機械工学概論 2015
流れの設計

担当　大島伸行 機械宇宙工学部門

6/19　流れに働く力
7/3　乱流入門
7/10　自動車の空気力学
7/17　小さな装置の流れ
（7/24　休講）
7/31　期末試験（全体）

機械工学概論　－流れの設計－

講義資料（流体設計）:
http://www.eng.hokudai.ac.jp/labo/fluid/lecture.html

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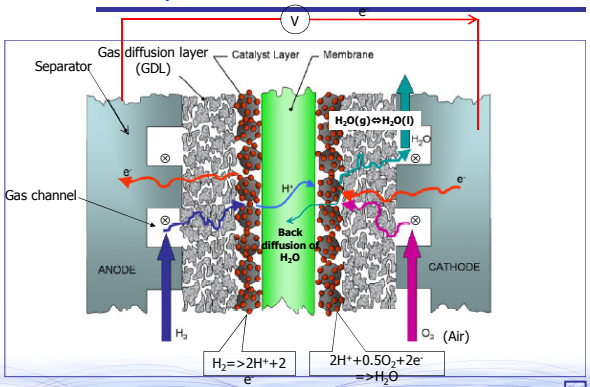
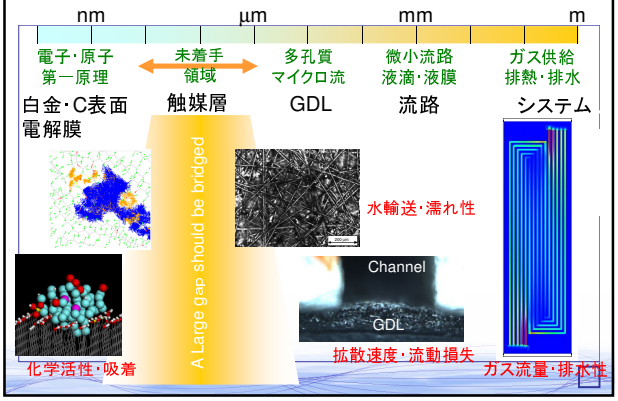
7/17　小さな装置の流れ
- 小さな隙間の流れ
- 表面張力

小さな装置の流れ ～燃料電池の事例

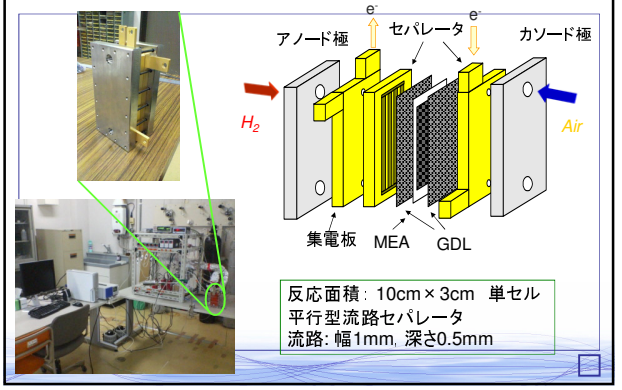


Trabold, J. Heat & Mass Trans. 2006

小さな装置の流れ ～燃料電池の事例



固体高分子形燃料電池の構造



反応面積：10cm×3cm　単セル
平行型流路セパレータ
流路: 幅1mm, 深さ0.5mm

流路と多孔質のガス流れのモデル

Momentum conservation:

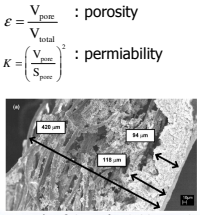
$$\frac{\partial \varepsilon\rho\mathbf{v}}{\partial t}+\nabla\cdot(\varepsilon\rho\mathbf{v}\mathbf{v})=-\nabla(\varepsilon p)+\nabla\cdot(\varepsilon\mu\nabla v)+\varepsilon\rho g-\frac{\mu}{K}\varepsilon^2\mathbf{v}$$

Mass conservation:

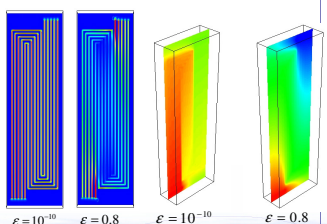
$$\frac{\partial(\varepsilon\rho)}{\partial t}+\nabla\cdot(\varepsilon\rho\mathbf{v})=0$$

$\varepsilon=\frac{V_{pore}}{V_{total}}$: porosity

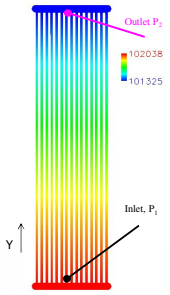
$K=\left(\frac{V_{pore}}{S_{pore}}\right)^2$: permiability



Photograph of GDL (ε=0.88, κ=18e-12 m²) by T. Gostick, et.al., ***J. Power sources*** (2006)



流路と多孔質のガス流れのモデル



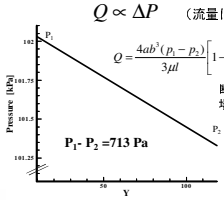
小さな流路の流れ （=レイノルズ数＜10）

$$\mathrm{Re} = \frac{\rho U a}{\mu}$$

$Q \propto \Delta P$ （流量は圧力差に比例する）

$$Q = \frac{4ab^3(p_1 - p_2)}{3\mu l}\left[1 - \frac{192b}{\pi^5 a}\sum_{n=1,3,..}^{\infty}\frac{1}{n^5}\tanh\left(\frac{n\pi a}{2b}\right)\right]$$

断面長方形(ab)流路の場合の理論解



Irvine Jr. T. F. and Hartnett J.P., Advances in heat transfer, supplement 1, (1978), 196, academic press

Only channel (Without GDL)

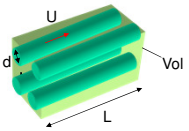
流路と多孔質のガス流れのモデル

Darcy's Law in Porous media

Porosity: $\varepsilon = \frac{LA_o}{V}$ **Permeability**: $\kappa = \left(\frac{\varepsilon V}{A_w}\right)^2$

$A_o = n\pi d^2/4$: total open area

$A_w = n\pi dL$: total wall area



Pressure loss in pipe:

$$\Delta p = \frac{32\mu UL}{d^2}$$

Total resistance per volume:

$$\zeta = \frac{A_0 \Delta p}{V} = \frac{32\mu U L A_o}{d^2 V} = 2\mu\frac{\varepsilon^2}{\kappa}U$$

❍Re-definition $|\nabla p| = \mu\frac{\varepsilon}{\kappa}U$ ➡ (κ/2⇒κ)

Cross flow in the parallel flow field

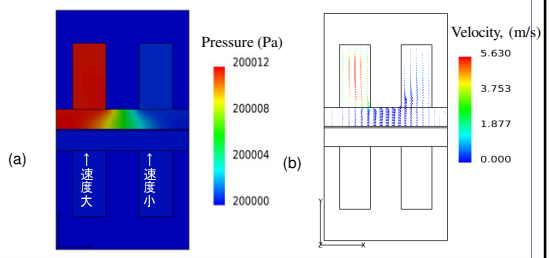


Fig: (a) Pressure (Pa)distribution in the middle cross-section of the channel (b) velocity (m s^{-1}) distribution in the *xy* –plane for case 3

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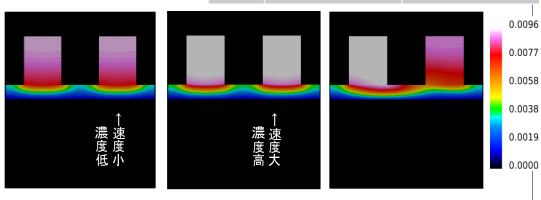
酸素輸送に与える影響

Case	Channel A	Channel B
Case 1	Inlet velocity=0.1 m/s	Inlet velocity=0.1 m/s
Case 2	Inlet velocity=4.0 m/s	Inlet velocity=4.0m/s
Case 3	Inlet velocity=4.0 m/s	Inlet velocity=0.1 m/s



Case1 Case 2 Case 3

Fig: Oxygen Mass fraction distribution in the channel and GDL at the middle cross section of the channel

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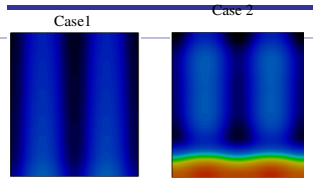
The effect of cross flow on current density



Oxygen concentration was used as 0.8%

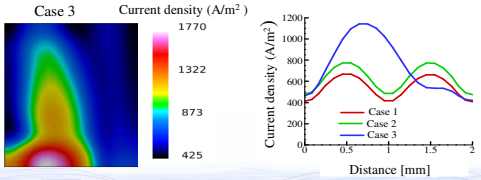


Fig: Current density (A/m^2) distribution in the membrane for different cases

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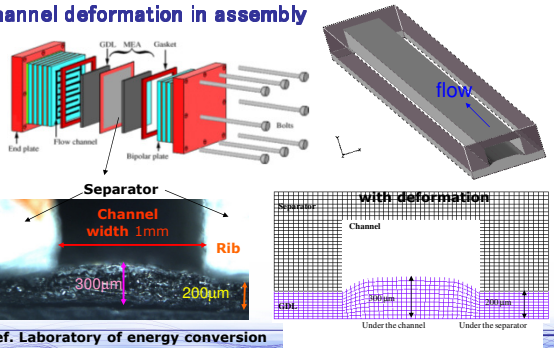
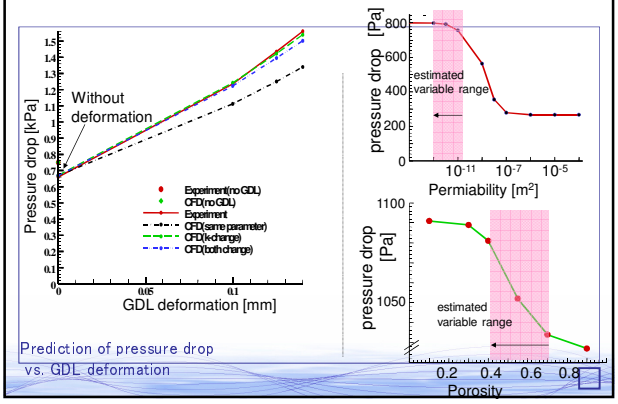
マイクロ流路／ガス拡散層の流動抵抗

Channel deformation in assembly



Ref. Laboratory of energy conversion system, Hokkaido University

流動抵抗（圧力損失）と多孔質の変形



Prediction of pressure drop vs. GDL deformation

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- 表面張力

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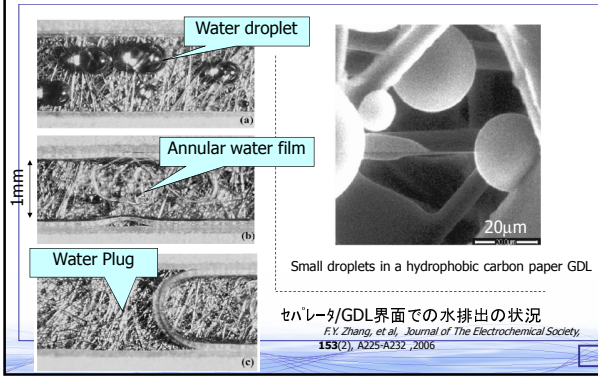
気液2相流れと表面張力

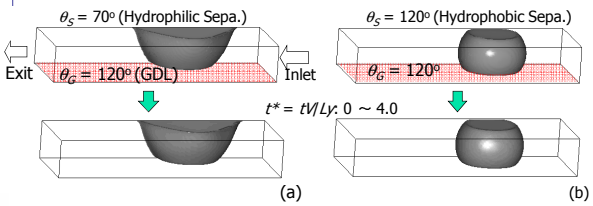


セパレータ/GDL界面での水排出の状況
F.Y. Zhang, et al, Journal of The Electrochemical Society, 153(2), A225-A232 ,2006

小さな流路での排水挙動

（北大：田部ら 2005）

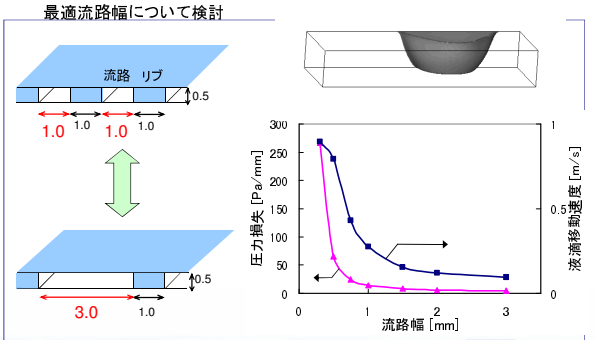
セパレータ流路寸法：1 mm×0.5 mm, $40\Delta x \times 20\Delta x \times 120\Delta x$, $Re = 25$



- **排水性や圧力損失におよぼす壁面の親水性・疎水性，ガス流速および液滴の大きさの影響の定量的評価**
- **壁面の濡れ性と凝縮水の安定形状の評価**

チャネル形状による流動抵抗の違い

最適流路幅について検討

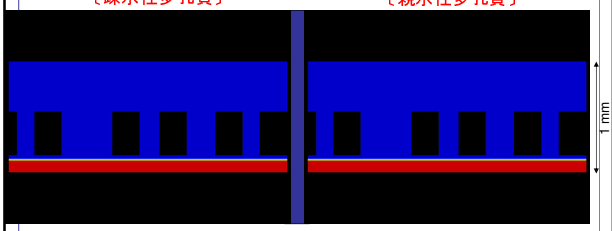


排水性を定量的に評価し最適化

多孔質層の水分排出機構

$\rho_L/\rho_G = 847$

〔疎水性多孔質〕　〔親水性多孔質〕



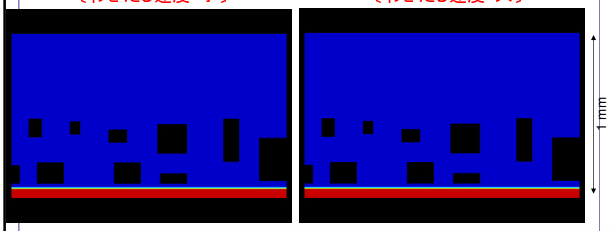
・最も径の大きい空孔を選択的に通って流入
・径の小さい空孔ほど流入速度が大きい
・最終的には径の大きい空孔から流出

多孔質内計算に適用可能

多孔質層の水分排出機構

$\rho_l/\rho_G = 847$

〔わきだし速度･小〕　〔わきだし速度･大〕

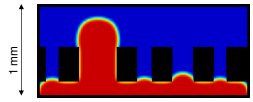


多孔質形状･水わきだし速度に依存するような挙動を解析可能

多孔質層の水分排出機構

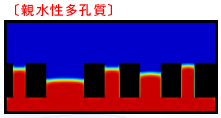
GDL内での排水挙動（2Dﾓﾃﾞﾙ）
ー疎･親水性の影響ー

〔疎水性多孔質〕



･最も径の大きい空孔を 選択的に 通って流入

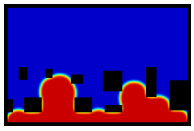
〔親水性多孔質〕



･径の小さい空孔ほど流入速度が大きい
･最終的には径の大きい空孔から流出

ーGDL内部形状と湧き出し速度の影響ー

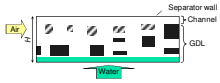
〔わきだし速度･小〕



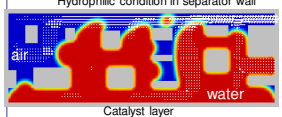
〔わきだし速度･大〕

多孔質･マイクロ流路の排水メカニズム

Water management in GDL & Channel (2D model)

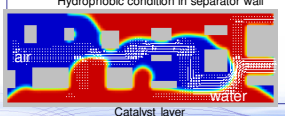


Hydrophilic condition in separator wall



Catalyst layer

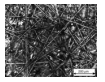
Hydrophobic condition in separator wall



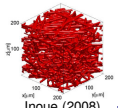
Catalyst layer

田部 ほか、伝熱シンポジウム (2008)

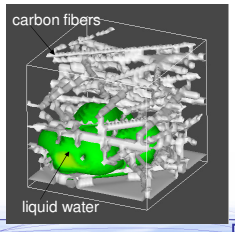
Water transport in GDL micro-structure (3D model)



Carbon paper GDL



Inoue (2008)



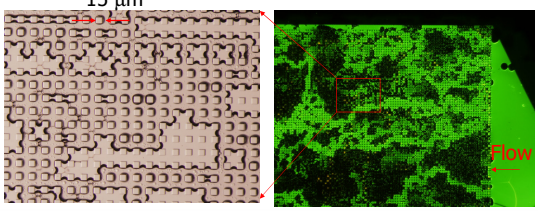
李、北大 ｴﾈﾙｷﾞｰ環境ｼｽﾃﾑ専攻 修士論文 (2009)

多孔質内の液水飽和度のモデル化

液水飽和度
(Water saturation rate)

$$S = \frac{\text{Liquid occupied volume}}{\text{Total pore volume}}$$

15 μm

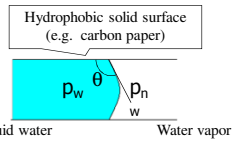


A sample of 2D micro channel by MEMS (block and channel sizes are 15μm)

A sample of flow visualization by 2D micro channel

Kinoshita H., 2008

キャピラリー圧力と飽和度



$$P_c \equiv (P_{nw} - P_w) = -\sigma\cos(\theta)\left(\frac{\varepsilon}{K}\right)^{1/2} J(s)$$

Traditional Cubic function

$$J(s) = 1.417s - 2.12s^2 + 1.263s^3$$

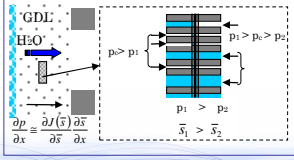
Statistical analysis formulation

$$J(\bar{s}) = \int P(s_0, \bar{s}, \overline{s'})\, d\bar{s}$$

β-function model

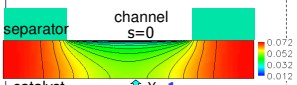
$$P(s, \bar{s}, \overline{s'^2}) = \frac{s^{\beta_1-1}(1-s)^{\beta_2-1}\, ds}{\int_0^1 s^{\beta_1-1}(1-s)^{\beta_2-1}\, ds}$$

$$\beta_1 = \bar{s}\left(\frac{\bar{s}(1-\bar{s})}{\overline{s'^2}} - 1\right), \quad \beta_2 = (1-\bar{s})\left(\frac{\bar{s}(1-\bar{s})}{\overline{s'^2}} - 1\right) = \frac{1-\bar{s}}{\bar{s}}\beta_1$$

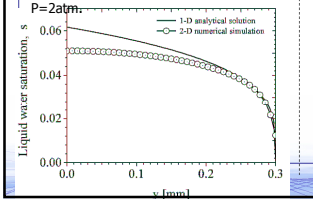


多孔質内の液水飽和度分布

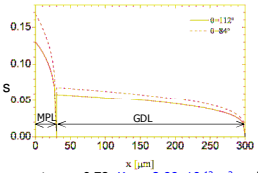
1D/2D Analysis of saturation, s, in GDL



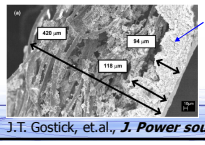
K=8.99×10^{-12} m^2, ε=0.78, θ=80°, σ=0.0725 N/m, I=1.0A/cm^2, T=353K, P=2atm.



Analysis of GDL with Micro Porous Layer (MPL)



at ε_{GDL}=0.78, K_{GDL}=8.99×10^{-12} m^2 and ε_{MPL}=0.5, K_{MPL}=2.47×10^{-16} m^2 *



J.T. Gostick, et.al., ***J. Power sources*** (2006)