブリンのゲル化)形成時における血漿タンパク (プロトロンビンとフィブリノーゲン)量と抵抗率との関係の知見

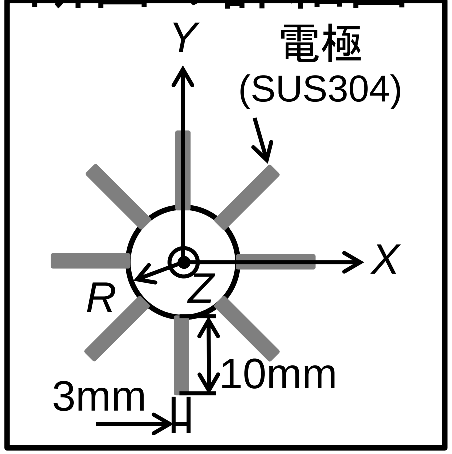
●高測定周波数 ⇒ **赤血球膜のキャパシタンス(リアクタンス)変化**

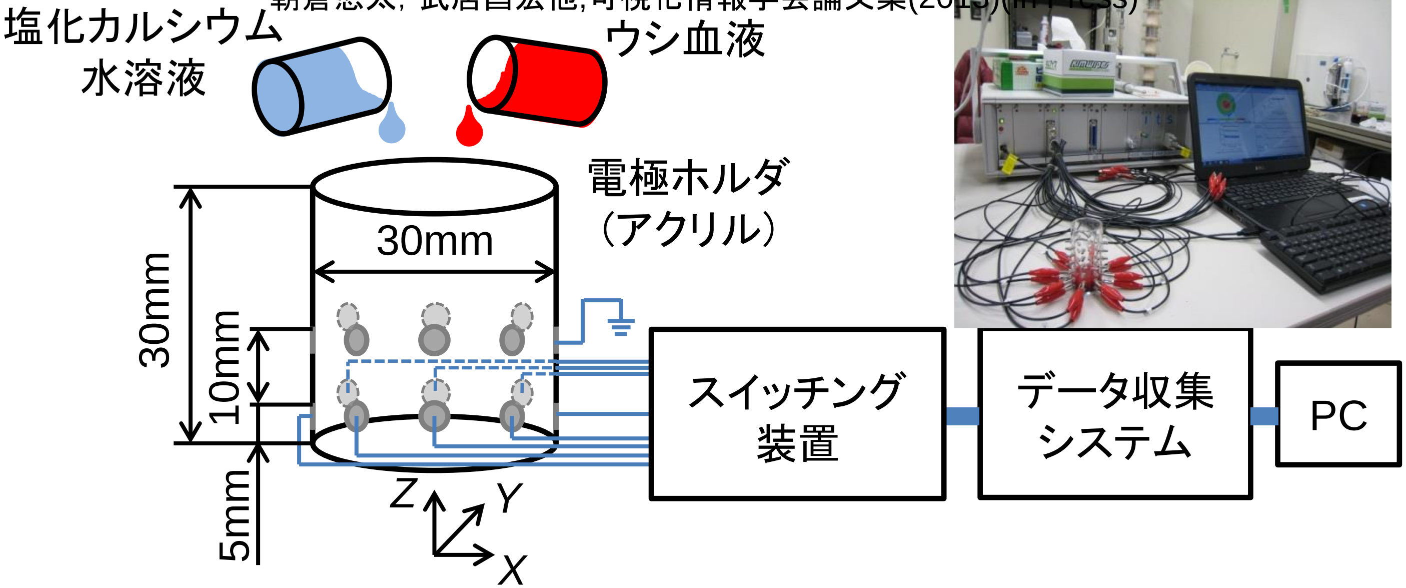
#2.　赤血球の凝集(血栓形成)により赤血球膜のリアクタンス変化の知見

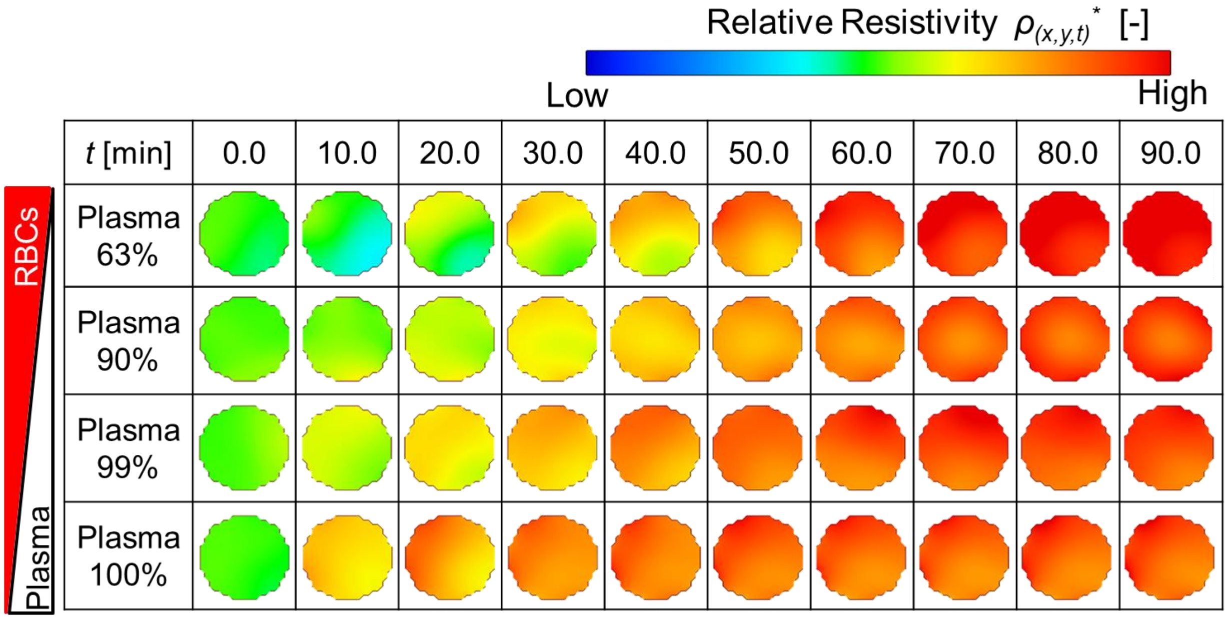
血栓*Insitu*検出の血栓形成過程の可視化

武居,（社）日本人工臓器学会2012年度　Grant
朝倉悠太，武居昌宏他,可視化情報学会論文集(2013)(In Press)

断面の詳細図

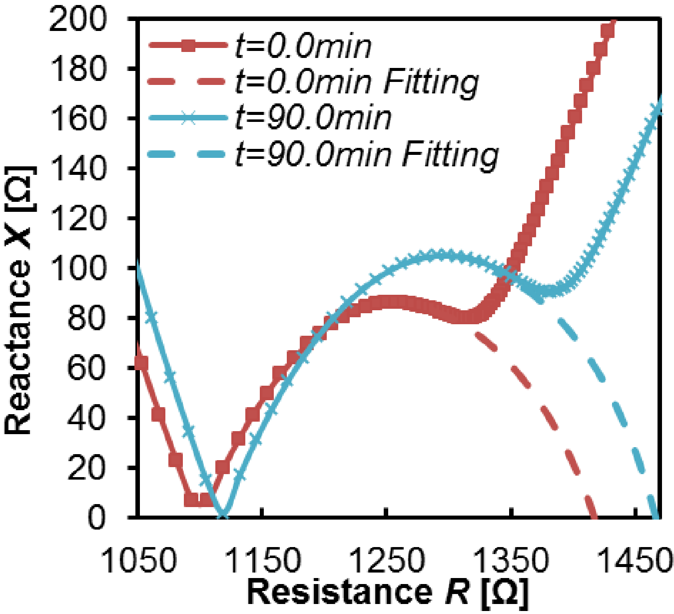






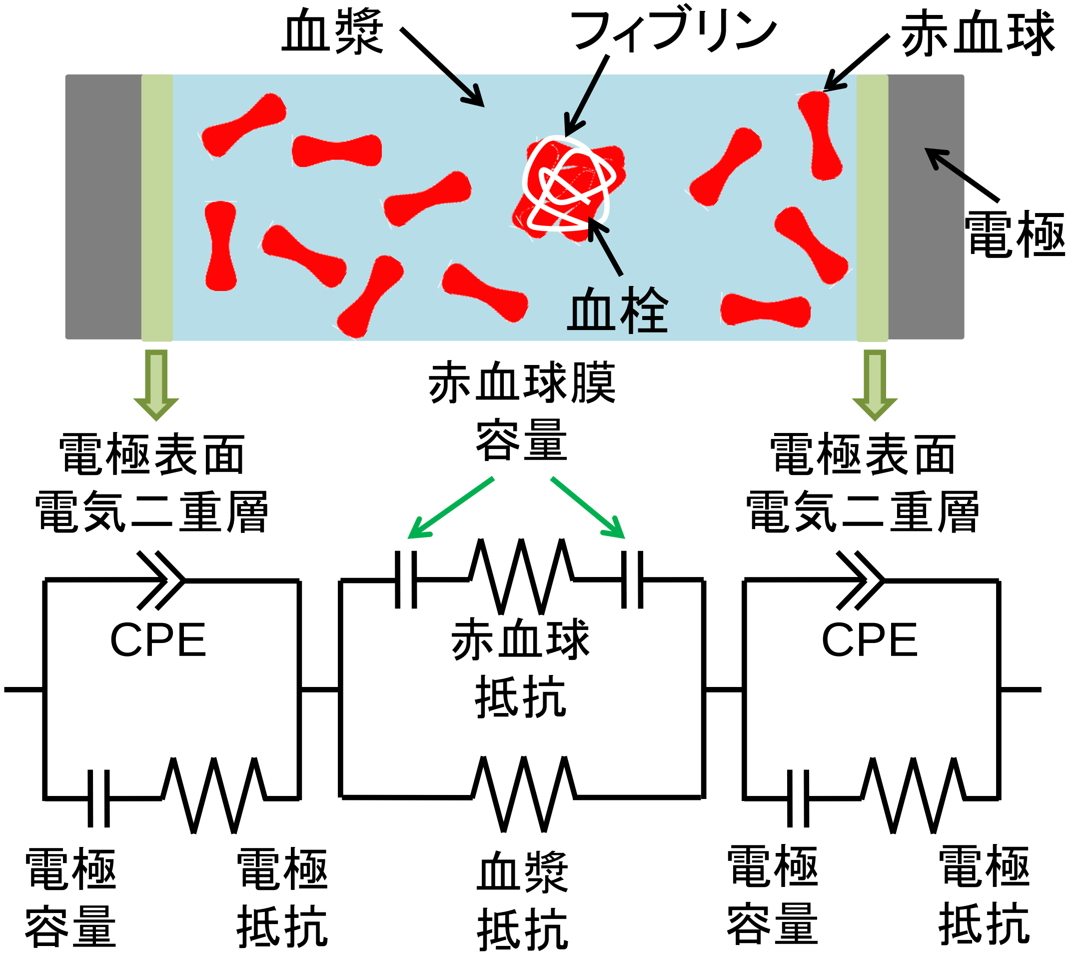
t [min]	0.0	10.0	20.0	30.0	40.0	50.0	60.0	70.0	80.0	90.0
Plasma 63%										
Plasma 90%										
Plasma 99%										
Plasma 100%										

血栓形成過程のPT可視化画像



血栓形成過程のCole-Cole plo

赤血球膜のリアクタンスの時間変化



血漿

フィブリン

赤血球

電極

血栓

電極表面
電気二重層

赤血球膜
容量

電極表面
電気二重層

CPE

赤血球
抵抗

CPE

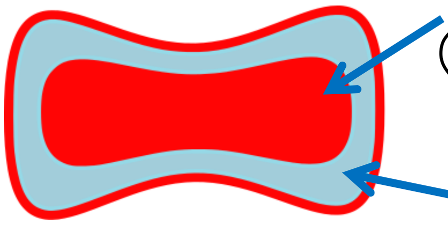
電極
容量

電極
抵抗

血漿
抵抗

電極
容量

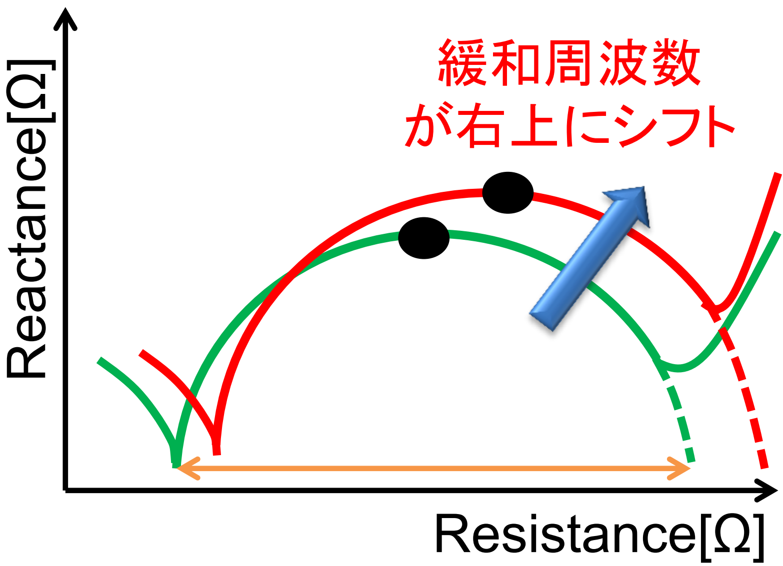
電極
抵抗



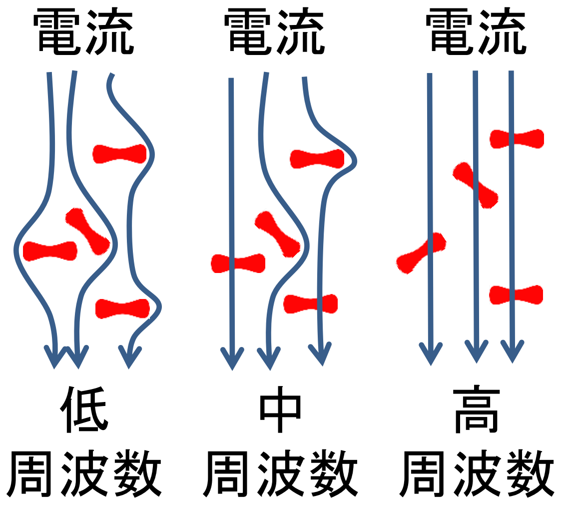
赤血球内部
（ヘモグロビン） → 抵抗（R）

赤血球膜 → 容量（C_p）

Cole-Cole Plot



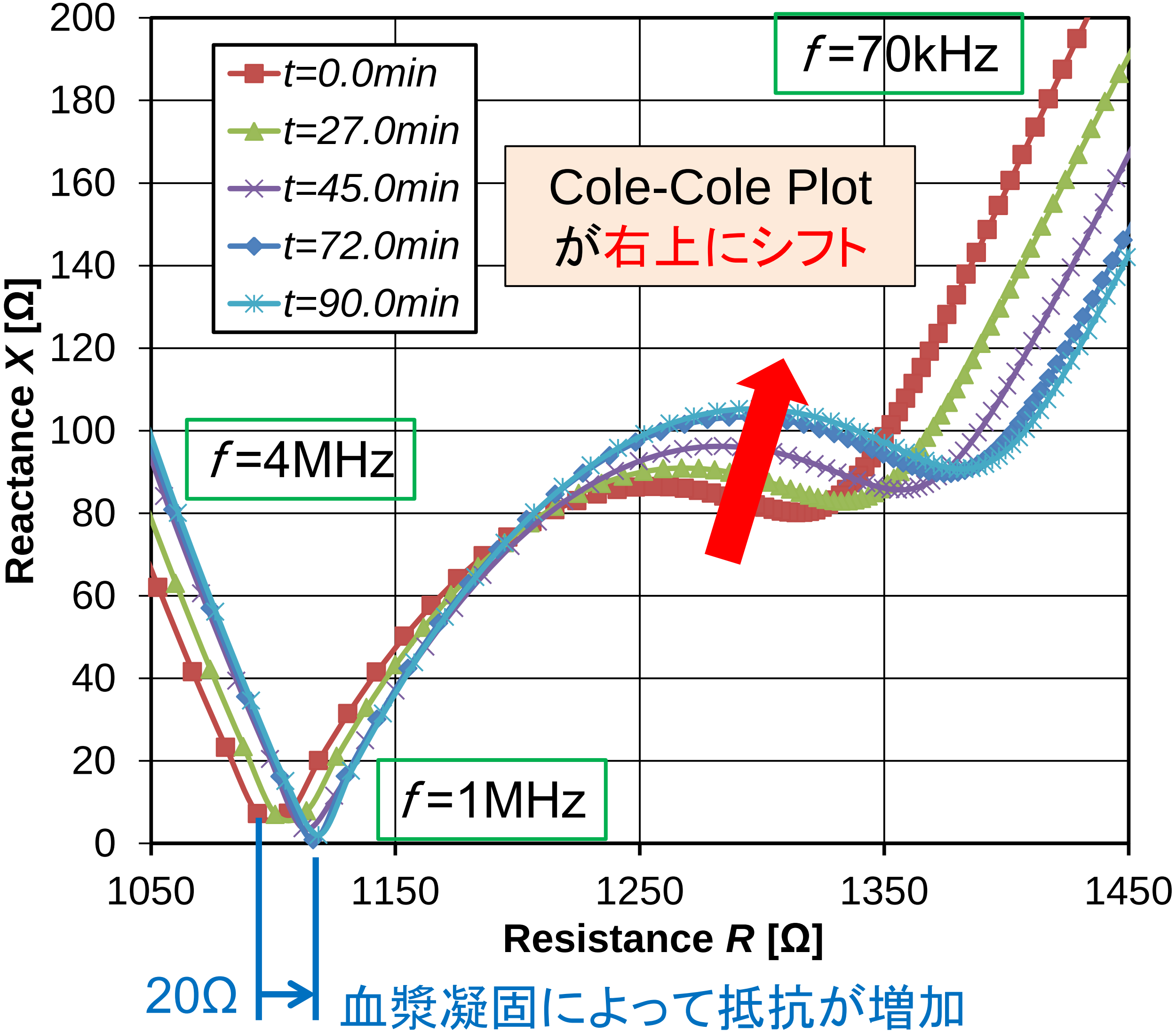
緩和周波数
が右上にシフト

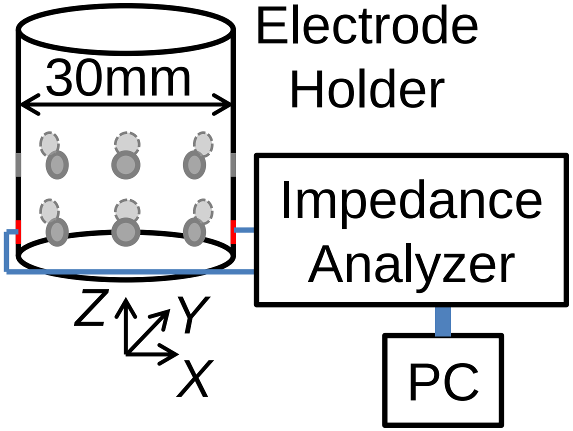


電流	電流	電流
低 周波数	中 周波数	高 周波数

赤血球膜のリアクタンスの時間変化

(Plasma 63%+30%$CaCl_2$)





印加電圧V	1[V]
測定周波数f	70kHz～ 4MHz
測定時間t	90min
測定点数	60 Point

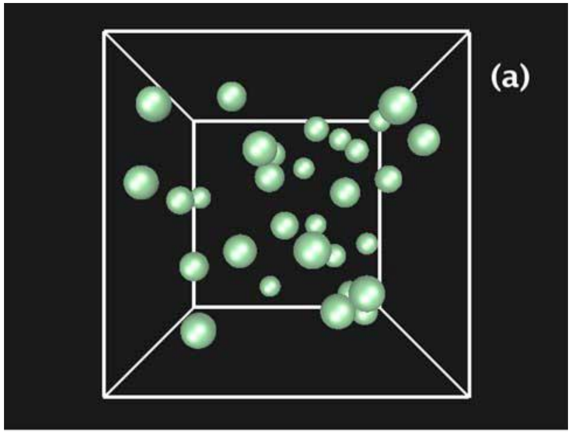
Cole-Cole Plotがシフト
赤血球の凝集(血栓形成)により赤血球膜のCが減少しXが増加

CONTENTS

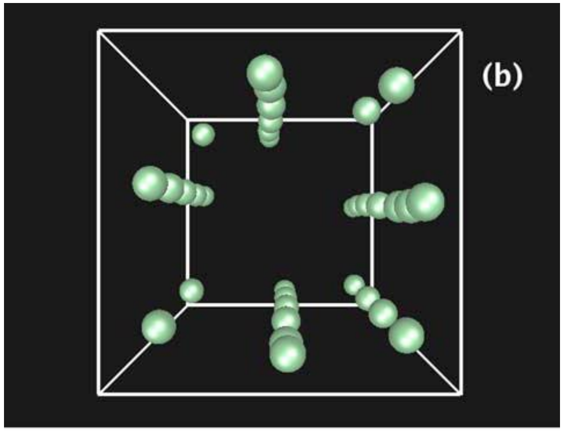
- PTの概要　ソフトフィールドとハードフィールド
- ソフトフィールドPT
    - 原理
    - プラントへの展開
    - 血流への展開
    - マイクロ流路への展開
- ハードフィールドPT
    - Optical CT
    - X ray CT
    - γ ray CT
    - Neutron Radiography
    - Ultrasound CT
    - MRI
    - Positron Emission Tomography (PET)
- まとめ

Previous Study on Particle Migration

B. Chun et al. *Physics of fluids* (2010)



Upstream
Uniform particles distribution



Downstream at Re=100,
Migrate 8 equilibrium positions, Linear chains

Migration Reynolds number Re, Particle Reynolds number Rep,
Initial particle concentration ξ, Particle size d_p
Downstream position z

How to measure 3D particle concentration?

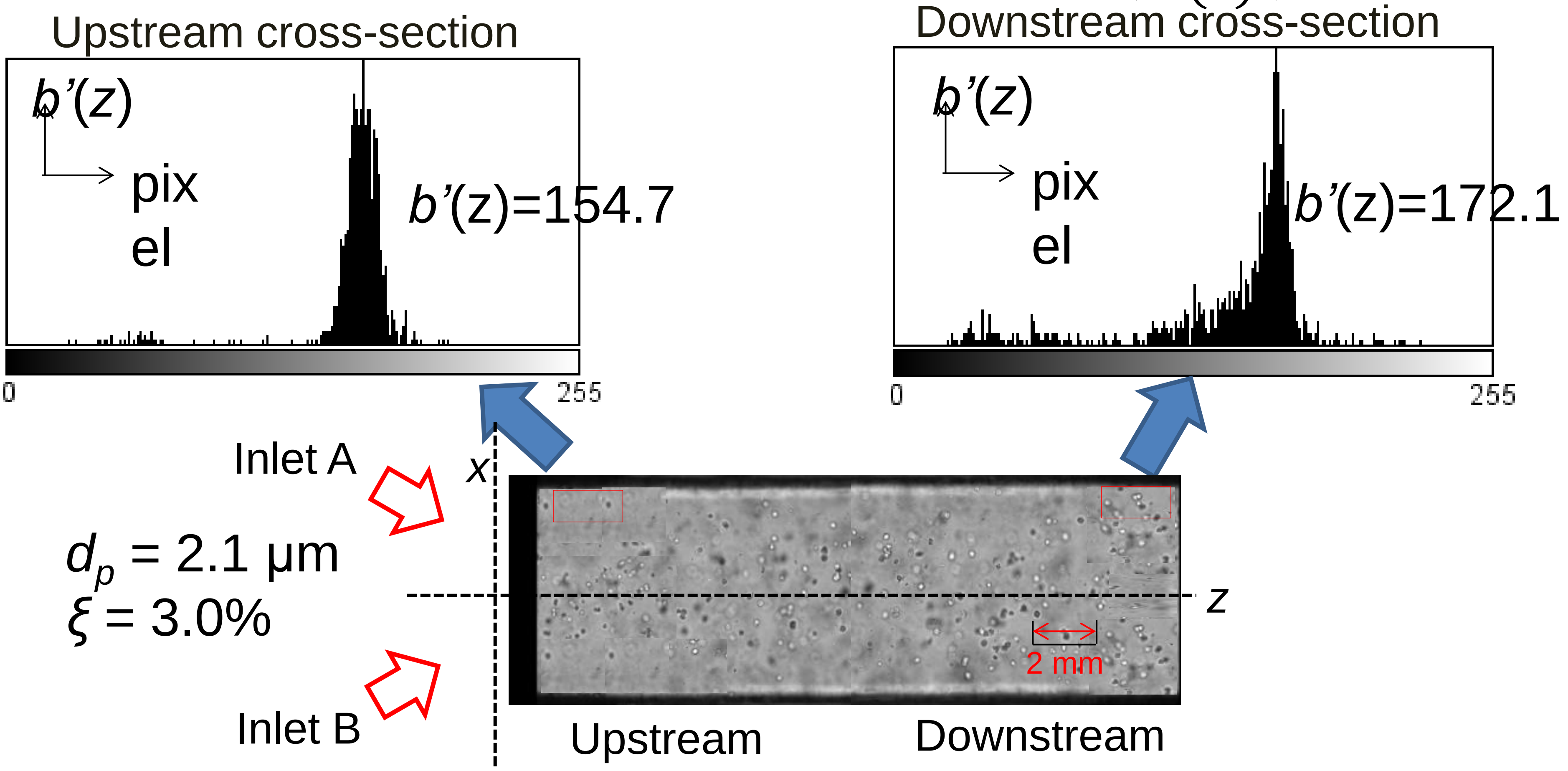
Typical measurement technique

Brightness from the 2D horizontal image by microscope

Brightness Fluctuation by Particle Migration

Brightness fluctuation $b'(z)$

$$b'(z) = \frac{\sqrt{(b(z) - < b(z) >)^2}}{< b(z) >}$$



$d_p = 2.1\ \mu m$

$\xi = 3.0\%$

Fig. Histograms of brightness at upstream and downstream by microscope

How to measure in dense particle phase?

Previous Studies of Multi-capacitance Sensing

Multi-capacitance sensing: High speed switching of electrodes
Process tomography: Imaging from multi capacitance data

T. York et al. *Sensors and Actuators A* (2006)

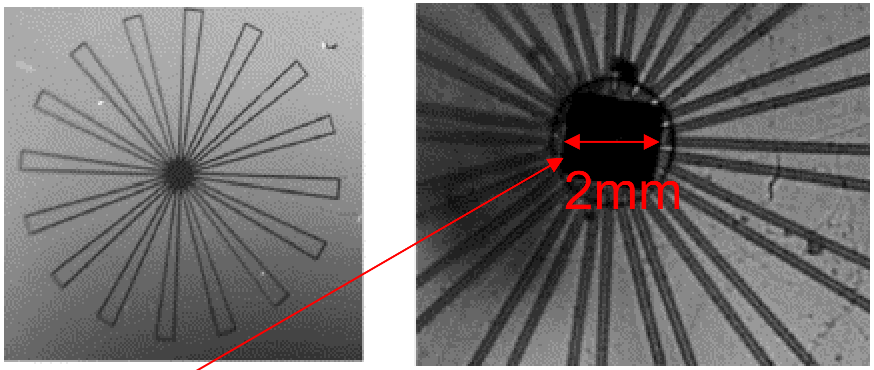


Fig. Hole type mini sensor

- 2 mm diameter
- 12 electrodes

T. Sun et al. *Biosensors and Bioelectronics* (2010)

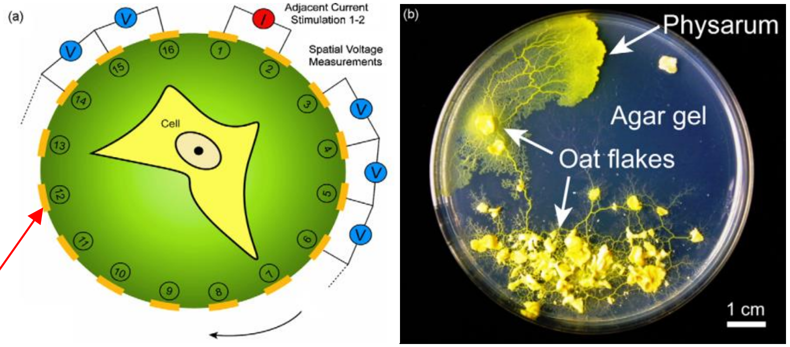


Fig. EIT for imaging single cell in culture in a circular electrode pattern

- 6 mm diameter
- 16 electrodes

Our research originality: Multilayer microchannel by MEMS

- 0.25μm x 200μm electrode size
- 700μm diameter of diamond shape cross-section
- 5 cross-sections with 12 electrodes per one cross-section
- 60 layered electrodes

Microchannel with 60 Layered Electrodes

N. T. A. Othman et al. *Flow Measurement and Instrumentation* (2013)
Z.Liu, M.Takei et al., *Heat and Mass Transfer*, *Springer*, (2007)

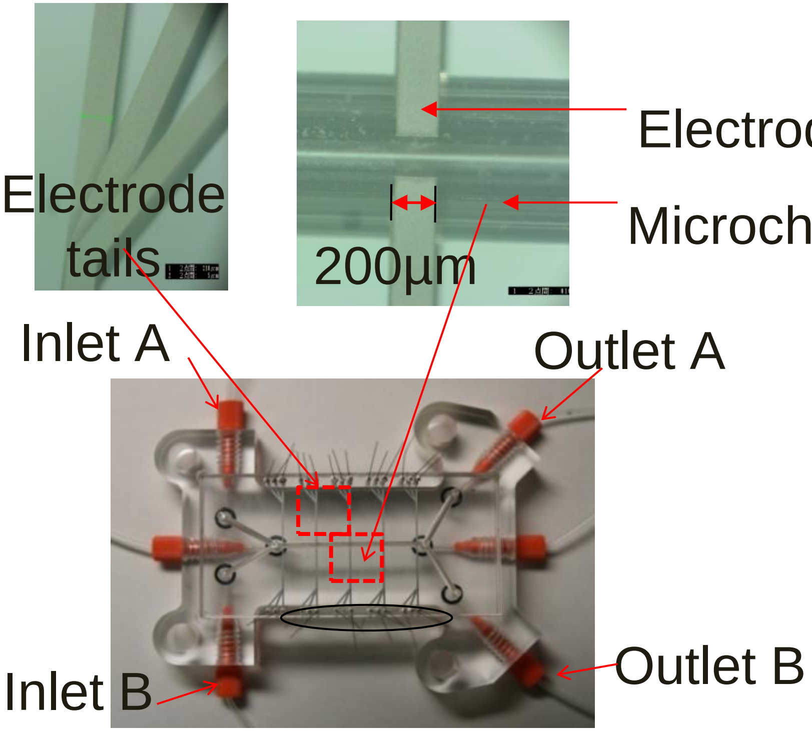


Fig. 60 electrodes of microchannel

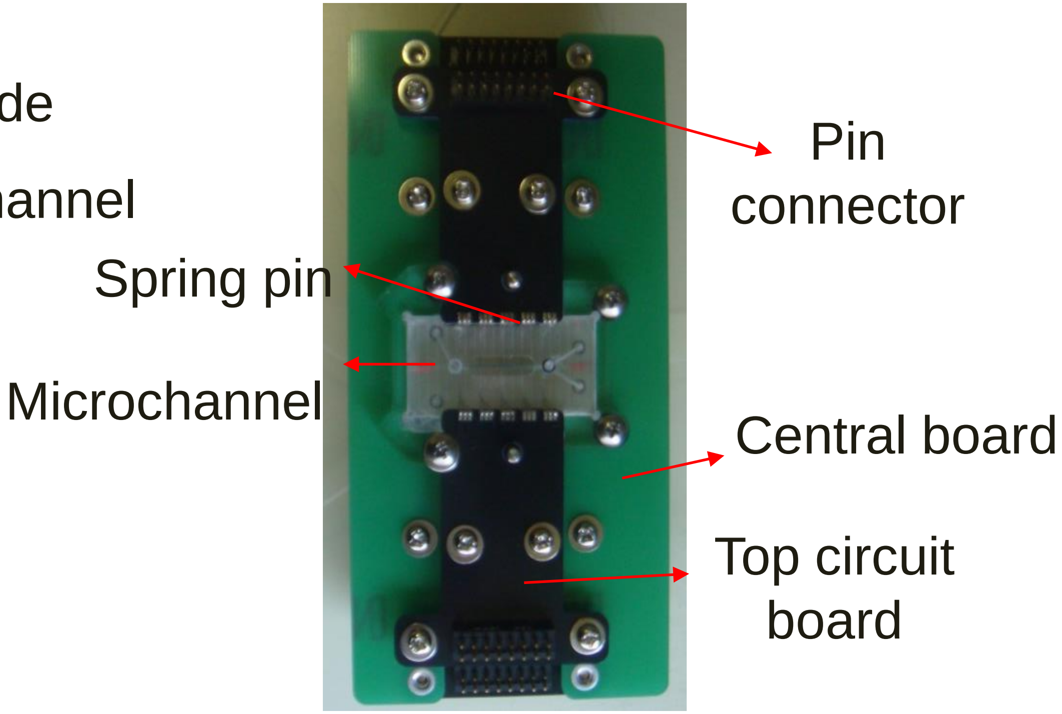


Fig. Microchannel with connector

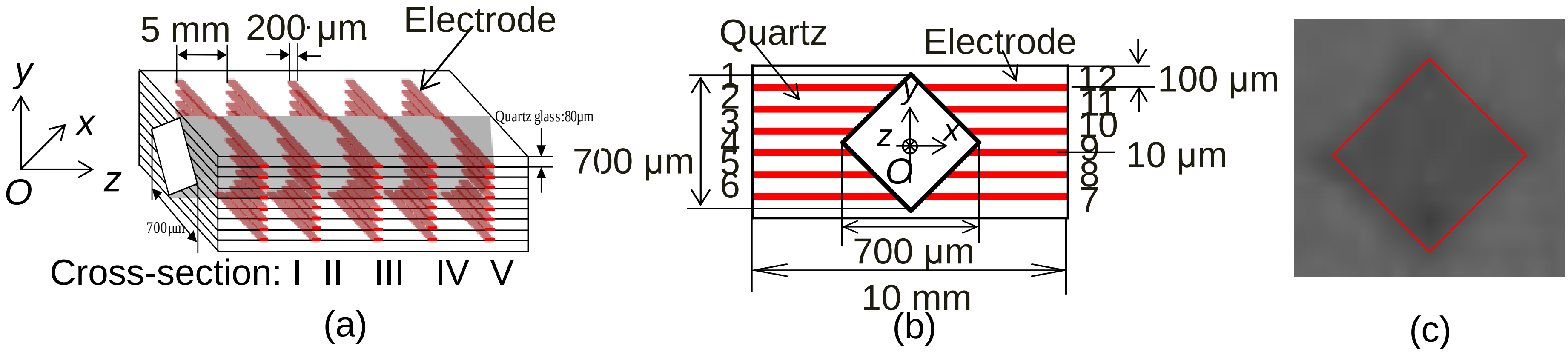
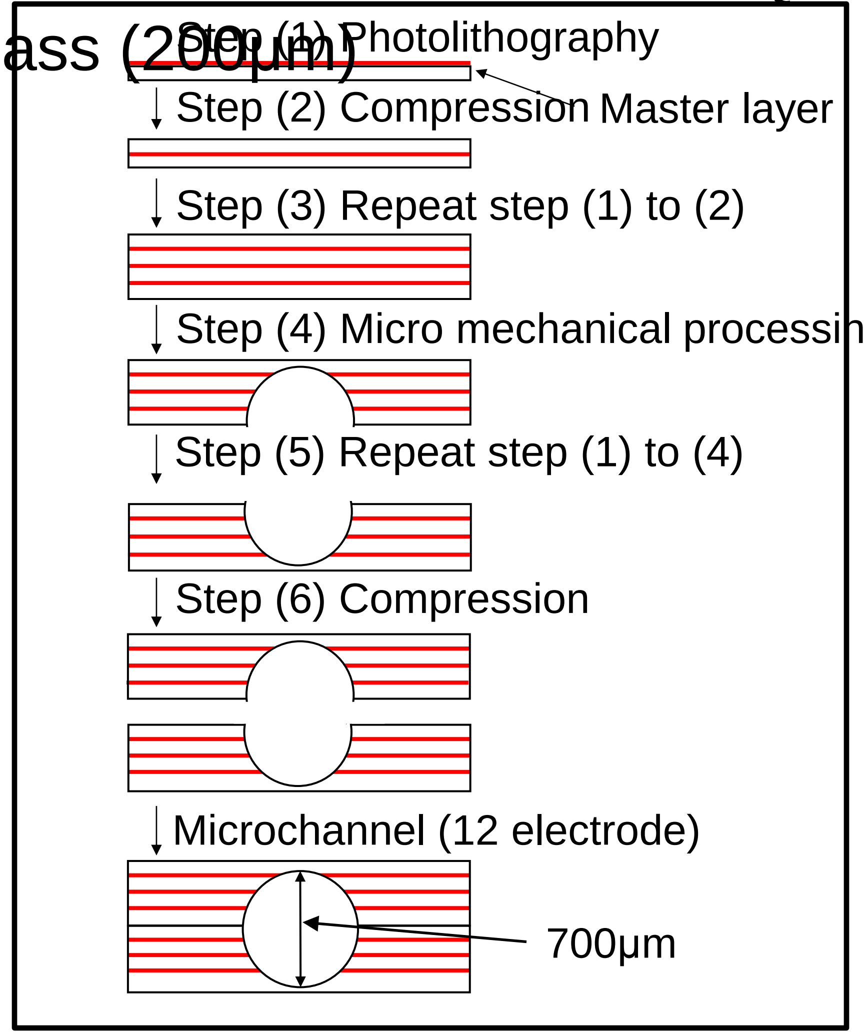


Fig. (a) 3D microchannel, (b) Cross-sectional and (c) Micro CT microchannel

Fabrication Process of Microchannel

Electrode : Platinum (2.5µm*200µm)

Substrate of Microchannel : Quartz glass (200µm)



Step (1) Photolithography

Master layer

Step (2) Compression

Step (3) Repeat step (1) to (2)

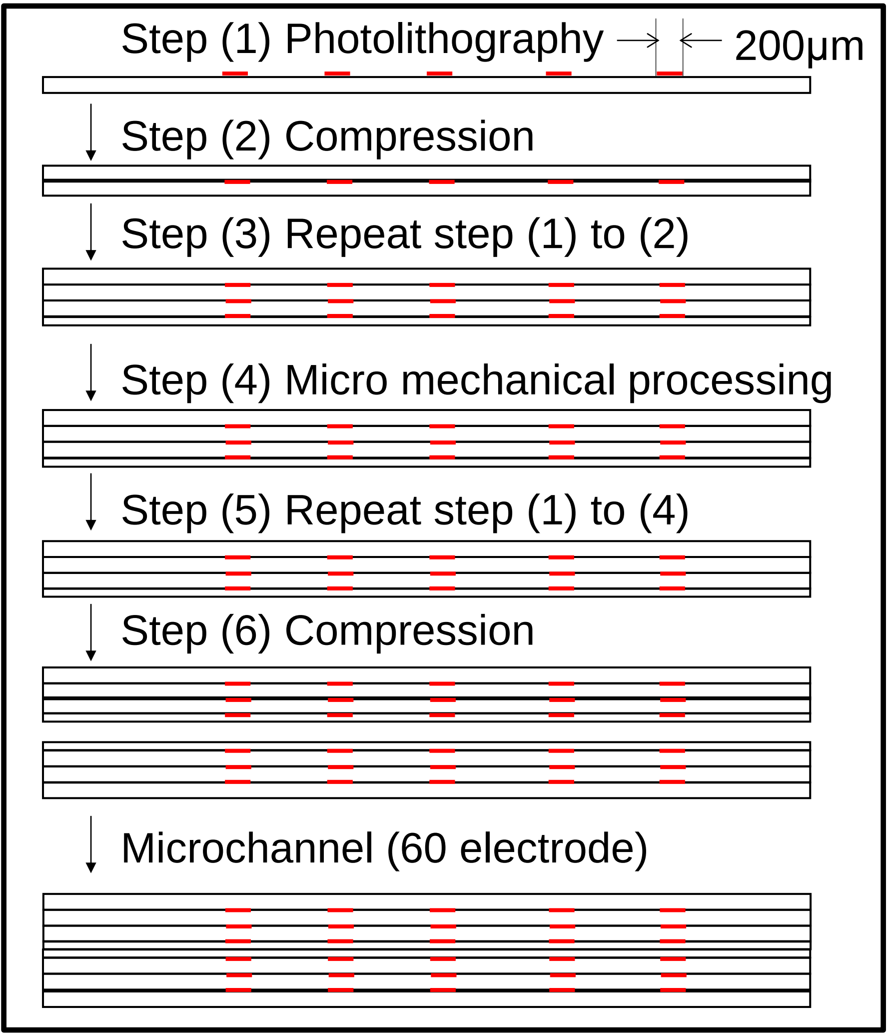
Step (4) Micro mechanical processing

Step (5) Repeat step (1) to (4)

Step (6) Compression

Microchannel (12 electrode)

Fig. Cross-section



Step (1) Photolithography

Step (2) Compression

Step (3) Repeat step (1) to (2)

Step (4) Micro mechanical processing

Step (5) Repeat step (1) to (4)

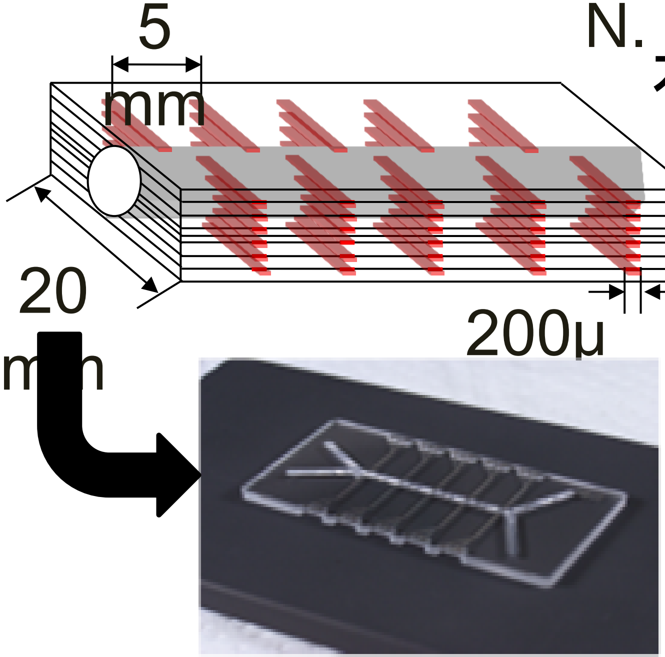
Step (6) Compression

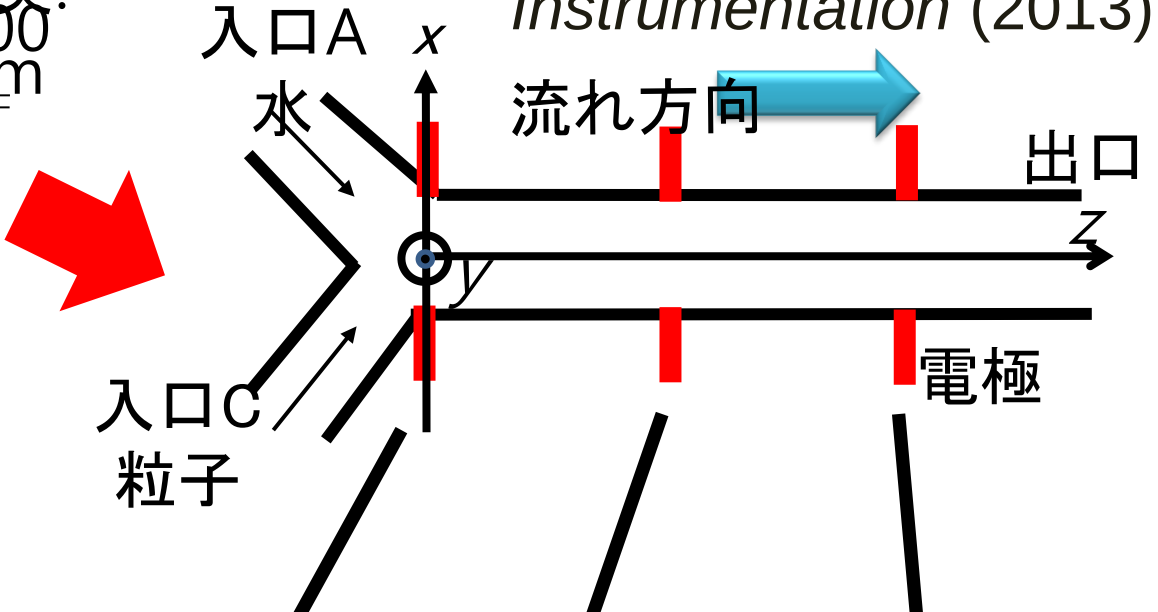
Microchannel (60 electrode)

Fig. Radial-section

PT法のマイクロ流路への応用

N. T. A. Othman et al. *Flow Measurement and Instrumentation* (2013)

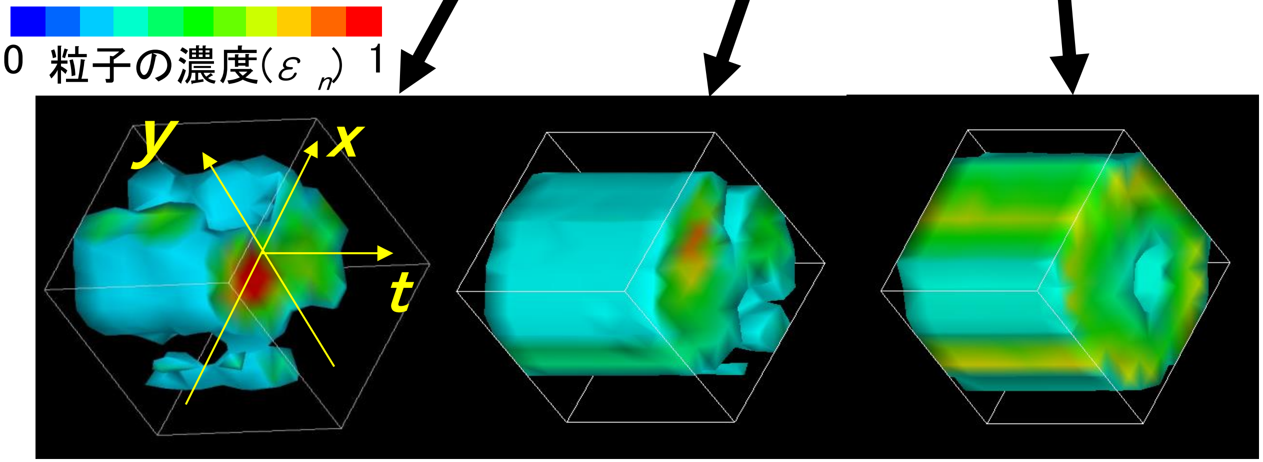




各電極間の電気量の超高速計測(1μs)

画像再構成

微粒子の濃度分布の3Dイメージング



垂直断面Ⅰ　垂直断面Ⅱ　垂直断面Ⅲ

図 PT法による微粒子の3D拡散現象のイメージング

Experimental Set-up, Method and Condition #1

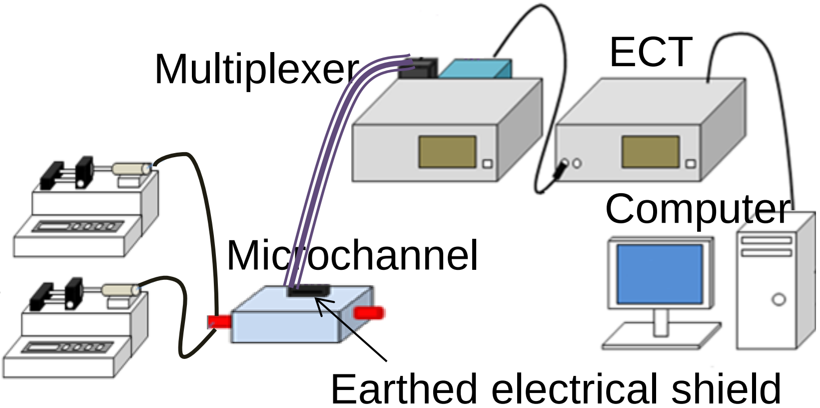


Fig. Experimental set-up

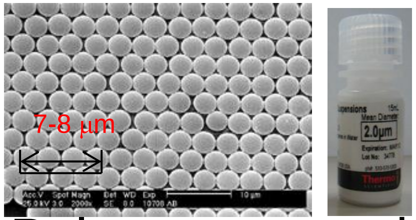
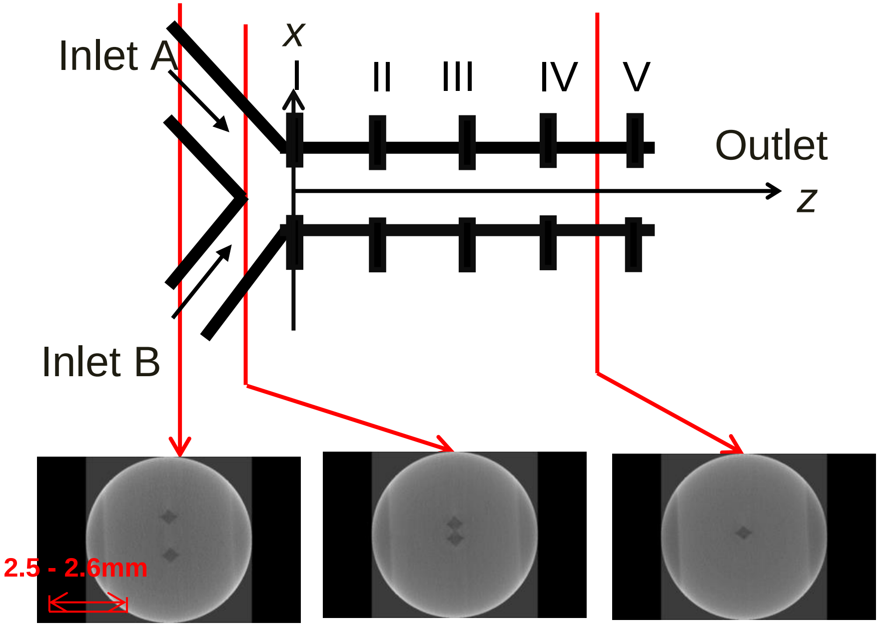


Fig. Polystyrene particle



(a) (b) (c)

Fig. Cross-sectional microchannel by micro CT

Properties of experimental condition	
Inlet A and B	Deionized water and particle
Initial particle concentration ξ [%]	3.0, 5.0 and 10.0
Particle diameter d_p [μm]	1.3, 1.5 and 2.1
Cross-section position z [mm] $z^*=z/D$ [-] with D=700μm Numbering of cross-section [-]	z=0 z=5 z=10 z=15 z=20 z^*=0 z^*=7.1 z^*=14.3 z^*=21.4 z^*=28.6 I II III IV V

Experimental Conditions #2

Liquid phase (non-conductive liquid)		Micro particle phase (dielectric particle)	
Fluid	Deionized water	Particle shape (Duke Scientific Co., USA)	Polystyrene Spherical
Density, ρ^L [kg/m^3]	1000	Density, ρ^P [kg/m^3]	1050
Flow Reynolds number R_e	4.0	Particle Reynolds number R_{ep}	0.42
Relative permittivity, ε^L	15.0	Relative permittivity, ε^P	2.55
Resistivity, ρ^L [Ωm]	1.8×10^5	Resistivity, ρ^P [Ωm]	2.8×10^5
Conductivity, σ^L [S/m]	5.5×10^{-6}	Conductivity, σ^P [S/m]	1.0×10^{-6}
Flow rate, v [μL/s]	1.0		

Properties of multi capacitance sensing	
Measurement frequency [MHz]	12.5
Voltage [V]	4.5
Electric fields, $\boldsymbol{E}$ [V/mm] where $\boldsymbol{E} = -\nabla \boldsymbol{V}(l)$	2.0 - 5.0
Sampling time, t [seconds]	100
Data measurement [frame/seconds]	820

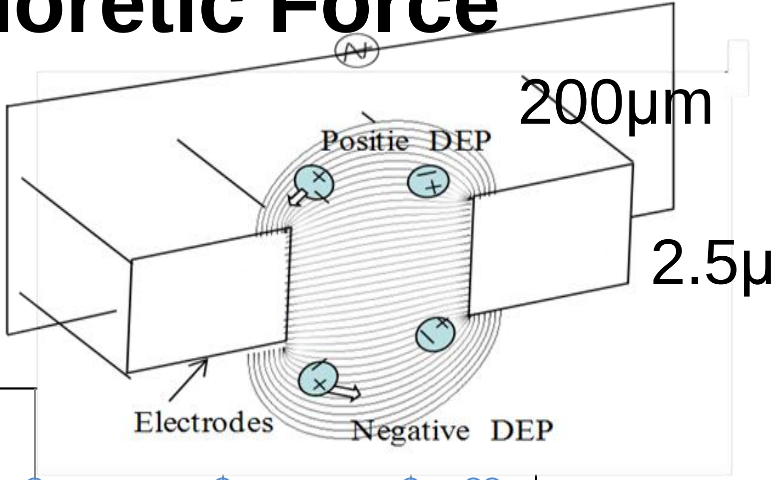
Negligible Dielectrophoretic Force

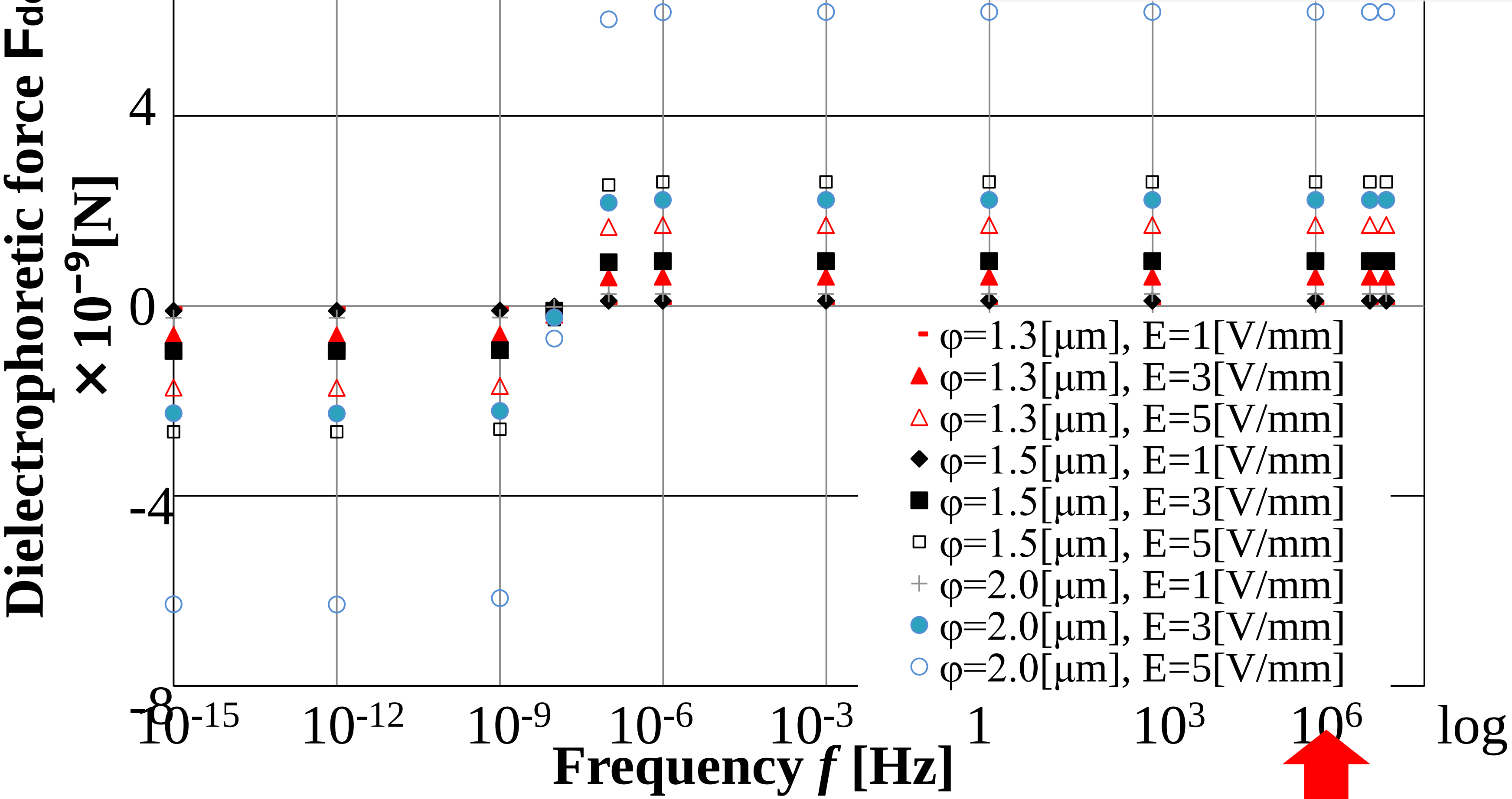
$$\mathbf{F}_{\mathbf{dep}} = 2\pi\left(\frac{d}{2}\right)^3 \varepsilon_m \,\mathrm{Re}\left[K(\omega)\right]\nabla\left|\mathbf{E}\right|^2$$

$$K(\omega)=\frac{\varepsilon_p{}^* - \varepsilon_m{}^*}{\varepsilon_p{}^* + 2\varepsilon_m{}^*}$$

$$\varepsilon_p{}^* = \varepsilon_p - j\frac{\sigma_p}{\omega}$$

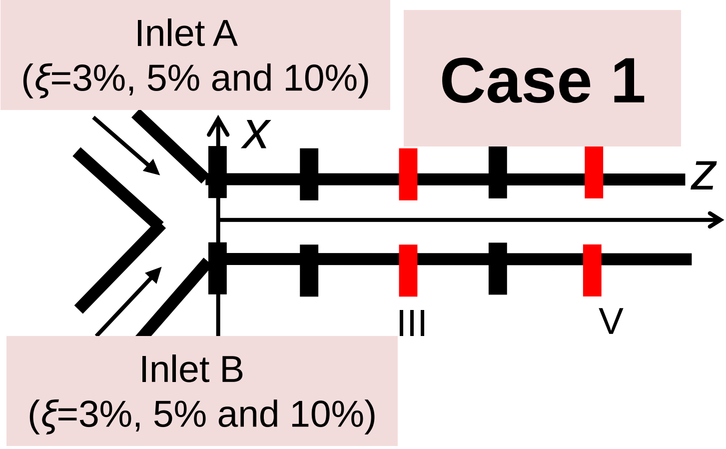
$$\varepsilon_m{}^* = \varepsilon_m - j\frac{\sigma_m}{\omega}$$





Experimental Conditions #3 --- *ξ*, d_p and *z* ---

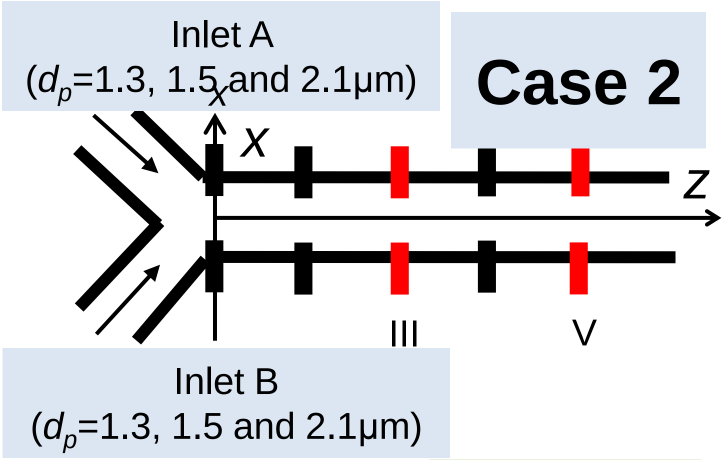
#	Initial concentration ξ [%]	Particle diameter d_p [μm]	Cross-sectional measurement position *z* I	II	III	IV	V
1	3.0 5.0 10.0	2.1			✓ ✓ ✓		✓ ✓ ✓
2	3.0	1.3 1.5 2.1			✓ ✓ ✓		✓ ✓ ✓
3	10.0	2.1	✓	✓	✓	✓	✓



Case 1

Inlet A
(ξ=3%, 5% and 10%)

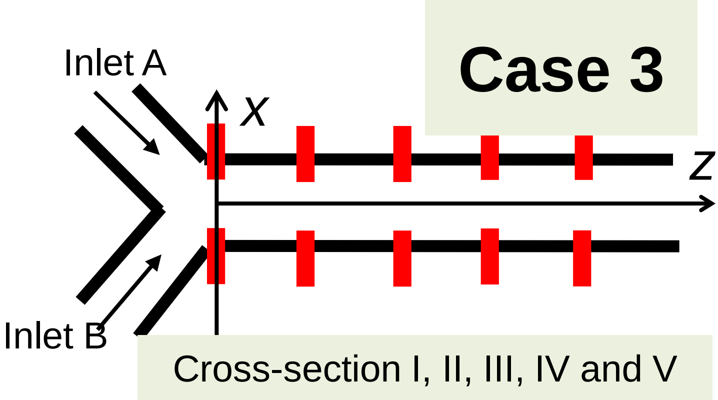
Inlet B
(ξ=3%, 5% and 10%)



Case 2

Inlet A
(d_p=1.3, 1.5 and 2.1μm)

Inlet B
(d_p=1.3, 1.5 and 2.1μm)



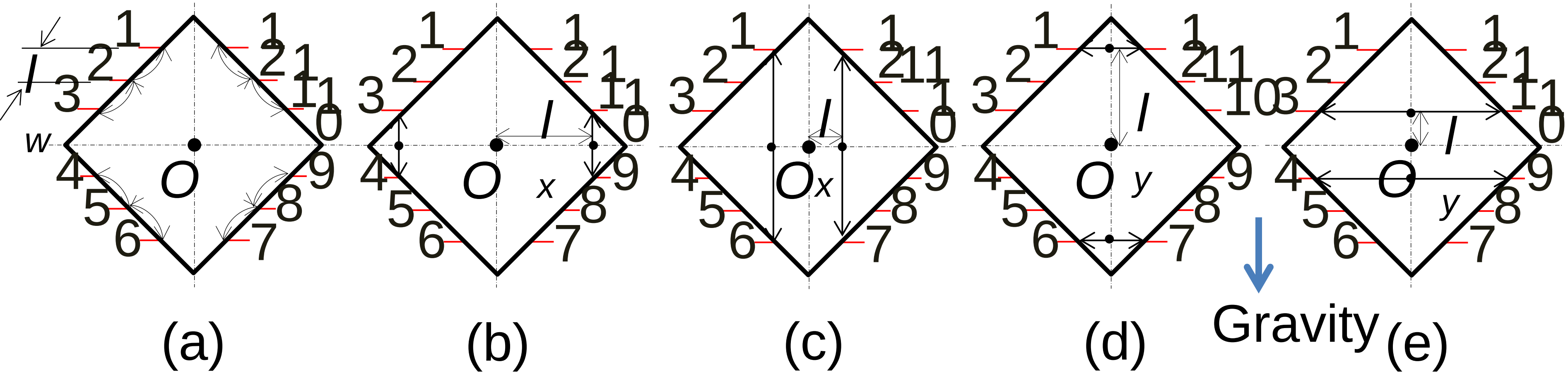
Case 3

Inlet A

Inlet B

Cross-section I, II, III, IV and V

Configuration Electrode Pair Areas



(a)Adjacent pair (b) Vertical wall (c)Vertical center (d)Horizontal wal
(e)Horizontal center

Adjacent pair	Electrode pair, i-j	1-2	2-3	4-5	5-6	7-8	10-11
	Distance between electrode, l_w [μm]	120	120	120	120	120	120
Vertical pair	Electrode pair, i-j	3-4	2-5	1-6	7-12	8-11	9-10
	Distance electrode from x-axis, l_x [μm]	-300	-180	-60	60	180	300
Horizontal pair	Electrode pair, i-j	1-12	2-11	3-10	4-9	5-8	6-7
	Distance electrode from y-axis, l_y [μm]	-300	-180	-60	60	180	300

Capacitance Measurement Circuit

Conventional circuit

Technical Report of Agilent Technology LCR meter

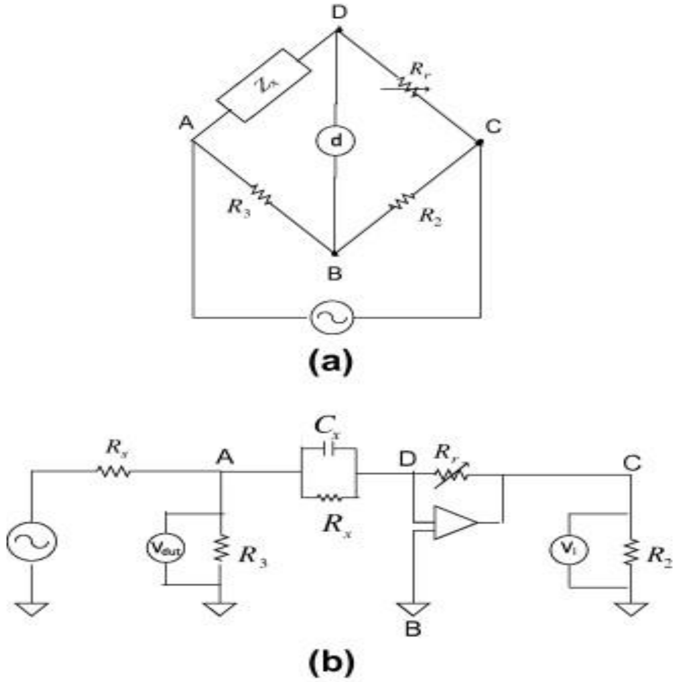


Fig. Equivalent circuit for the capacitance measuring module: (a) Bridge method and (b) Auto balancing bridge method

Equivalent circuit not measure capacitance directly but from reactance.

Direct measurement circuit

W Q Yang, et al.,*Meas. Sci. Technol*.(1997)

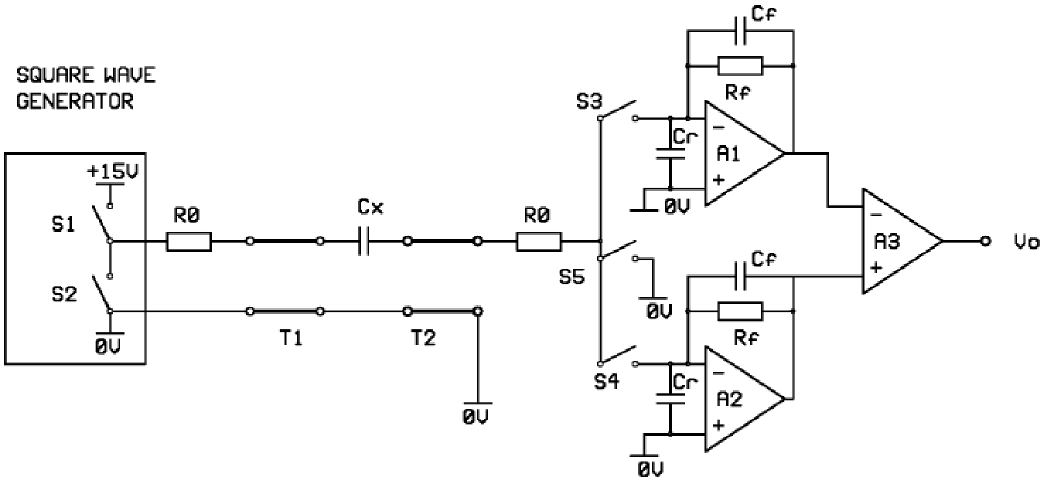
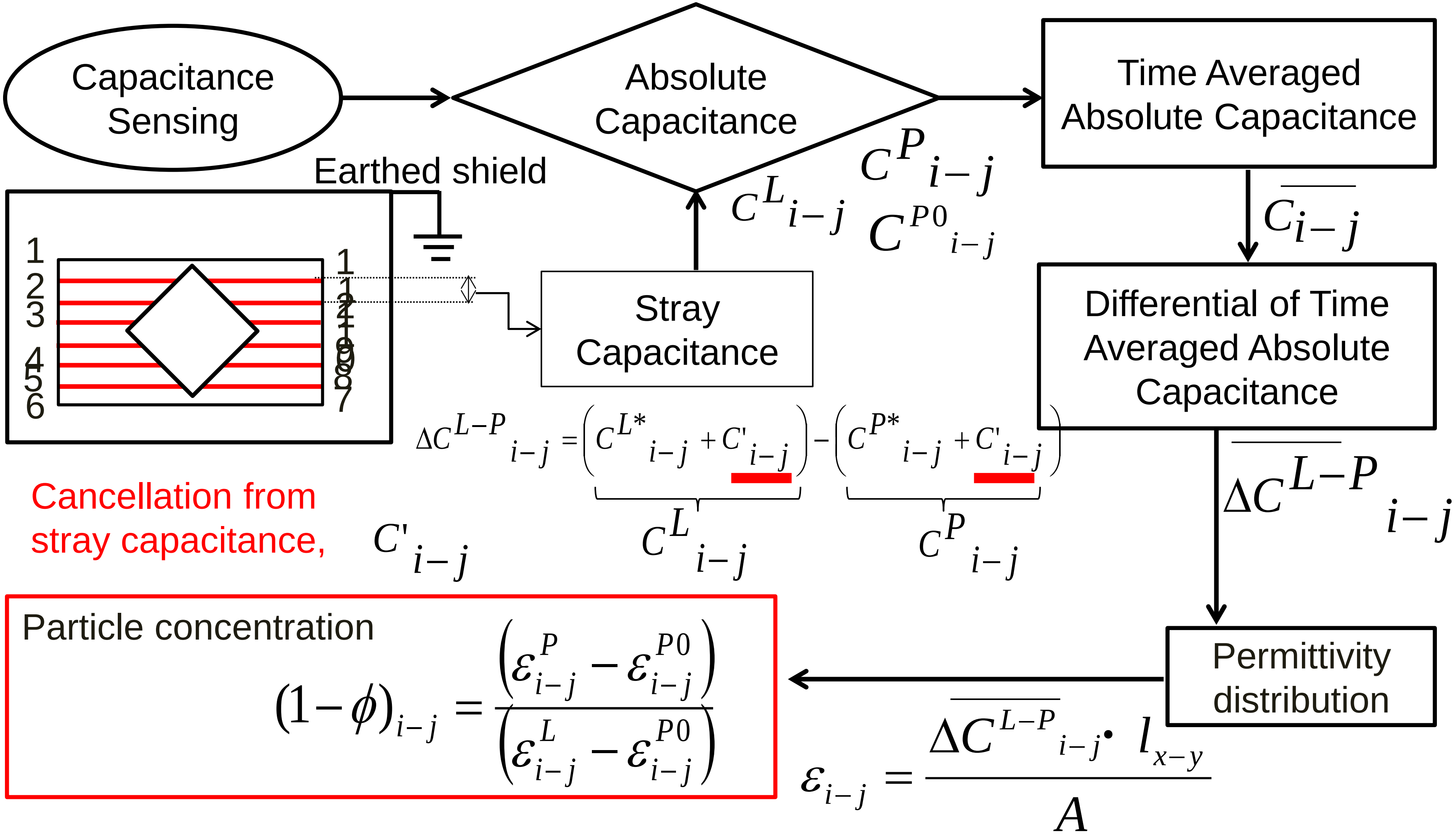


Fig. Direct capacitance measurement circuitry for a single plane of electrodes

- Very small changes in inter-electrode capacitances; order of 10^{-17} Farads (0.01 fF)
- Small capacitances between opposing electrodes (10fF)
- Larger capacitances between adjacent electrodes (500fF) at

Calculation Process on Particle Concentration



Capacitance Sensing

Absolute Capacitance

Time Averaged Absolute Capacitance

Earthed shield

C^{P}_{i-j} C^{L}_{i-j} C^{P0}_{i-j}

$\overline{C_{i-j}}$

Stray Capacitance

Differential of Time Averaged Absolute Capacitance

$$\Delta C^{L-P}_{i-j} = \underbrace{\left(C^{L*}_{i-j} + C'_{i-j}\right)}_{C^{L}_{i-j}} - \underbrace{\left(C^{P*}_{i-j} + C'_{i-j}\right)}_{C^{P}_{i-j}}$$

Cancellation from stray capacitance, C'_{i-j}

$\overline{\Delta C^{L-P}}_{i-j}$

Permittivity distribution

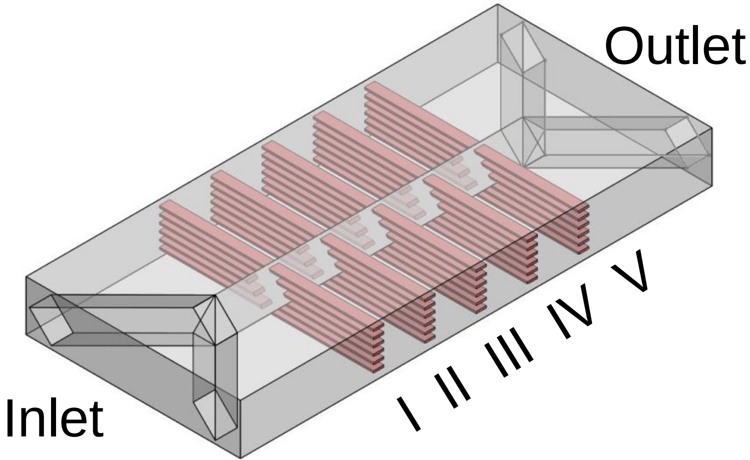
Particle concentration

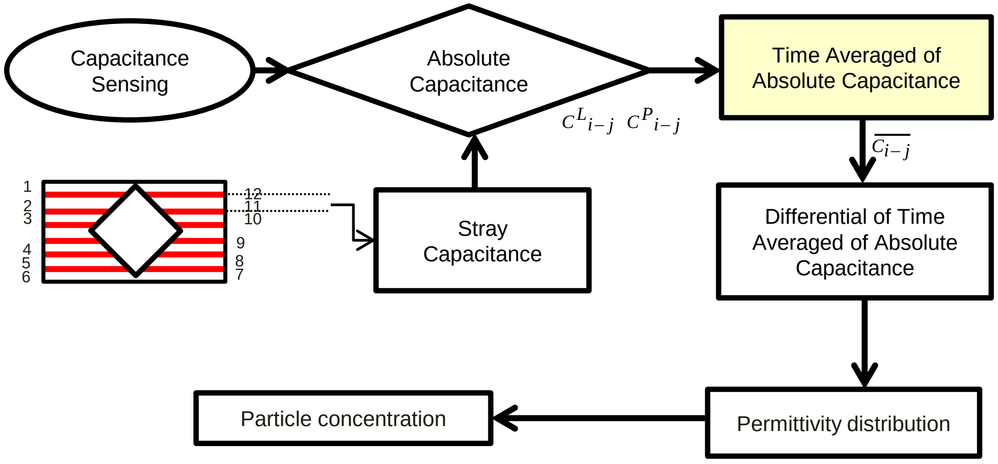
$$(1-\phi)_{i-j} = \frac{\left(\varepsilon^{P}_{i-j} - \varepsilon^{P0}_{i-j}\right)}{\left(\varepsilon^{L}_{i-j} - \varepsilon^{P0}_{i-j}\right)}$$

$$\varepsilon_{i-j} = \frac{\overline{\Delta C^{L-P}}_{i-j} \cdot l_{x-y}}{A}$$

Symbol: *C* = capacitance, *ε* = permittivity, (1-*ϕ*) = particle concentration, l_{x-y} = distance between electrode pair, *A* = area of electrode, *i* = source electrode and *j* = detector electrode Superscript : *L* = deionized water flow, *P0* = static particle, *P* = particle flow, *C** = actual capacitance value and *C'* = stray capacitance

Time Averaged Absolute Capacitance in Case 1





Capacitance Sensing

Absolute Capacitance

Time Averaged of Absolute Capacitance

$C^{L}{}_{i-j}$ $C^{P}{}_{i-j}$

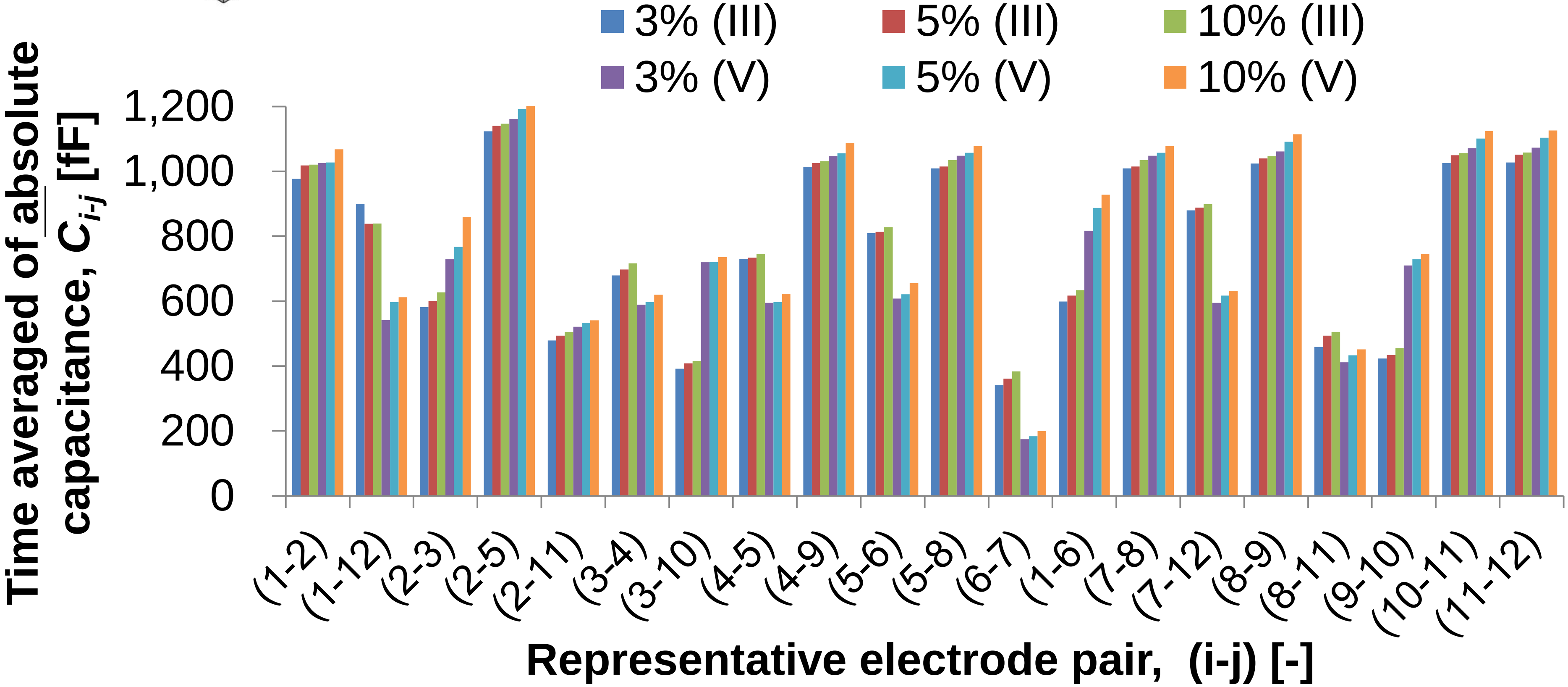
$\overline{C_{i-j}}$

Stray Capacitance

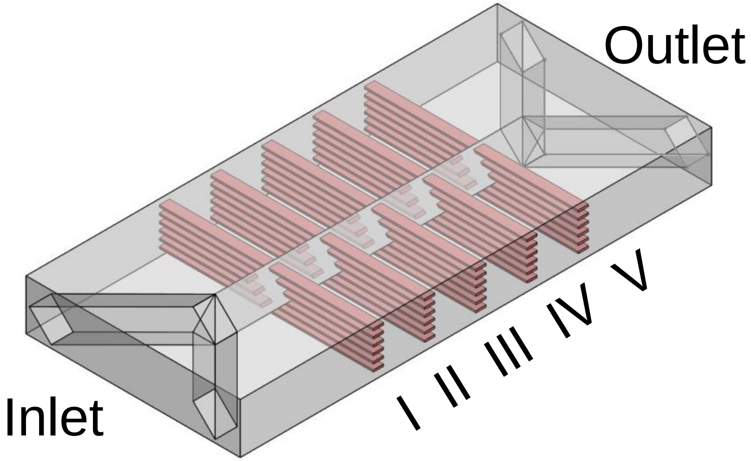
Differential of Time Averaged of Absolute Capacitance

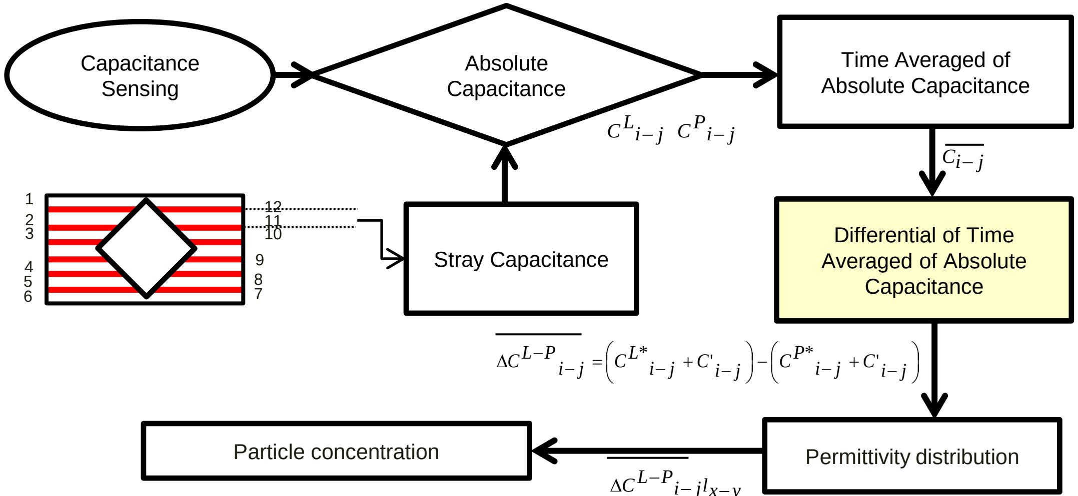
Permittivity distribution

Particle concentration



Differential of Time Averaged Absolute Capacitance in Case 1





Capacitance Sensing

Absolute Capacitance

$C^{L}{}_{i-j}$ $C^{P}{}_{i-j}$

Time Averaged of Absolute Capacitance

$\overline{C_{i-j}}$

Stray Capacitance

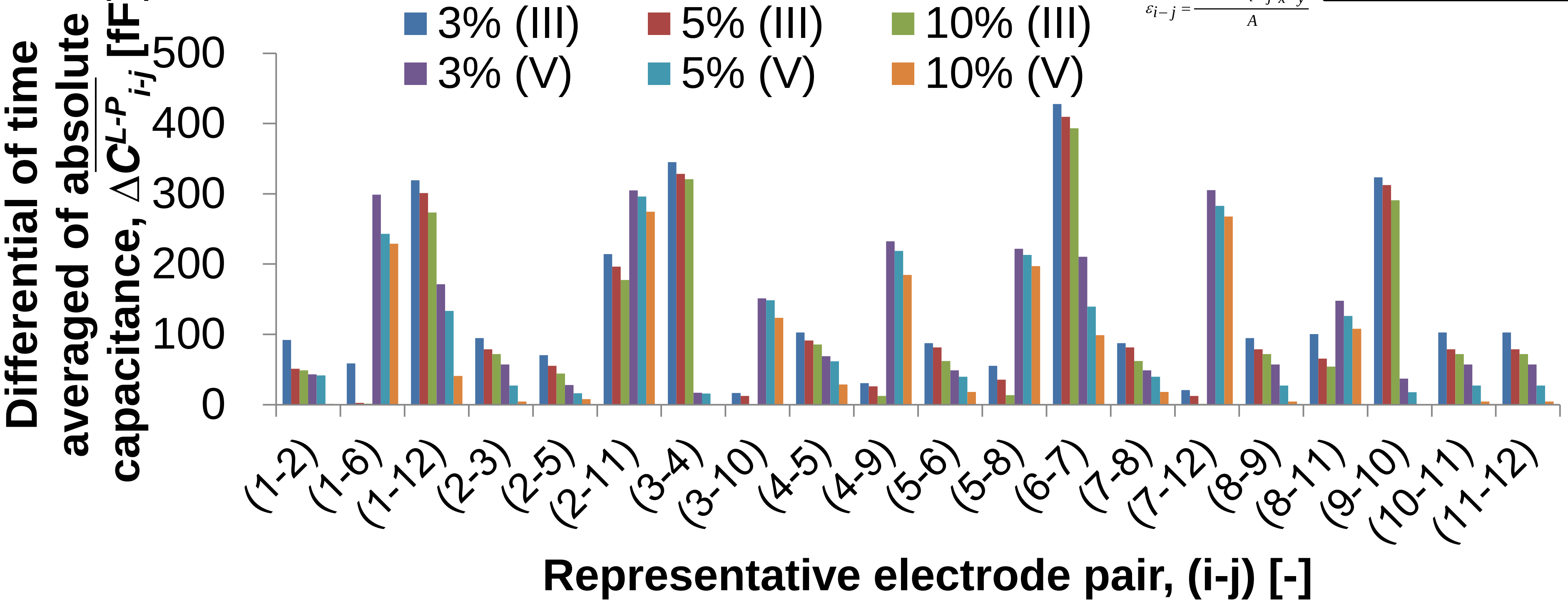
Differential of Time Averaged of Absolute Capacitance

$$\overline{\Delta C^{L-P}{}_{i-j}} = \left(C^{L*}{}_{i-j} + C'_{i-j}\right) - \left(C^{P*}{}_{i-j} + C'_{i-j}\right)$$

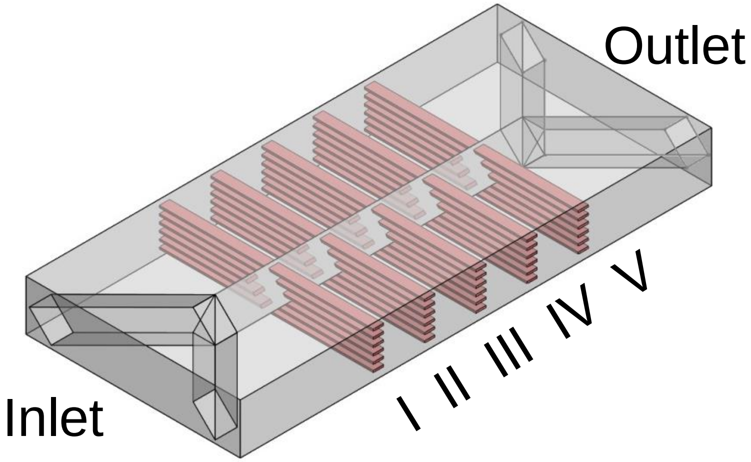
Permittivity distribution

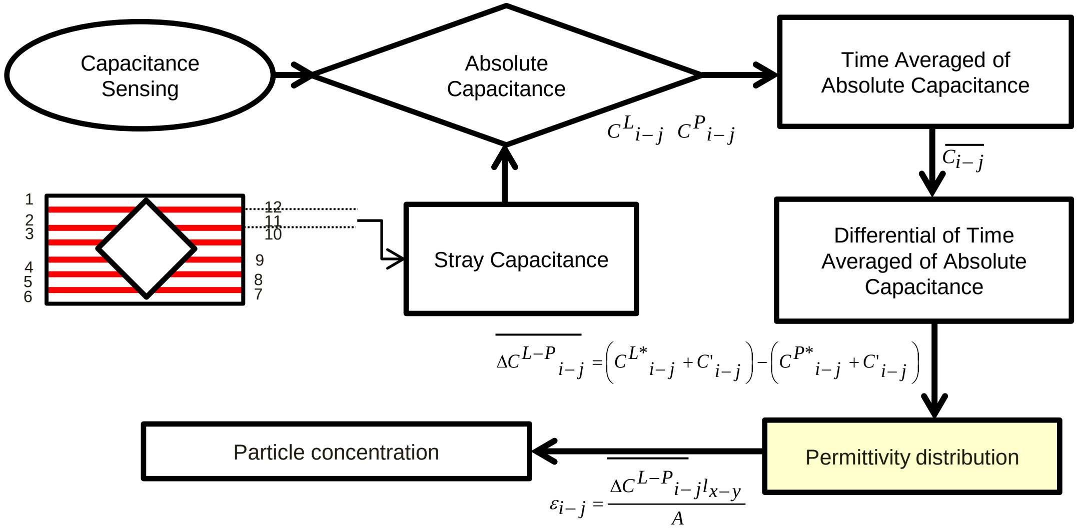
$$\varepsilon_{i-j} = \frac{\overline{\Delta C^{L-P}{}_{i-j}} l_{x-y}}{A}$$

Particle concentration



Permittivity Distribution in Case 1





Capacitance Sensing

Absolute Capacitance

C^{L}_{i-j} C^{P}_{i-j}

Time Averaged of Absolute Capacitance

$\overline{C_{i-j}}$

Stray Capacitance

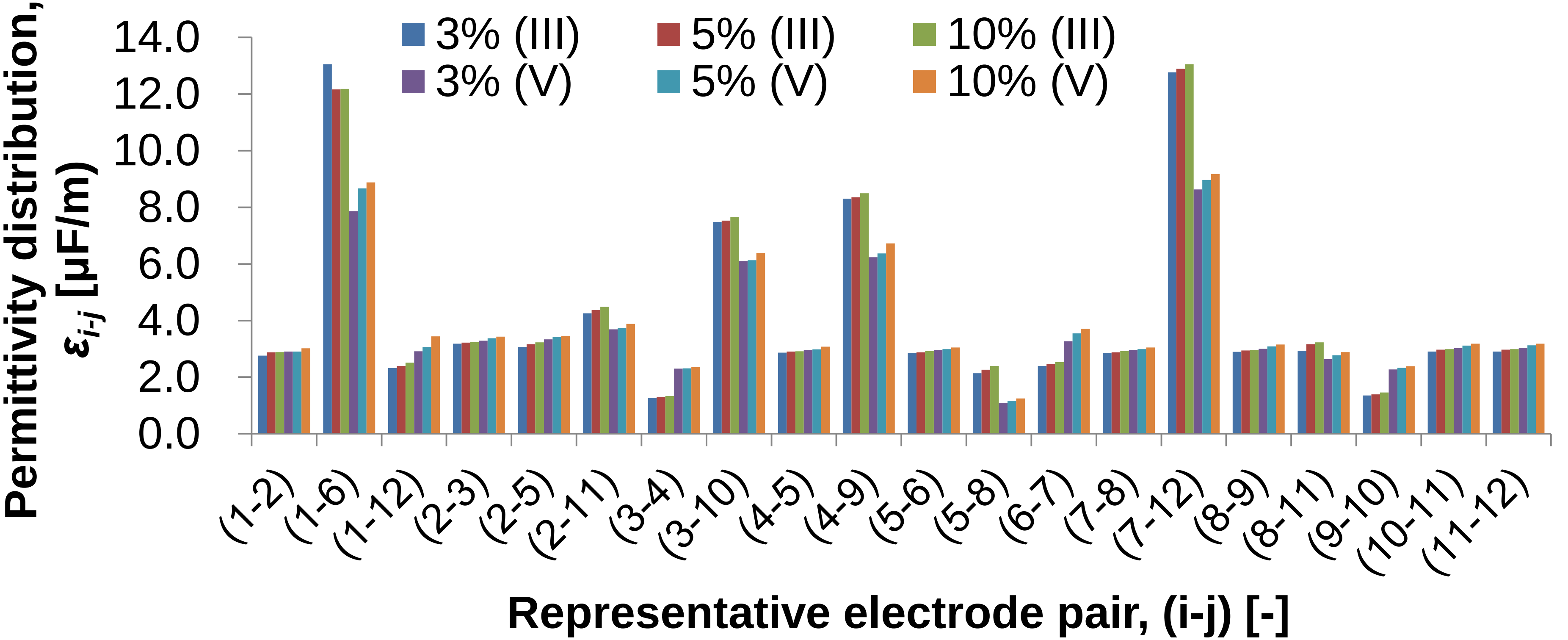
Differential of Time Averaged of Absolute Capacitance

$$\overline{\Delta C^{L-P}_{i-j}} = \left(C^{L*}_{i-j} + C'_{i-j}\right) - \left(C^{P*}_{i-j} + C'_{i-j}\right)$$

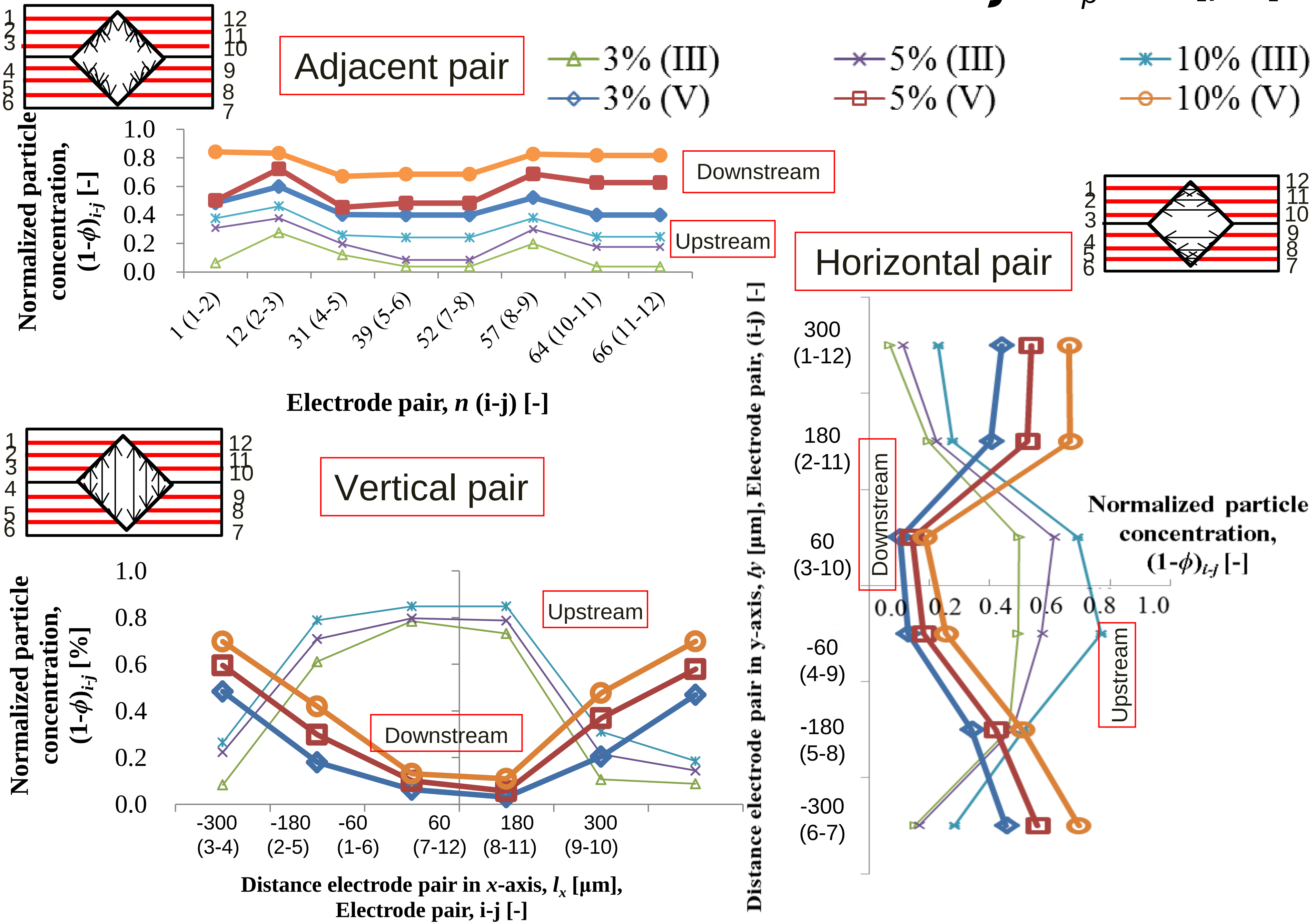
Permittivity distribution

$$\varepsilon_{i-j} = \frac{\overline{\Delta C^{L-P}_{i-j}}\, l_{x-y}}{A}$$

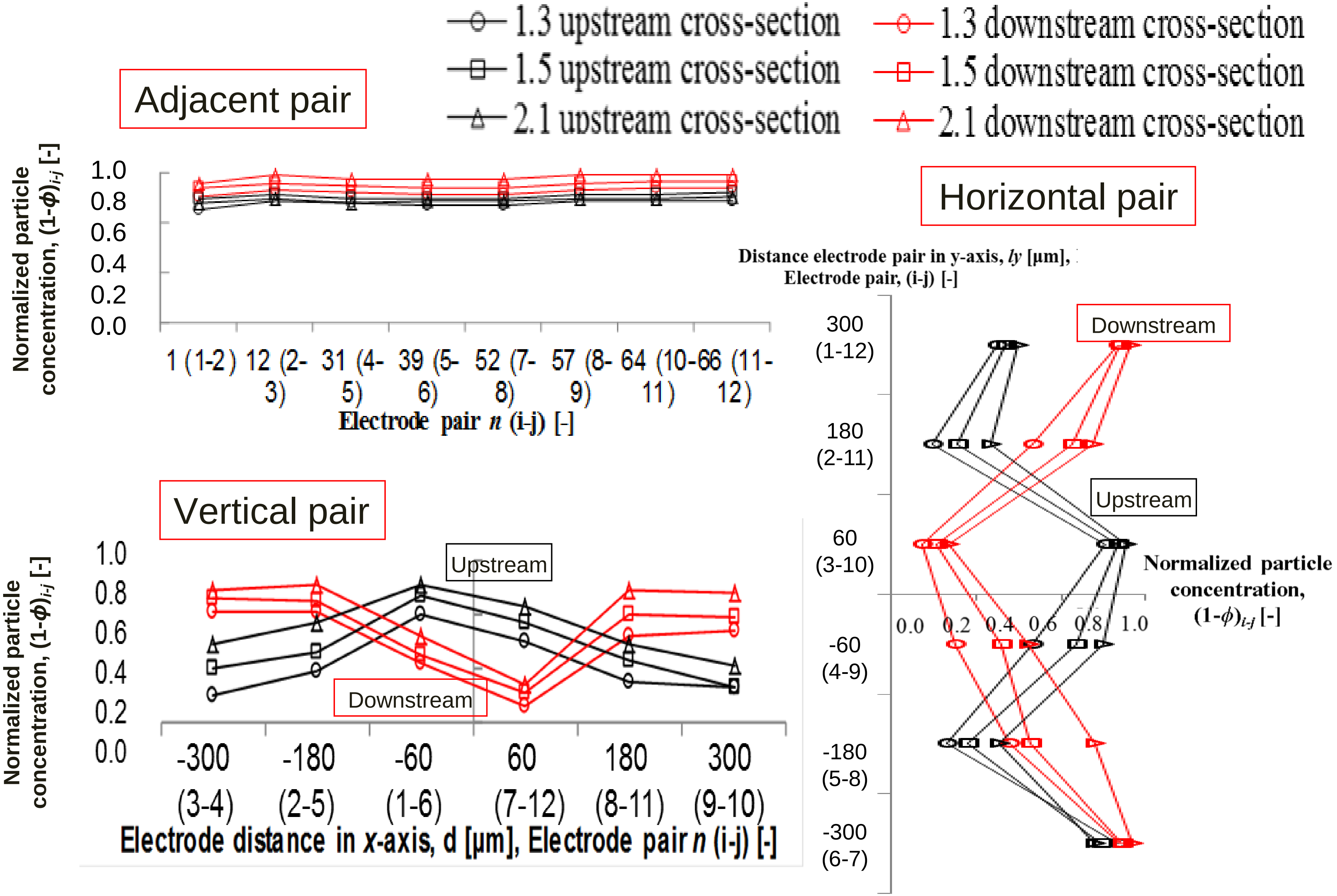
Particle concentration



Particle Concentration : Effect of ξ d_p =2.1[μm]



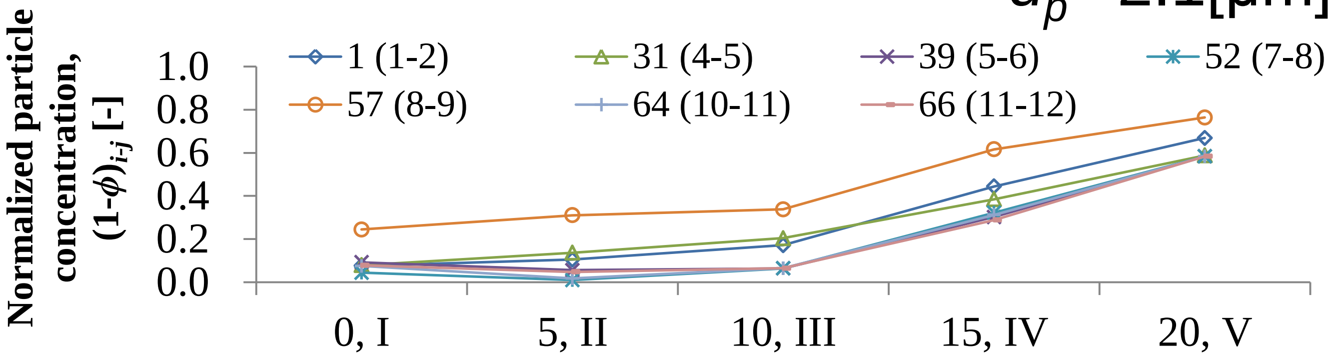
Particle Concentration : Effect of d_p ξ=3.0[%],



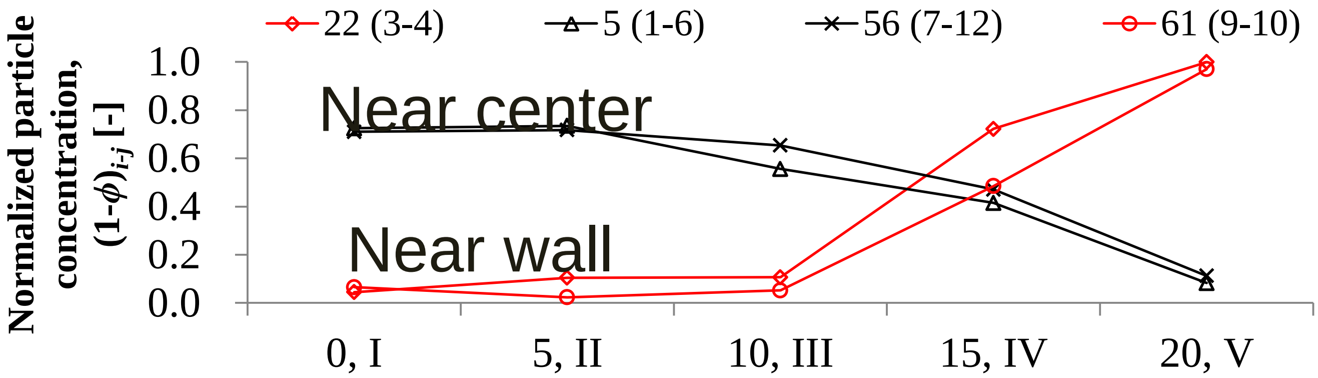
Particle Concentration : Effect of *z*

ξ=10.0[%],
d_p =2.1[μm]

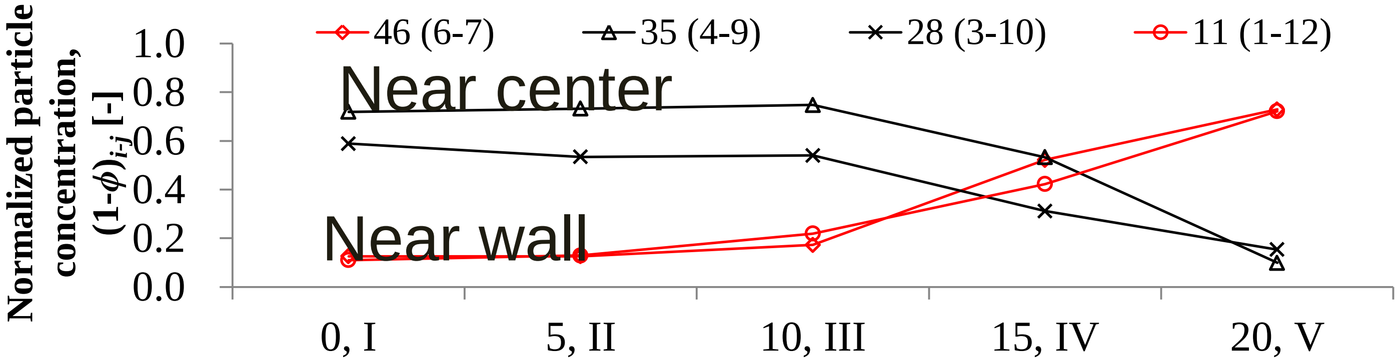
Adjacent pair



Vertical pair



Horizontal pair



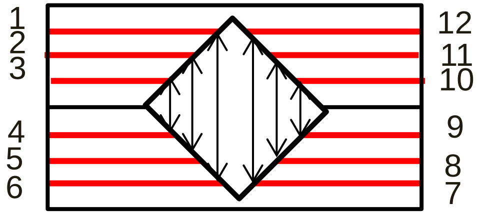
Position from inlets, *z* [mm], Cross-section [-]

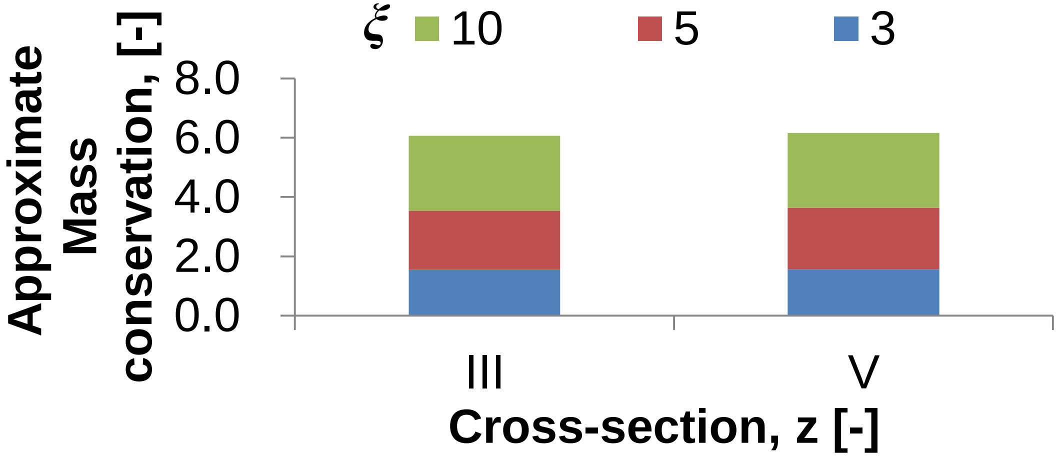
Mass Conservation in ξ

Mass Conservation [kg/s] $\iint \rho_p (1-\phi) u_p \, dx\, dy$

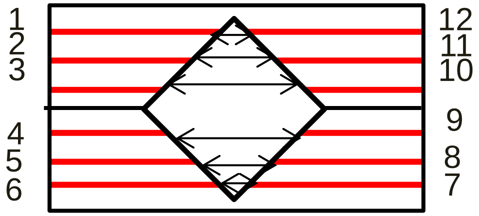
Approximate Mass Conservation [-] $\Sigma[\rho_p(1-\phi)]_{i\text{-}j}$

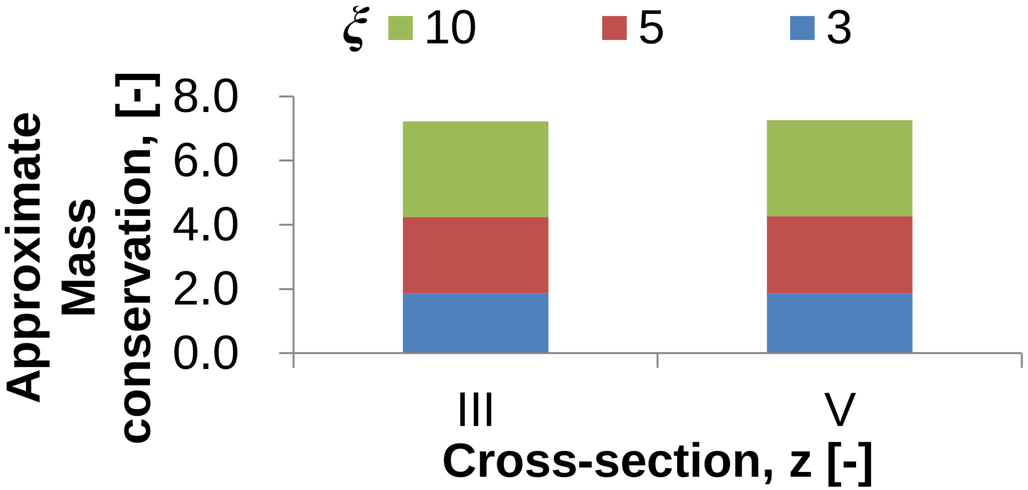
Vertical pair



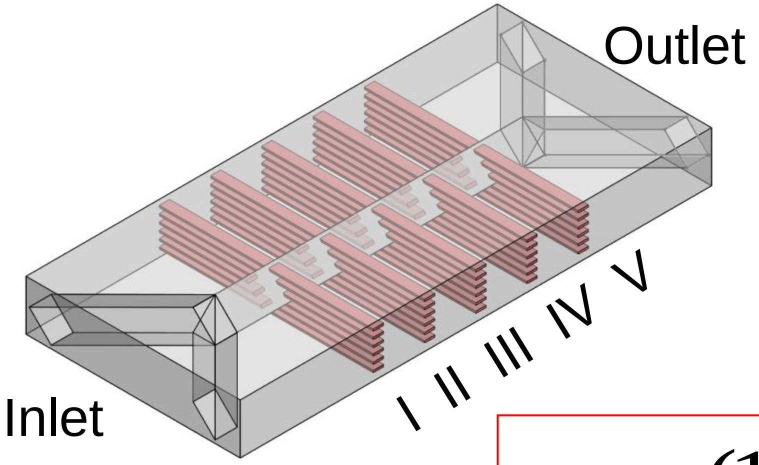


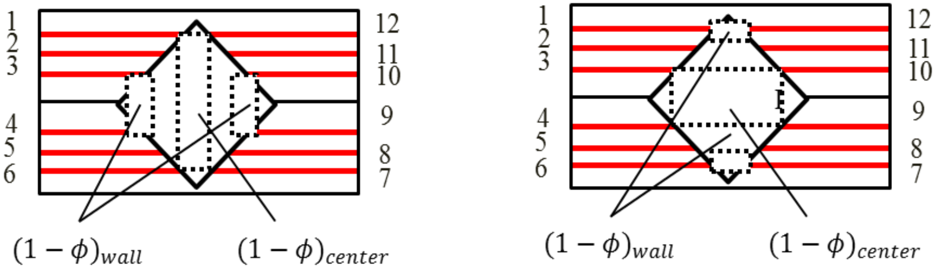
Horizontal pair





Particle Migration Ratio Φ --Effect of *ξ* and *z*--





$$\Phi = \frac{(1-\phi)_{wall}}{(1-\phi)_{center}}$$

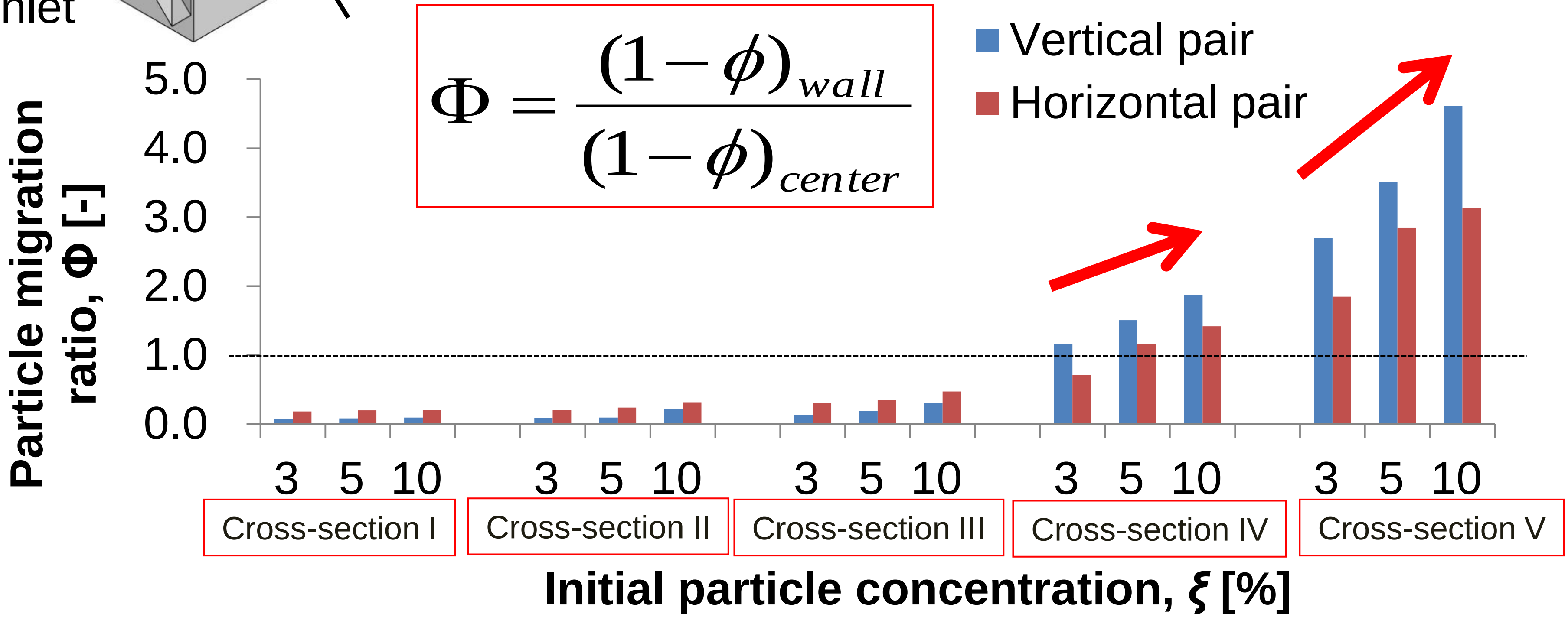
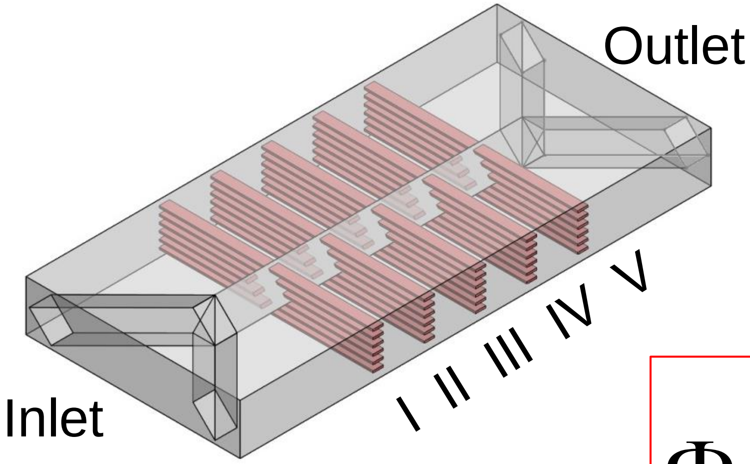
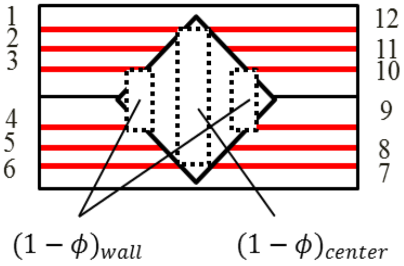
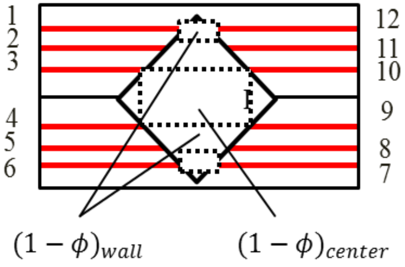


Fig. Particle migration ratio at cross-section I to V, at vertical and horizontal pair for *ξ*=3.0, 5.0 and 10.0%

Particle Migration Ratio Φ -- Effect of d_p --







$$\Phi = \frac{(1-\phi)_{wall}}{(1-\phi)_{center}}$$

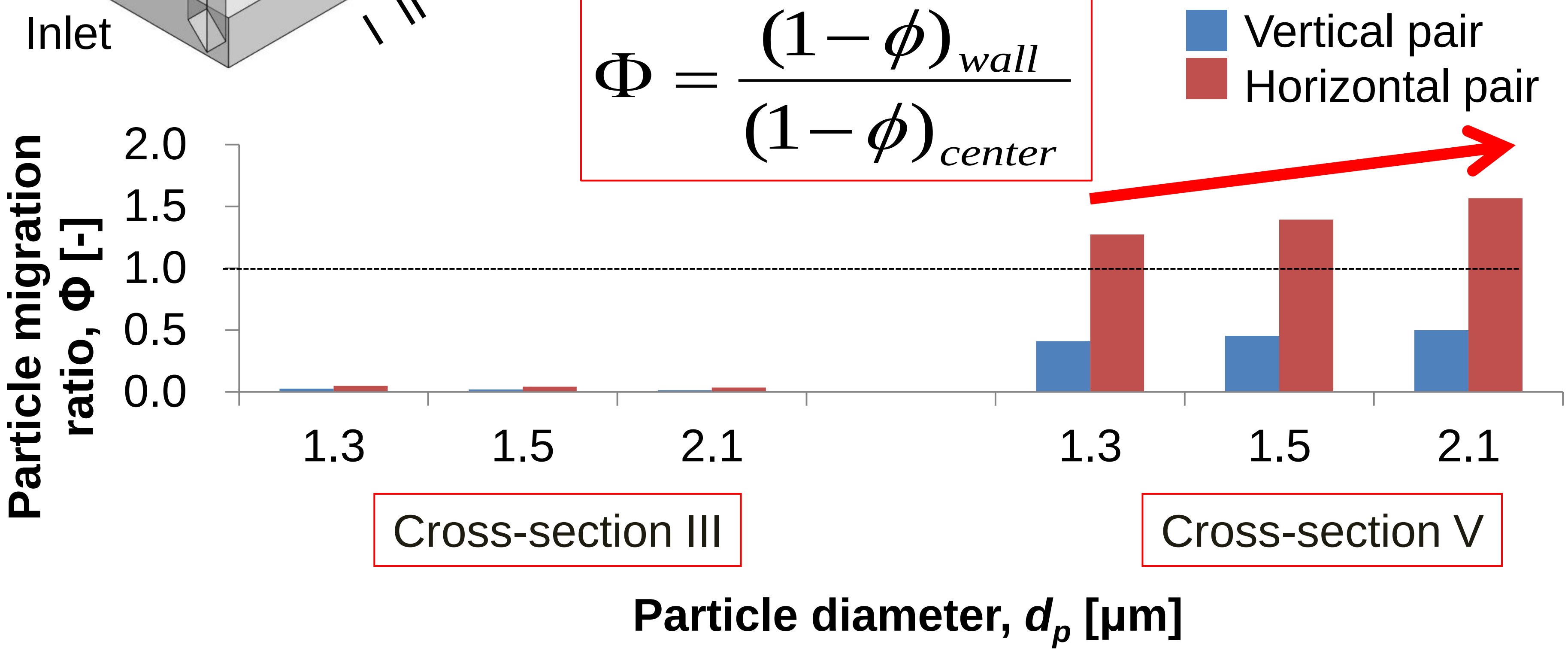


Fig. Particle migration ratio at cross-section III and V, at vertical and horizontal pair for d_p=1.3 μm, 1.5 μm and 2.1 μm

Streamline Migration Ψ --Effect of *ξ* and *z*--

$$\Psi_{wall,center}^{(n)to(n+1)} = \frac{(1-\phi)_{wall,center}^{(n+1)}}{(1-\phi)_{wall,center}^{(n)}}$$

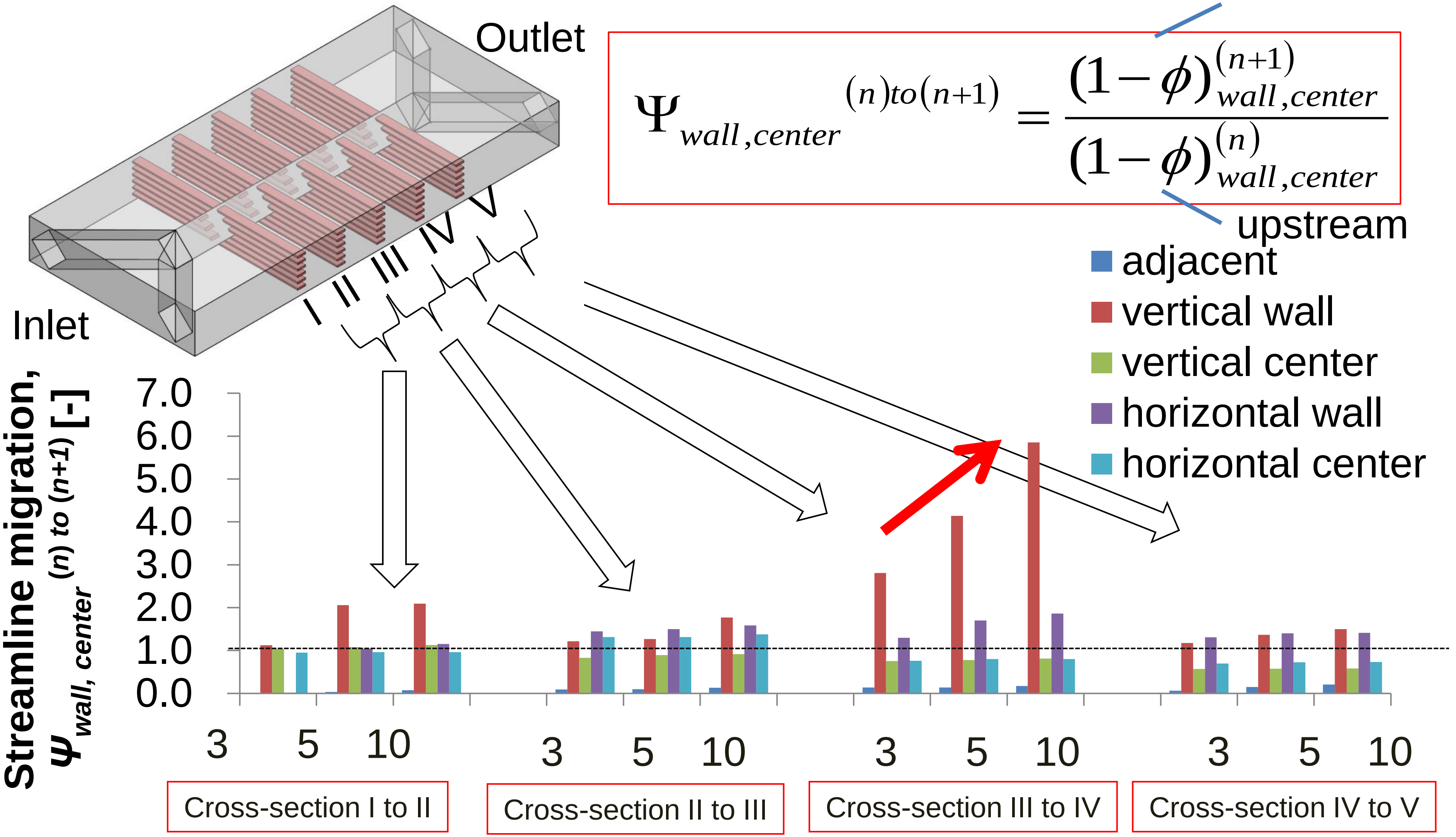
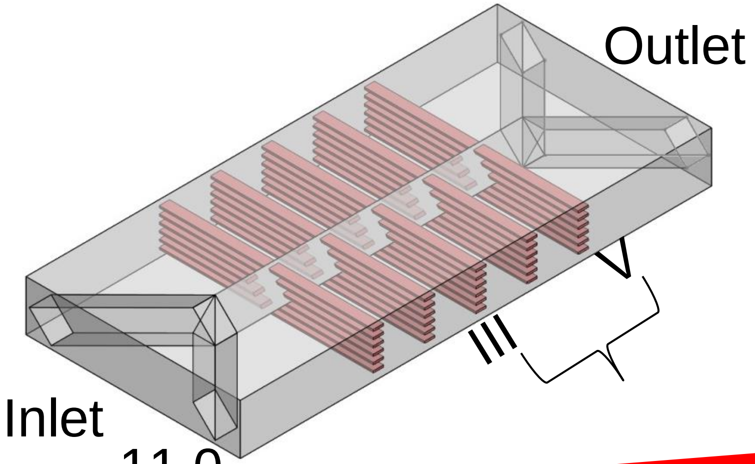


Fig. Streamline migration ratio at adjacent, wall and center of vertical and horizontal pair from cross-section I to V at ξ=3.0, 5.0 and 10.0%

Streamline Migration Ψ -- Effect of d_p --



downstream

$$\Psi_{wall,center}^{(n)to(n+1)} = \frac{(1-\phi)_{wall,center}^{(n+1)}}{(1-\phi)_{wall,center}^{(n)}}$$

upstream

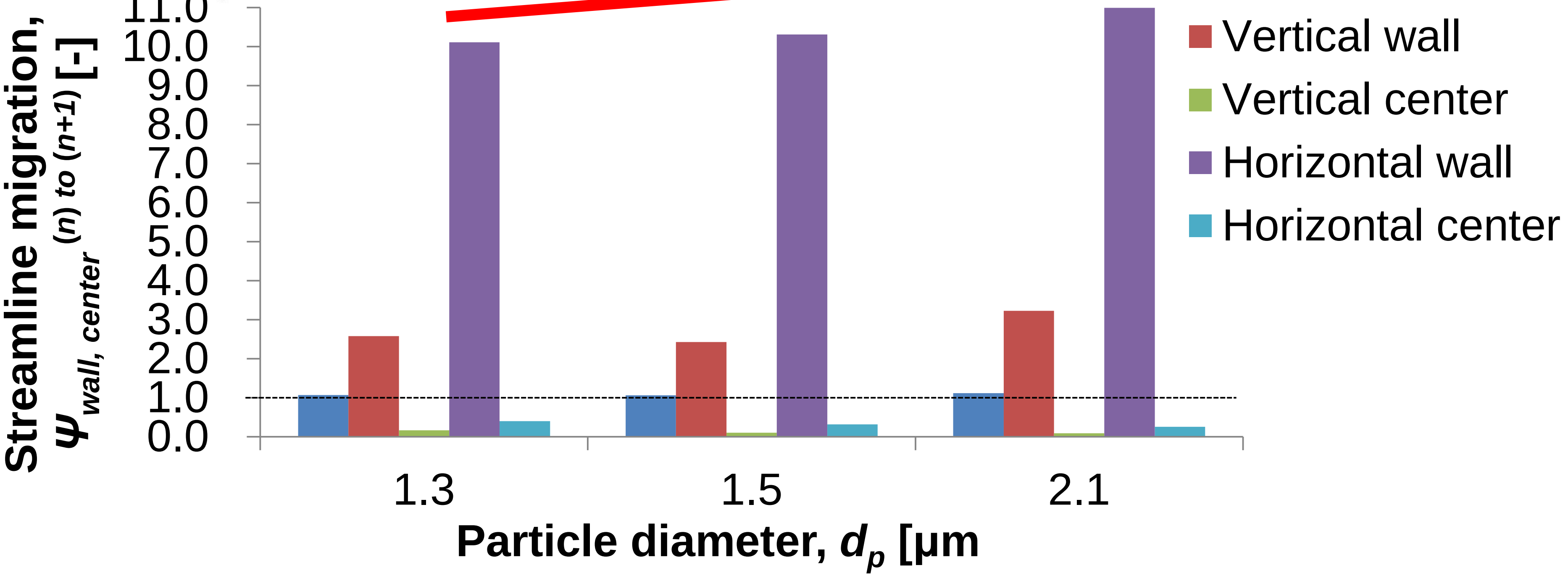


Fig. Streamline migration ratio at adjacent, wall and center of vertical and horizontal pair from upstream to downstream for d_p=1.3 μm, 1.5 μm and 2.1 μm

まとめ

- **PTの概要　ソフトフィールドとハードフィールド**
- **ソフトフィールドPT**
  - **原理、プラントへの展開、血流への展開、マイクロ流路への展開**
- **ハードフィールドPT**
  - **Optical CT、X ray CT、γ ray CT、Neutron Radiography、Ultrasound CT、MRI、Positron Emission Tomography (PET)**

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