

PHOENICSの出会いと 凝固・溶融計算

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PHOENICSへの道のり

濃度融解の数値解析を模索

SIMPLER Algorithm (Patankar)が文献で良く見られた

Patankarも**自然対流**を伴った融解解析に成功 (Sparrow, Patankar, Ramadhyani (1977), Analysis of Melting in the Presence of Natural Convection in the Melt Region, J. Heat Transfer, Vol.99, p520)

SIMPLER法で成功する予感がして始めてみた

そして格闘が始まった→一応成功 (ASME に掲載)

高齢でプログラムの自作は無理→ソフトウェアを模索

PHOENICSはSIMPLEST Algorithmを用いた有限体積法→信頼できるのではと思った(実験でvalidated)

ソフトウェアを甘く考えた→再び格闘が始まった

厳密解などでValidationが必要→実験などで伝熱感覚が身につく

**series in computational
methods in mechanics
and thermal sciences**



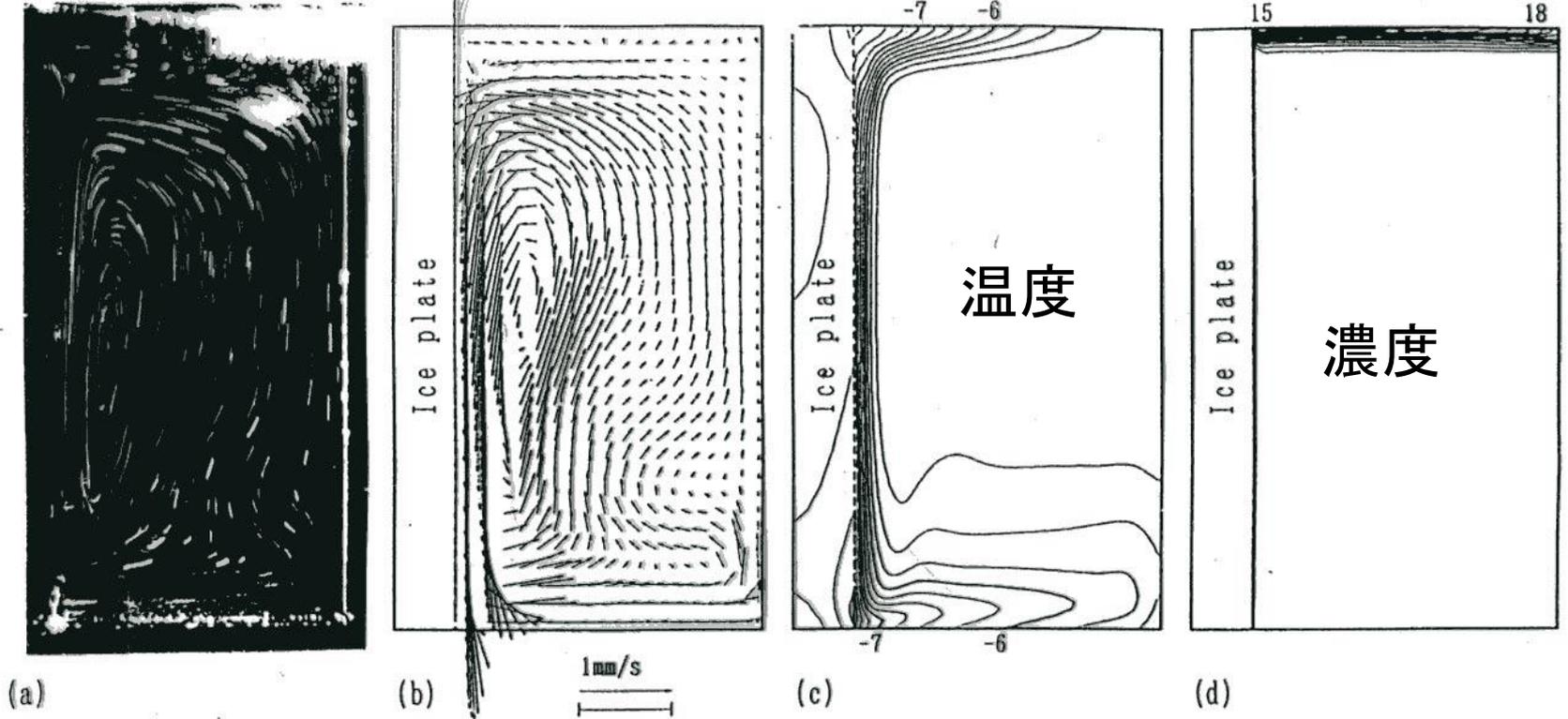
Numerical Heat Transfer and Fluid Flow

**Suhas V.
Patankar**

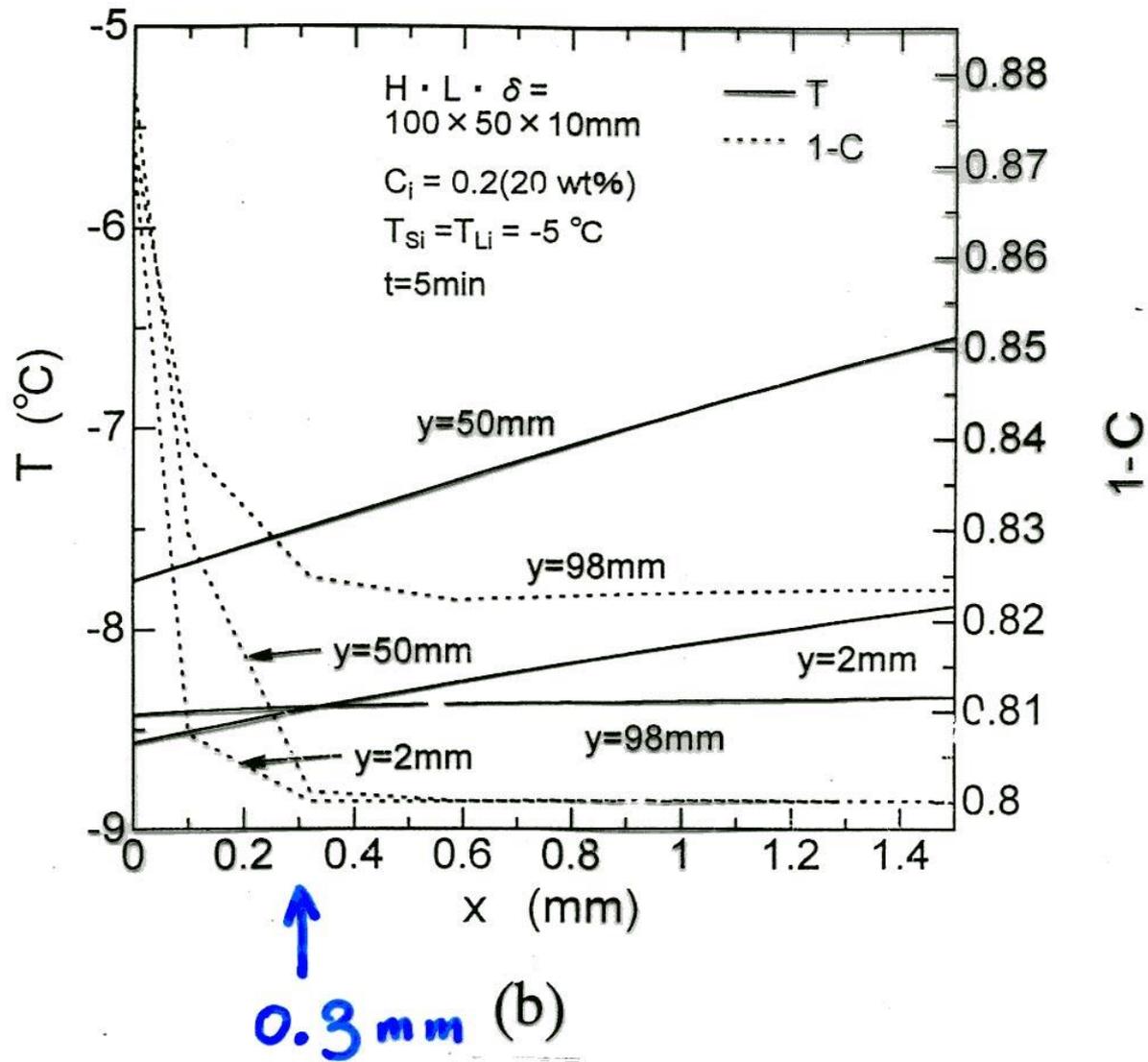
可視化実験

流れ

$t = 3 \text{ min}$



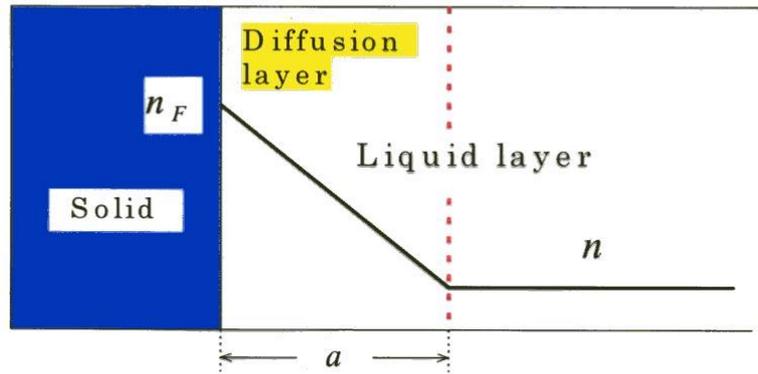
融解水溶液内の2重拡散対流の実験結果
と計算結果との比較



融解水溶液内の温度と濃度勾配の比較

Nernst's model (1904) for dissolution of solid in mixture

E. A. Moelwyn-Hughes, "The kinetics of REACTION IN SOLUTION,"
Second Edition, Oxford at The Clarendon Press.)



Nernstも同じ濃度分布
を示唆していた

Thickness of a diffusion layer $a = 0.03 \text{ m m}$

$$\frac{dn}{dt} = -D \frac{S}{V} \frac{dn}{dx} = \frac{DS}{V} \frac{n_F - n}{a} \quad \text{Fick's law}$$
$$n = n_F \left[1 - \exp\left\{ - (DS / Va) t \right\} \right],$$

where, n : concentration (molecules/cc), n_F : equilibrium concentration ,
 D : diffusion coefficient, S : area, V : volume, t : time.

The thickness of a diffusion layer, a , was determined by the results of a number of experiment.

This somewhat fictitious thickness (i.e., very thin thickness) is a physically improbable result ?

The melting rate has not yet theoretically determined although many years have passed.

解析の概要

(参考文献：Sugawara M and Beer H (2009) Numerical analysis for freezing/melting around vertically arranged four cylinders, Heat Mass Transf 45:1223-1231)

Phoenics の支配方程式の一般形 (マニュアル, Ver.2006, 式 (3.19)参照)

$$\frac{\partial}{\partial t}(r\rho\phi) + \text{div}(r\rho V\phi) - r\Gamma_{\phi} \text{grad}\phi = S_{\phi} + S_{bc}$$

固相 (氷) と液相 (水) の2相が共存するときの支配方程式.

$$\frac{\partial T}{\partial t}(\rho c_{\ell} T) + \nabla \cdot (\rho c_{\ell} VT) = \nabla \cdot (k\nabla T) - \rho h_f \frac{\partial f_{\ell}}{\partial t} + (c_{\ell} - c_s) \frac{\partial}{\partial t}(\rho f_s T)$$

f_{ℓ} は液相率を示し, $f_s (= 1 - f_{\ell})$ は固相率を示す.

相変化量は例えば合金や水溶液などのような混合相の相変化のように温度幅 (DTF>0) をもって凍結・融解すると仮定して次式で計算する (テコの原理), T_{ph} は凍結温度, h_f は相変化潜熱.

凍結

$$\begin{aligned} f_s &= 0, & T &> T_{ph} \\ f_s &= \frac{T_{ph} - T}{DTF}, & -DTF &\leq T \leq T_{ph} \\ f_s &= 1, & T &< -DTF \end{aligned}$$

融解

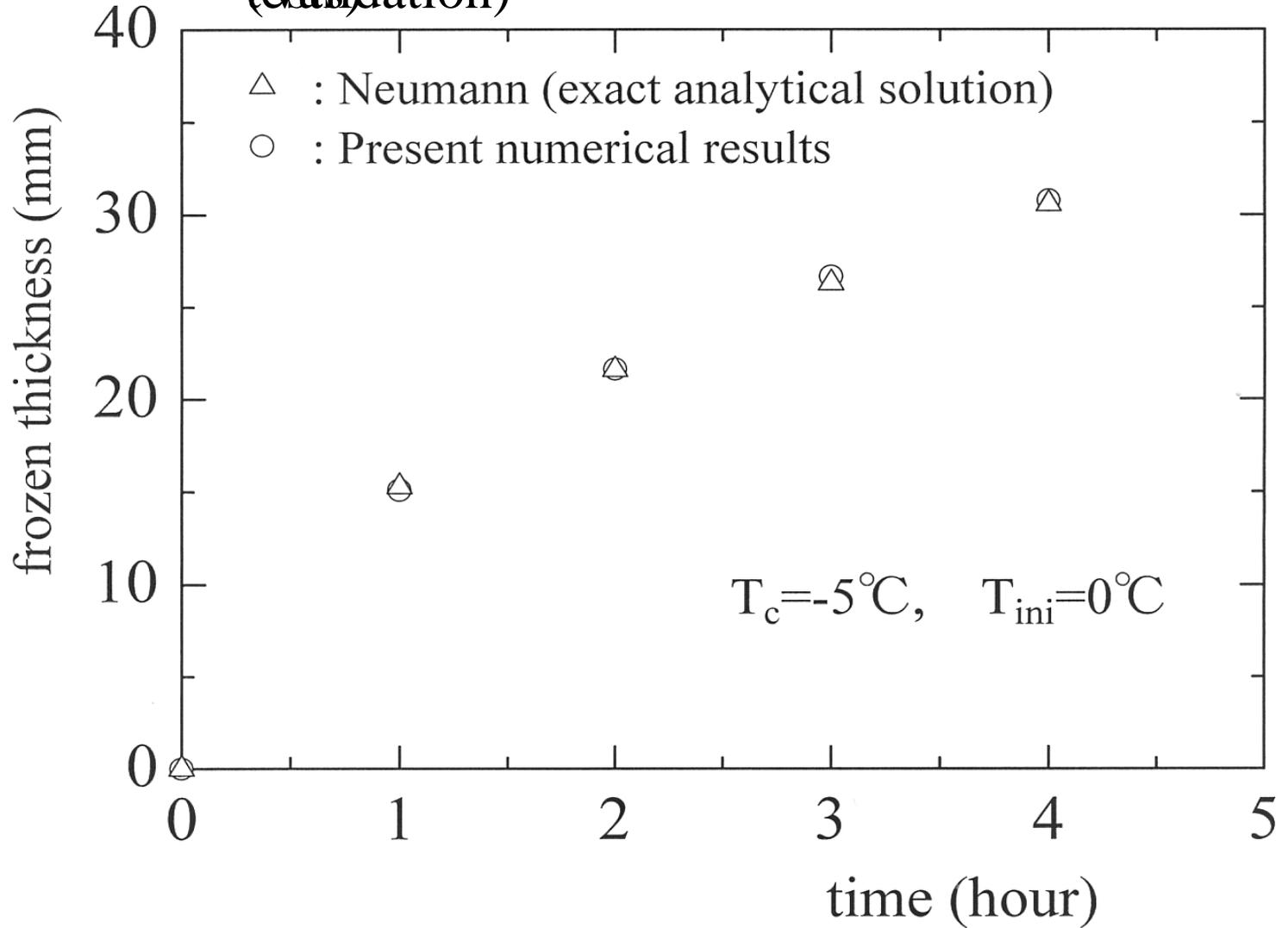
$$\begin{aligned} f_s &= 0, & T &> DTF \\ f_s &= 1 - \frac{T - T_{ph}}{DTF}, & T_{ph} &\leq T \leq DTF \\ f_s &= 1, & T &< T_{ph} \end{aligned}$$

DTFは0.1°Cから1°Cの範囲が望ましい.

相変化界面は固相と液相が共存 (mushy域) するので, 運動量式に流動抵抗を次式で与える (Cは係数であり -10^6 なる大きな値を与える).

$$F_x = C \cdot f_s \cdot u, \quad F_y = C \cdot f_s \cdot v$$

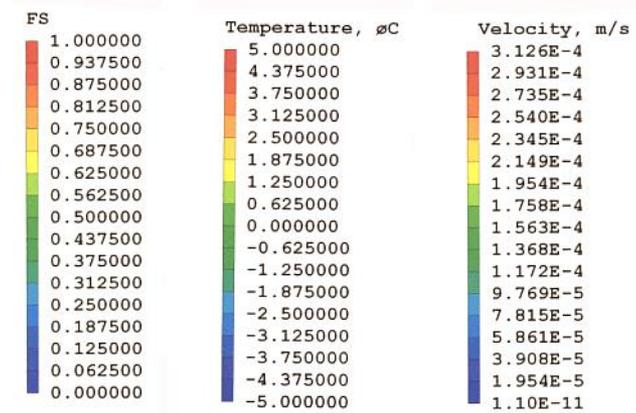
Neumannの厳密解と比較 (Validation)



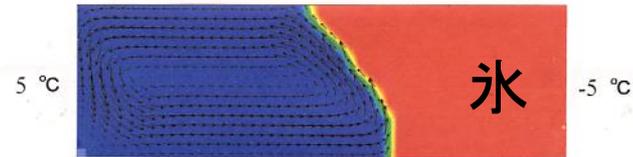
bench mark tests

Seybertら[1]の実験 結果との比較計算 (加熱面温度: 5°C)

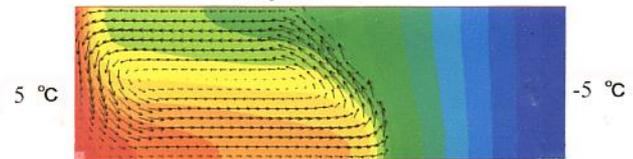
文献1: Seybert CD, Evans JW
(2005) PIV measurements of
velocity of water in the presence of
ice and comparison with calculated
values, Int J Heat Mass Transf
48:67-73



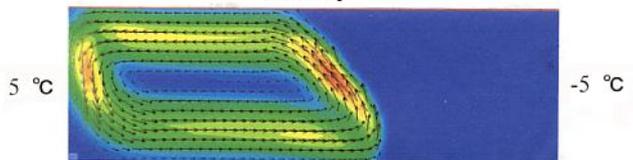
FS (solid mass fraction)



Temperature



Velocity



定常状態の結果であり
氷の成長が停止した状態

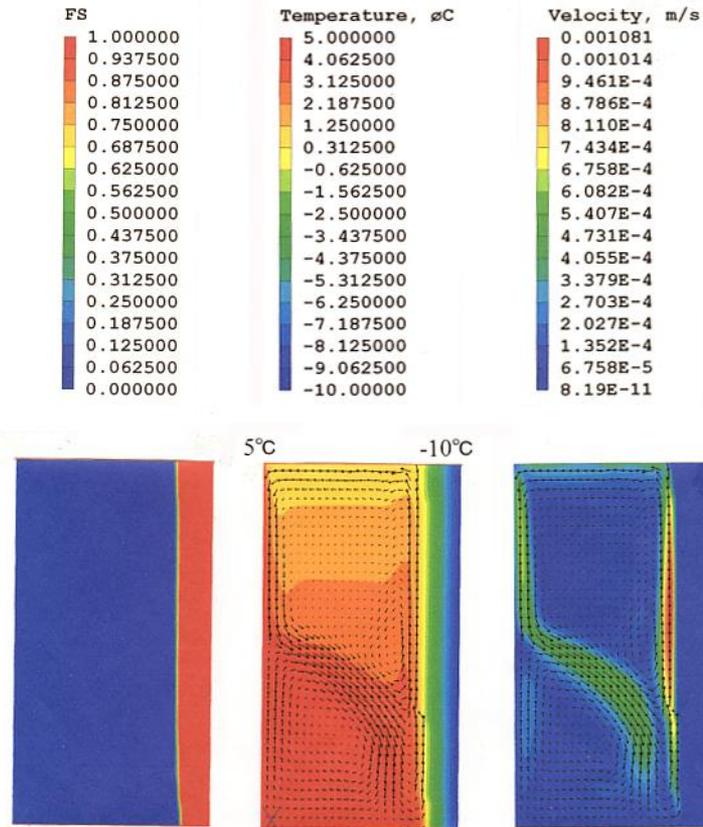
Sticklandら[2]の実験結果との比較計算(加熱面温度: 5°C, 冷却面温度: -10°C)

非定常状態, $t=1800$ s

文献2: Stickland MT, Scanlon T, MacKenzie J (2007) An experimental investigation of natural convection with solidification in a differentially heated cavity, Int J Heat Mass Transf 50:36-44

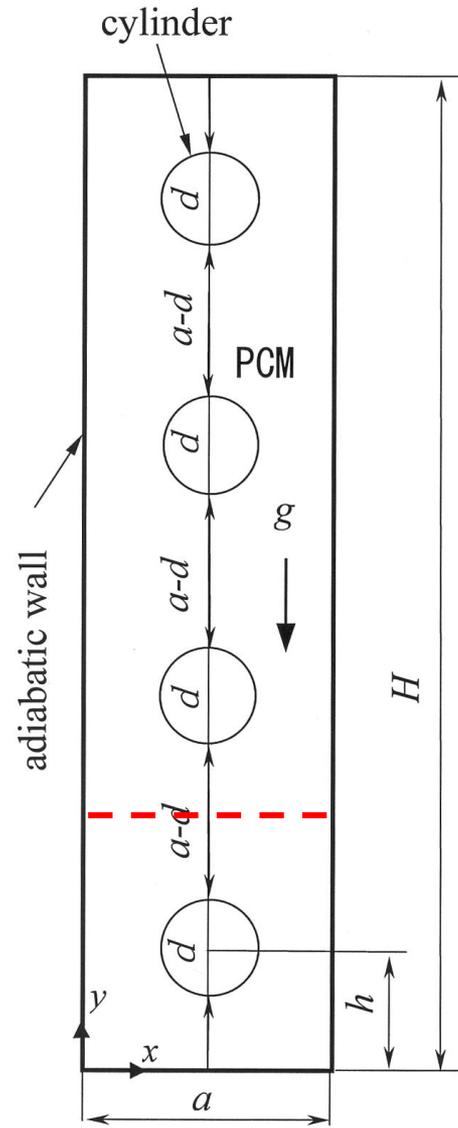
氷が成長している非定常の状態であり, 最大密度の影響が現れている

bench mark tests

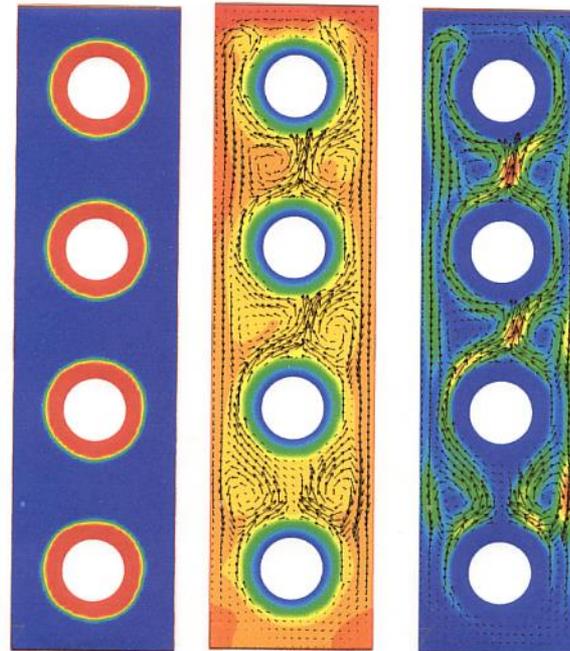
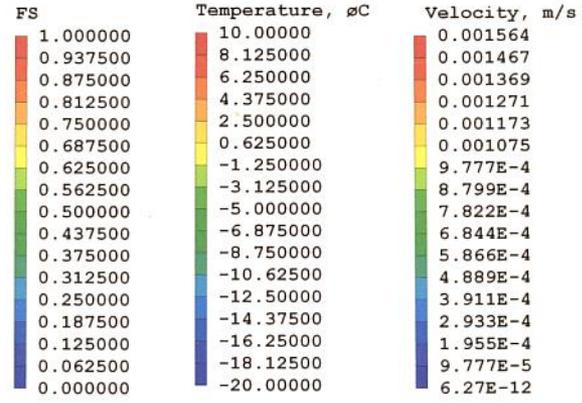


垂直に配列された4円管周りの凍結・融解

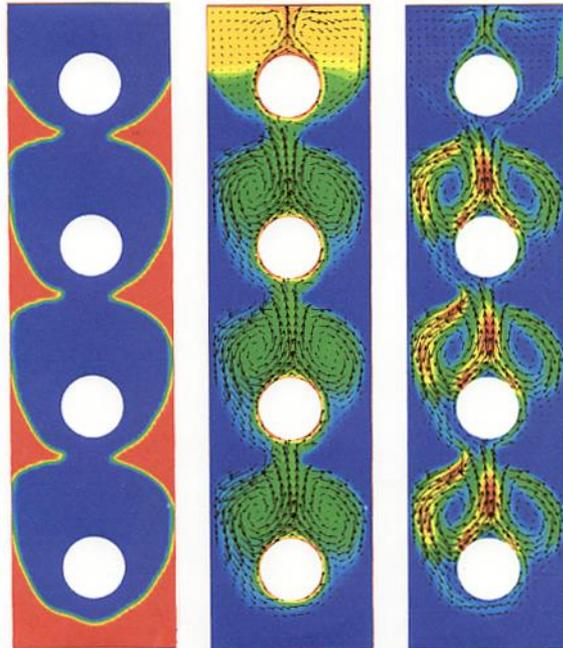
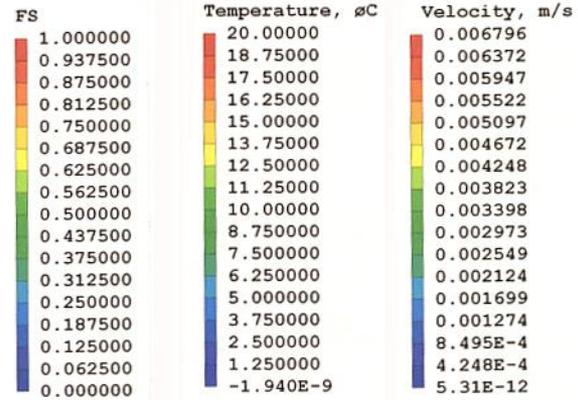
各円管の相変換物質 (PCM) は互いに干渉して成長する.



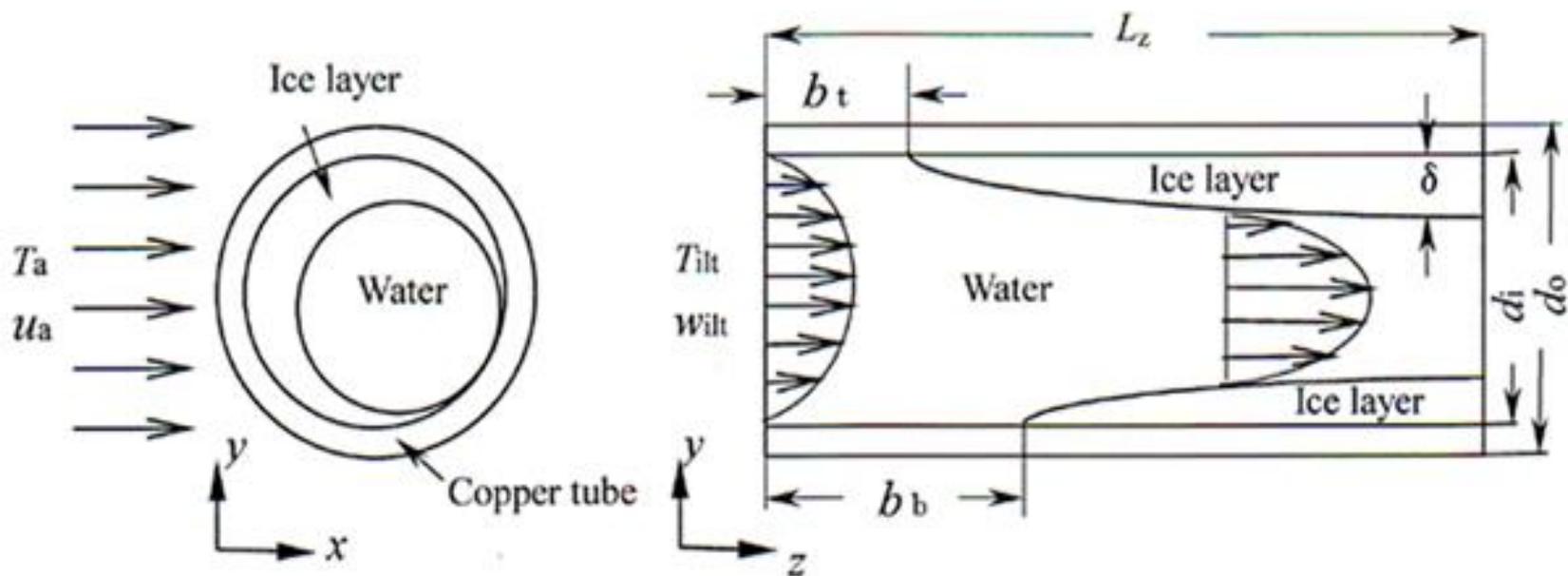
凍結 $t=400s$



融解 $t=1550s$

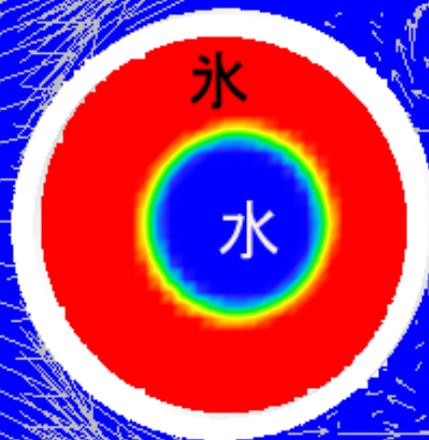


空気冷却による管内水の凍結



管内流水の3次元凍結問題

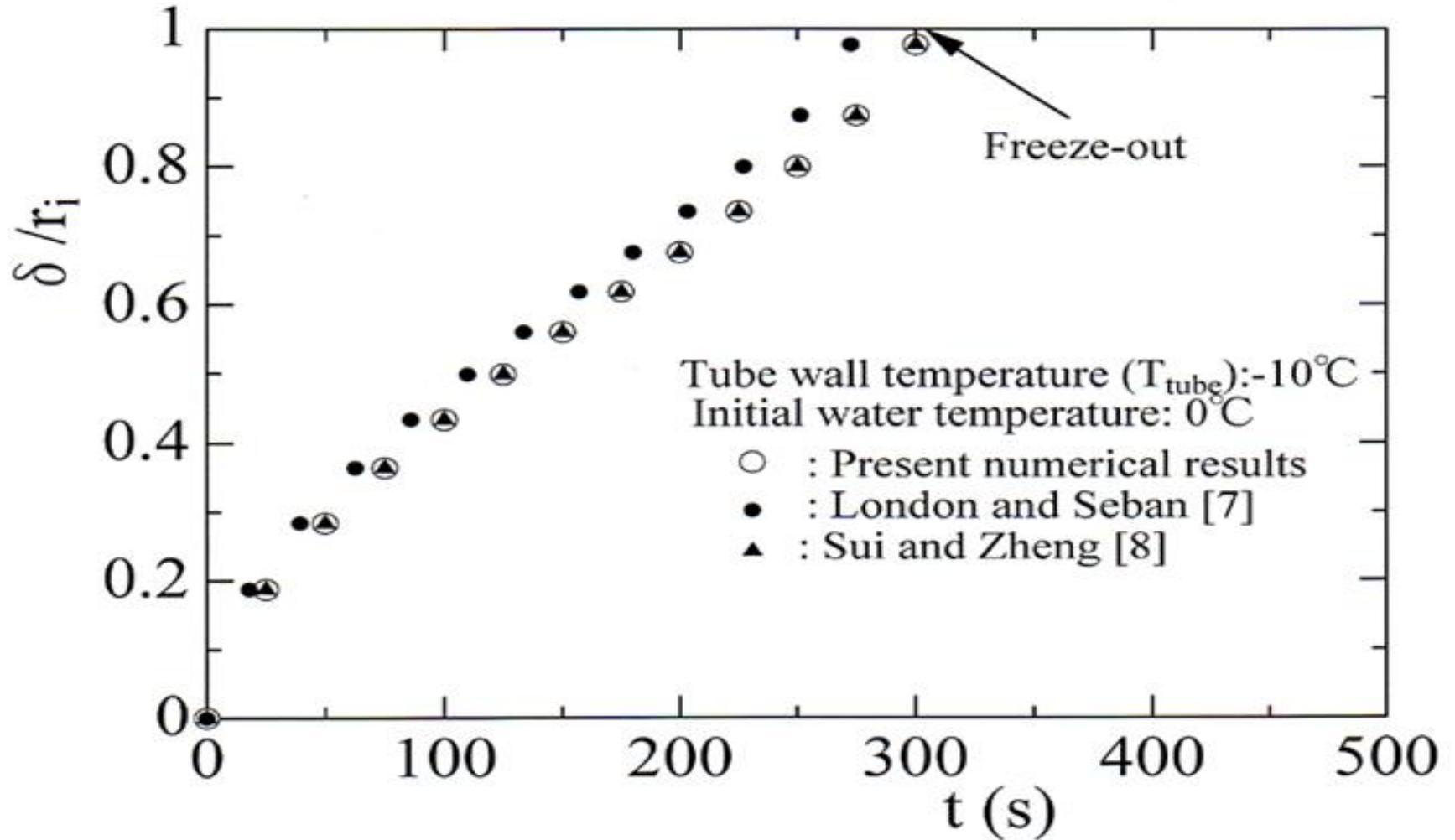
-10°Cの外気

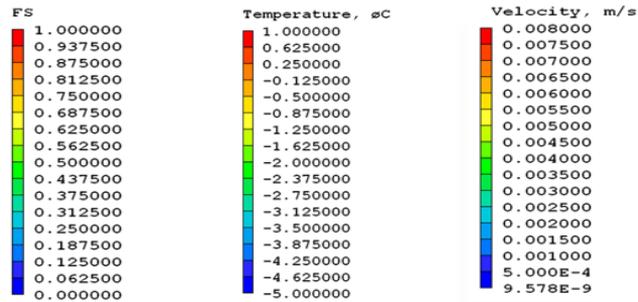


水道管

40分経過

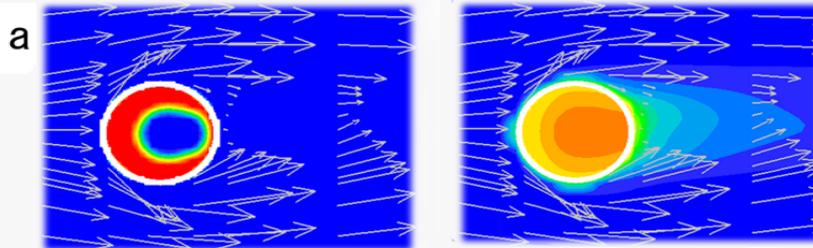
Suiらの近似解と比較(Validation)





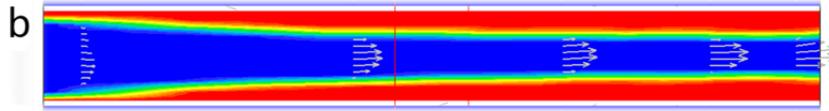
冷風が当たっている左側から氷が成長している

FS, x-y plane ($z=0.5L$) Tem, x-y plane ($z=0.5L$)

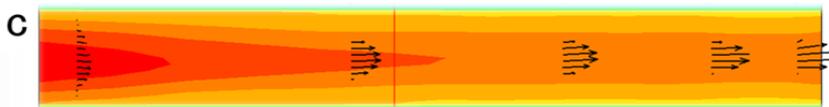


流れ方向に向かって氷が厚くなっている

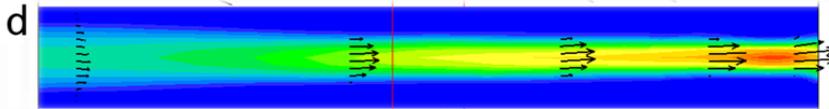
FS, y-z plane ($x=0.5H$)



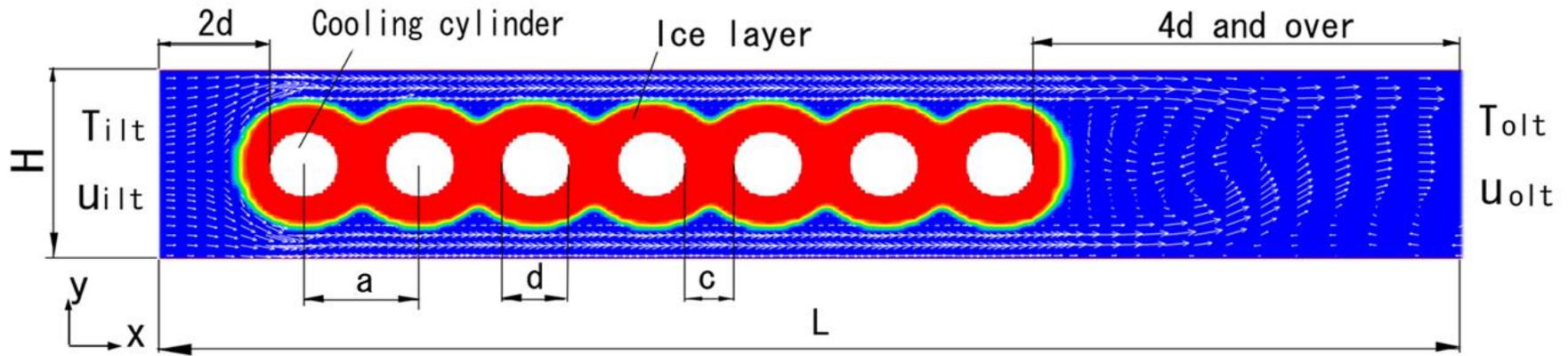
Tem, y-z plane ($x=0.5H$)



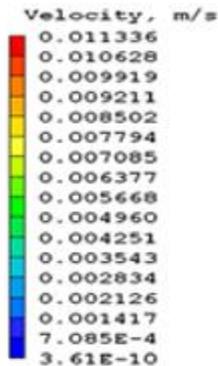
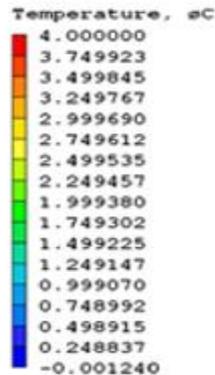
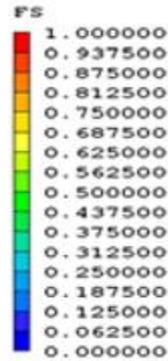
Ve, y-z plane ($x=0.5H$)



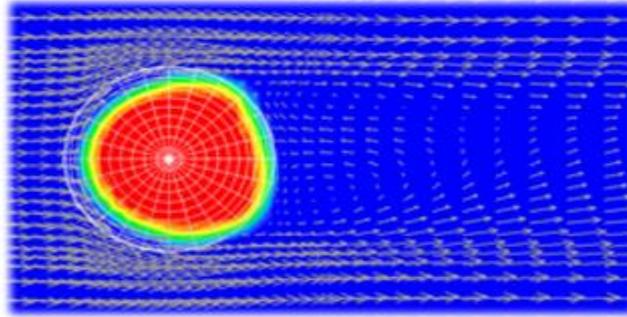
管外凍結層の強制対流融解



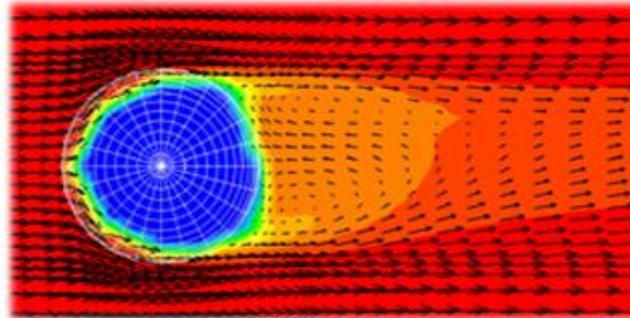
氷球の3D融解
Validation(Haoら
の融解実験
ASME(2001)Vol.
123:937-950と
比較



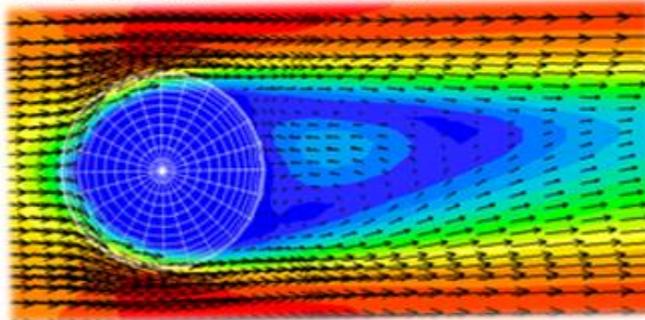
x-y plane ($z=0.5Lz$)



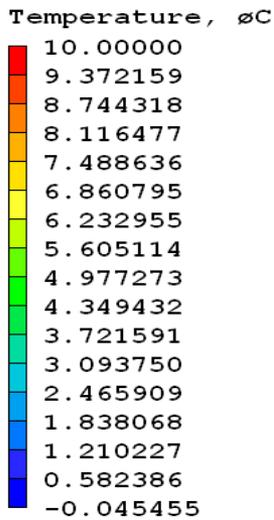
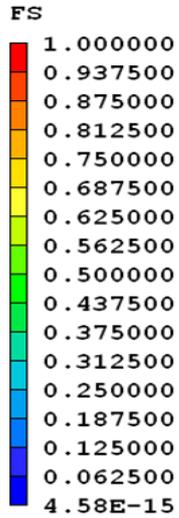
x-y plane ($z=0.5Lz$)



x-y plane ($z=0.5Lz$)



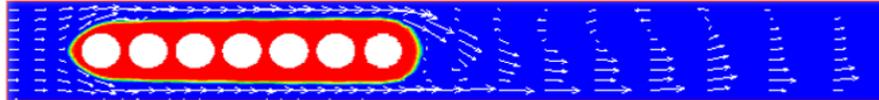
管間隔が狭い場合



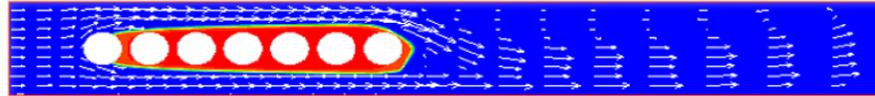
t=0s (before melting)



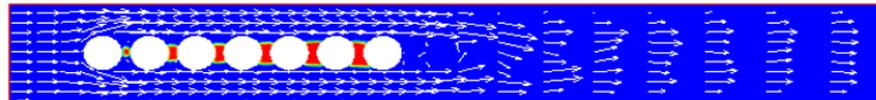
t=1200s



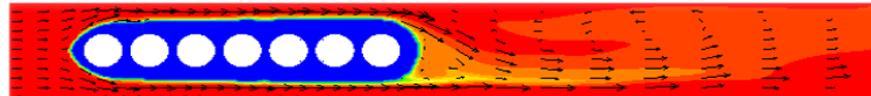
t=2400s



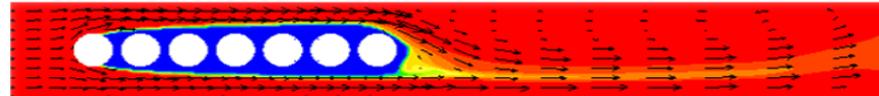
t=4800s



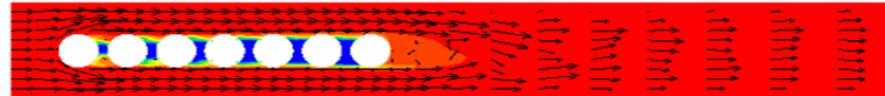
t=1200s



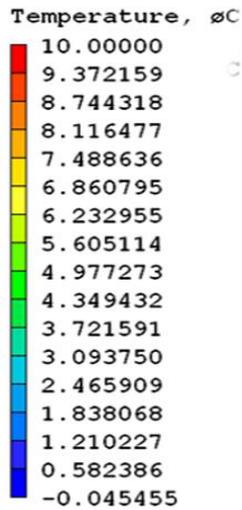
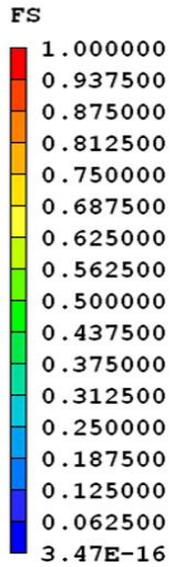
t=2400s



t=4800s



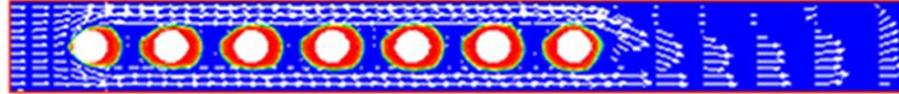
管間隔が
広い場合



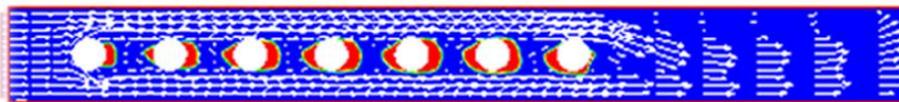
t=0s (before melting)



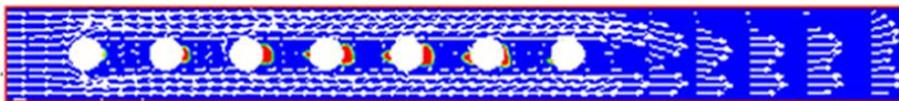
t=1200s



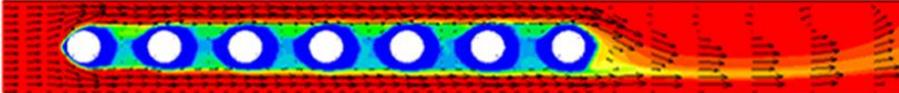
t=2400s



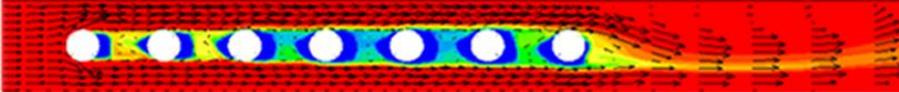
t=3600s



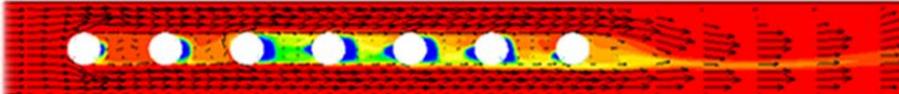
t=1200s



t=2400s



t=3600s



Phoenicsを活用するに当たり

的確に活用すればVirtual Experiment (仮想実験)が可能である→実験装置に必要な部品, 計器などのハードが必要でなく低価格で有益なデータが得られる

広義の境界条件を如何に正しく支配方程式のソース項に組み入れるかが重要→PATCH コマンドに対して, q1のINFORMとパネル入力の関連が重要

ソフトウェア独自の決まりがあり, 計算が動かない場合ユーザー自身で切り抜けるには限界があり, サポーターの協力が必要→ユーザーは一刻も早く計算を成功させたい