[Regular Paper]

Effect of Wettability on Flow in Porous Media

Yutaka ONAKA^{†1)*}, Afshin GOHARZADEH^{†2)}, and Kozo SATO^{†1)}^{†1)} Graduate School of Engineering, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, JAPAN^{†2)} Dept. of Mechanical Engineering, Khalifa University of Science and Technology, Petroleum Institute, P.O. Box 2533, Abu Dhabi, UAE

(Received March 29, 2018)

Viscous flow in porous media with different surface wettabilities was experimentally studied to investigate the effect of liquid slip on the flow using the micro-particle image velocimetry (μ -PIV) technique. A transparent microchannel, made of polydimethylsiloxane (PDMS), with a depth of 100 μm was used for flow visualization. The micro porous medium was made of solid cylinders with a diameter of 180 μm . The cylinders were arranged in line inside the microchannel. The surface wettability of the microchannel was modified by O_2 plasma treatments to prepare both water-wet and oil-wet conditions. Measured velocity profiles were compared with numerical simulations. Both experimental and numerical results showed that the difference in the velocity profiles with the wettabilities was under 2.4 % at the center of the throats. The ratio of absolute permeability under the oil-wet condition to the water-wet condition was calculated as 1.2. This study provides the criterion of the slip impacts on the velocity profiles and permeability of single-phase flow in porous media under the oil-wet condition. The results can be used for the verification of data when extending the investigation to two-phase flow for understanding oil displacement behavior.

Keywords

Absolute permeability, Micro-particle image velocimetry, Porous media, Wettability

1. Introduction

Study of fluid flow in micro-sized porous media is essential for understanding the pore-scale flow and the prediction of absolute permeability, k , in reservoir engineering or soil science¹⁾. Surface wettability is one of the parameters that control the flow. At a surface, liquid fluid shows non-zero velocity due to the movement of molecules²⁾. This phenomenon is called liquid slip. The flow velocity tangential to the surface, $u_{||}$, is defined as Eq. (1) under Navier's slip boundary condition²⁾, where $\mathbf{K} = \mathbf{n} \cdot (\nabla \mathbf{u} + (\nabla \mathbf{u})^T)$ and $\mathbf{n}$ denotes the vector normal to the surface, directed outward relative to the flow domains. Equation (1) shows that $u_{||}$ is proportional to the shear rate and slip length β . The slip length of water is regarded as zero ($\beta = 0$) under the water-wet condition (WWC), that is, with zero velocity. However, fluid slip occurs with $\beta > 0$ under the oil-wet condition (OWC)^{3)~9)}.

$$u_{||} = -\beta(\mathbf{K} - (\mathbf{K} \cdot \mathbf{n})\mathbf{n}) \quad (1)$$

Reported β values ranges from hundred nanometer

(nm) to several micrometer (μm) under the OWC with contact angle $\theta > 83^\circ$ as summarized in **Table 1**. In these experiments, capillary or parallel planes are prepared as channels. The OWC is achieved by coating glass with several types of oil^{3)~7)} or polydimethylsiloxane (PDMS)^{8),9)}, treated by O_2 plasma¹¹⁾. The pressure gradient *versus* flow rate^{3)~5)} or flow velocity^{6)~9)} of the flow in the channels is measured. To estimate β , the results are compared with analytical results of Poiseuille flow solved with Eq. (1). The flow velocity is obtained by image analysis of particles flow in the microchannels using micro-particle image velocimetry (μ -PIV) or particle streak velocimetry techniques. Such investigations have succeeded in representing the slip impacts on the flow through straight channels. However, flow in porous media is more complex and has not been fully studied.

Two-dimensional Stokes flow in a porous medium was analytically solved with Eq. (1) to show the slip impacts on the flow in porous media¹²⁾. Cylinders were arranged in line inside the porous medium. The depicted streamlines suggested that the slope of parabolic profiles of flow velocity is relatively gentle under the OWC in the throat between the cylinders adjacent in the y-direction. Circulation of the flow was confirmed in some cases which depend on the wettabilities and throat size between the cylinders adjacent in the x-

DOI: doi.org/10.1627/jpi.61.342

* To whom correspondence should be addressed.

* E-mail: yutaka.onaka.edu@gmail.com

Table 1 Experimental Values of β and θ Examined by Experiments

References	Measured values	Channels	A radius of capillaries/ an aperture size of parallel planes [μm]	Fluid	Materials of OWC	θ [$^\circ$]	β [μm]
Schnell ³⁾	Flow rates and pressure	Capillary	100	Water	Glass covered with (GCW) DDS ^{a)}	-	5.0 ^{f)}
Churaev <i>et al.</i> ⁴⁾	Flow rates and pressure	Capillary	0.8-7.2	Water	GCW 5 % TMCS ^{b)} in benzene	83 ^{e)}	0.03
Lee <i>et al.</i> ⁵⁾	Flow rates and pressure	Parallel planes	500	Water	GCW light oil	121	5.1
				Water	GCW OTS ^{c)}	142	8.1
Tretheway and Meinhart ⁶⁾	Flow velocity	Parallel planes	300	Water	GCW OTS	120	1.0
Joseph and Tabeling ⁷⁾	Flow velocity	Parallel planes	10	Water	GCW DMOS-Cl ^{d)}	95	0.1
Tsai <i>et al.</i> ⁸⁾	Flow velocity	Parallel planes	320	Water	PDMS	120	0.2
Chun and Lee ⁹⁾	Flow velocity	Parallel planes	90	1 mM KCl	PDMS	99	6-8

a) DDS: dimethyldichlorosilane, b) TMCS: trimethylchlorosilane, c) OTS: octadecyltrichlorosilane, d) DMOS-Cl: chlorodimethyloctylsilane, e) θ average of 10 results, f) β estimated by Lauga and Stone¹⁰⁾.

Fig. 1 Experimental Setup

direction. The minimum β assumed in the calculation was $28 \mu\text{m}$. The ratio of k under the OWC to WWC, $k_{\text{OWC}}/k_{\text{WWC}}$, depends on both β and the size of the porous media. The presented ratio with $\beta = 28 \mu\text{m}$ ranged from 0 to around 2. These results indicate the changes in the velocity profiles and permeability dependent on the wettabilities. However, the velocity profiles were not shown in detail and no quantitative evaluation was conducted. In addition, the assumed β was at least 3.5 times larger than the experimental values of β as described in **Table 1**. With realistic β , the streamlines or permeability ratio might be different. Furthermore, no study has experimentally examined the effect of the slip on the flow.

The present study investigated the influence of the slip, which is caused by the wettability, on single-phase viscous flow in porous media. Velocity profiles were obtained both experimentally and numerically. The velocity profiles at the entrance of the microchannel were measured and β was estimated by comparing the experimental results with the numerical results. The

velocity profiles in a porous area of the microchannel were measured to determine the microscopic impact of the slip on the flow. Finally, pressure gradients were derived from the numerical results to examine the effect on permeability.

2. Experimental Conditions

2.1. Experimental Setup

The experimental setup consists of a transparent microchannel, a syringe pump and a microscope for flow visualization (**Fig. 1**). The microchannel is made of polydimethylsiloxane (PDMS) with a size of $5.39 \times 0.84 \text{ mm}^2$ as shown in **Fig. 2**. The porosity ($\phi = 0.68$) is calculated from $\phi = 1 - \pi d^2/4(d + s)^2$. The surfaces of the microchannel are exposed to O_2 plasma and then attached to a PDMS plane. The exposure time and post treatments were optimized to ensure WWC and OWC¹¹⁾. θ was measured by a sessile drop method using a contact angle meter adopting Young-Laplace fitting, showing 30° and 96° , respectively (**Fig. 3**).

Fig. 2 Structure of the Microchannel

Fig. 3 Sessile Drops on the Plasma Treated PDMS ((a) $\theta = 30^\circ$ under the WWC and (b) $\theta = 96^\circ$ under the OWC)

Distilled water (density of $\rho = 1.0 \text{ g/cm}^3$ and viscosity of $\mu = 0.89 \times 10^{-3} \text{ Pa s}$ at 25°C) was injected into the microchannel using a syringe pump with an accuracy of $\pm 0.35\%$ (Cole-Parmer). Stokes flow was obtained with a constant flow rate of $1.5 \mu\text{L/min}$. Reynolds number was 0.06 calculated by $\rho U d / \mu$ with surface velocity U .

2. 2. Flow Visualization (μ -PIV)

Flow velocity inside the transparent microchannel was measured by the μ -PIV technique. To visualize the flow, the distilled water was seeded with $1.0\text{-}\mu\text{m}$ diameter fluorescent polystyrene micro-particles (Thermo Fisher Scientific) as tracers at $0.005 \text{ vol}\%$. The microchannel was placed under an inverted microscope (Leica) and illuminated by a Nd-Yag, double-pulsed 532-nm wavelength laser to record the movements of the particles. The fluorescence images were recorded using Charge-Coupled Device (CCD) camera with 1344×1024 pixels, corresponding to a field of view of $8.67 \times 6.60 \text{ mm}^2$. The spatial resolution was $0.65 \mu\text{m}$ with $10\times$ magnification and 0.25 numerical aperture objective lens. The depth of field was $8.8 \mu\text{m}^{13}$ which was sufficiently smaller than h . The particle image diameter was 4.7 pixels^{14} which is larger than 2 pixels to avoid peak locking¹⁵. ρ of the particle (1.06 g/cm^3) was close to that of water to minimize particle sedimentation. Measurements were performed in the entrance area (EA) and porous area (PA) as shown in Fig. 2. The distance between the inlet and EA was longer than

Table 2 Parameters of the Measurements

Case	EA-I	EA-II	PA-I	PA-II
Time between laser pulses dT [ms]	11	73	3.6-3.7	80
Size of interrogation window N [pixels]	32 by 32	64 by 16	32 by 32	32 by 16

the hydrodynamic entrance length¹⁶ to achieve developed-flow. PA was set at more than three columns of the cylinders behind the first column to avoid the entrance effect on the flow¹⁷. Five-hundred pairs of images were collected with the camera at 6 Hz frame rate and analyzed by image processing using the Dynamic Studio software (Dantec Dynamics). The Fast Fourier Transform-based cross-correlation method with 50% overlapping of the interrogation window was adopted for each pair of images to obtain the flow velocity field. The velocity fields were averaged over all sets to minimize the error due to Brownian motion. The error was calculated¹⁸ as 1.0% at maximum. In the measurement, the time between pulses dT of the laser and interrogation window size, N , in the analysis should satisfy the sampling criterion, $(\text{flow velocity} \times 4dT) < N^{15}$, to avoid the aliasing of data due to a periodic assumption of FFT. Therefore, the parameter settings were adjusted as shown in Table 2 according to measurement purposes. In EA, measurement was performed to confirm developed-flow (Case EA-I) and to estimate slip length (Case EA-II). For the estimation, lower velocity was measured in the vicinity of the wall of the microchannel. In PA, the flow velocity between the cylinders adjacent to each other in the y -direction (Case PA-I) and the x -direction (Case PA-II) was measured to verify the difference in the velocity profiles with wettability.

2. 3. Data Normalization

The flow velocity is affected by the PDMS walls limiting the microchannel in the z -direction. Therefore, the difference in a focal point position in the z -direction results in different flow velocity at the same x and y coordinates. According to the numerical simulation, the difference in the maximum velocity is estimated to be around 80% under the WWC. This large difference makes it difficult to evaluate the fluid velocity quantitatively. In this study, normalized velocity was adopted to investigate velocity profiles. The flow velocity was normalized by the velocity averaged along the y -direction and line 1 in the EA and PA, respectively. Line 1 is shown in Fig. 4 and its coordinates are shown in part 4. The difference in the maximum normalized velocity due to the focal point position is nearly zero in the center of the EA and 5.4% at the center of line 1 in the PA.

Fig. 4 A Geometries of the (a) EA and (b) PA Used for the Numerical Simulations

3. Numerical Simulation

Numerical simulations were conducted to verify the experimental results from the EA and PA. Flow was obtained by solving the continuity equation (Eq. (2)) and the momentum equation (Eq. (3)) for steady-state Stokes-flow with Navier's slip boundary condition (Eq. (1)). In the equations, $\mathbf{u}$ is velocity field, and p is pressure.

$$\nabla \cdot \mathbf{u} = 0 \quad (2)$$

$$0 = -\nabla p + \nabla \cdot \mu (\nabla \mathbf{u} + (\nabla \mathbf{u})^T) \quad (3)$$

The governing equations were solved using a finite element based software package COMSOL Multiphysics^{®19)}. Figure 4 depicts the geometries used for the simulations. To reduce the computational cost, only the part of each area that could reproduce the experimental results was considered. The x -direction length of both EA and PA geometries was long enough to achieve developed-flow. To decide the length of the PA geometry, the simulation was conducted with a longer geometry at first and the transition of velocity profiles was examined. Unlike the experimental setup, developed-flow was confirmed at the first column of cylinders in the simulation. Since surface shear stress at the wall of the microchannel is not negligible, the y and z -direction lengths of the geometries were set to be consistent with the sizes of the microchannel. The injection rate was set at the inlet boundaries and pressure was zero at the outlet boundaries. For the other boundaries, Eq. (1) with $\beta = 0$ was assumed under the WWC and appropriate β was assumed under the OWC. The geometries were discretized in 2.0×10^5 and 4.0×10^5 elements for the EA and PA, respectively, after checking the mesh convergence.

4. Results

4.1. Verification of Experimental Findings

The normalized flow velocity of Case EA-I under the WWC was compared with the numerical and analytical results of laminar flow in a rectangular duct¹⁶⁾ to verify the presence of developed-flow. As shown in Fig. 5, the analytical and numerical solutions overlapped,

Fig. 5 Velocity Profiles of the Analytical, the Experimental (Exp.) and the Numerical (Num.) Results in the EA

Fig. 6 Velocity Profiles of the Analytical, the Experimental (Exp.) and the Numerical (Num.) Results in the Vicinity of the Wall in the EA

showing complete matching. The velocity profile of the experimental result is consistent with the other solutions, indicating that developed-flow is achieved before entering the PA. The flow velocity was not detected at $y < 0.02$ mm since the particles displacements during dT were smaller than the camera resolution ($1.3 \mu\text{m}$) in Fig. 5.

4.2. Slip Length Estimation

The flow velocity of Case EA-II was measured in the vicinity of the wall of the microchannel under the WWC and OWC as shown in Fig. 6. As with the

numerical results, the normalized velocity at each measurement point under the OWC was higher than the normalized velocity under the WWC. Except at $y = 0.015$ mm, the difference in normalized velocity was larger closer to the wall due to the wettability. The experimental result was compared with the numerical results to estimate β . The analytical result of the flow in parallel planes used in previous studies^{5)~9)} was not available since the effect of walls limiting the micro-channel in the z -direction was not negligible. β was estimated to be $2.4 \mu\text{m}$. Fitting of β was defined to minimize the sum of squared residuals of the numerical results and the experimental results. As shown in Fig. 6, the profile and the magnitude relationships of

Fig. 7 Contact Angle θ and Slip Lengths β of Estimated Value in this Study (Exp.) and the Previous Research (Table 1)

the experimental results for the WWC and OWC were consistent with the numerical results. The estimated value of β was compared with the previous reports as shown in Fig. 7, which shows β versus θ of the experimental results, as summarized in Table 1. The plot indicates that the present estimated β was within the range of the previously reported experimental values.

4.3. Investigation of Slip Impacts

Figure 8(a) is the normalized velocity field of the experimental results of Case PA-I under the WWC. Figure 9(a) compares the findings with the numerical result under the WWC. Each experimental result is depicted in the two-dimensional (x - y) plane and lines 1-4 are marked. Black circles represent solid cylinders, normalized velocity is represented as a color map, and velocity vectors are shown as black arrows. Similar flow characteristics were observed in the results. Injected fluid showed dominant flow in the x -direction which is expressed by the velocity vectors. After passing line 1, the flow decelerates until it reaches line 4. Lines 2 and 3 are marked to show the later transition of the flow. The findings of Area 1 depicted in Fig. 8(a) are shown in Fig. 8(b) for Case PA-II. The experimental result is compared with the numerical result as shown in Fig. 9(b). The black color region where normalized velocity value exceeds 0.1 in Fig. 9(b) was not observed in Fig. 8(b) as for Case PA-II, measurement parameters were set specifically for the measurement of the lower velocity between the solid cylinders and not optimized to detect normalized velocity larger than 0.1. Results under the OWC are not shown since no significant difference in the wettabilities was observed in both experimental and numerical

Fig. 8 Experimental Result of Normalized Velocity Field of the Flow in the (a) PA and (b) Area 1 under the WWC ($x = 2.93$ and $y = 0.37$ - 0.47 for line 1, $x = 2.98$ and $y = 0.36$ - 0.48 for line 2, $x = 3.02$ and $y = 0.28$ - 0.56 for line 3 and $x = 3.07$ and $y = 0.28$ - 0.56 for line 4)

Fig. 9 Numerical Result of Normalized Velocity Field of the Flow in the (a) PA and (b) Area 1 under the WWC (lines 1-4 and Area 1 are shown at the same coordinate position as Fig. 8)

results for the normalized velocity field.

To investigate the findings in detail, the normalized velocity profiles in the x -direction of the experimental and numerical results were compared along lines 1-4 as shown in Fig. 10. In the figure, the parabolic profiles of the experimental results followed the numerical results for every lines. The maximum normalized velocity of the flow from line 1 to line 4 decreased by 40 %. According to the numerical results, the difference in the maximum normalized velocity with wettabilities was 2.4 % at line 1, 2 % at line 2, 0.9 % at line 3 and 0.2 % at line 4. These small differences are consistent with the experimental results. These results indicate that, around the center of the throats, the difference in the velocity profiles with the wettabilities was approximately under 2.4 %. At the surfaces of the cylinders, the flow separated into the x and y -directions along the curve of the surfaces. This behavior resulted in complex motion of the particles, so reliable data could not be obtained.

4. 4. Slip Impacts on Permeability

k was derived from the numerical results. Considering the periodicity of the arrangement of the cylinders, the pressure gradient dp/dx of the PA was defined between line 1 and line 4 as shown in Fig. 4. k_{owc} and k_{wwc} were calculated as 2.5×10^{-10} (m^2) and 2.1×10^{-10} (m^2), respectively, by substituting the pressure gradient for Darcy's law, $U = k/\mu(dp/dx)$. The

result shows 20 % higher permeability of k_{owc} compared to k_{wwc} .

In this study, the flow was assumed to be two-dimensional. For three-dimensional flow, the capillary tube model with equivalent radius r has been adopted to investigate the slip impact on the flow in porous media²¹⁾. By solving the Poiseuille flow with Navier's slip boundary condition, k_{owc}/k_{wwc} was described as $1 + 4\beta/r^{21)}$ where r was estimated from $5 \cdot \sqrt{k_{wwc}/\phi}$ ²²⁾. Although based on different assumptions, the parameters of this work were substituted in the equation to gain some insights. The calculated k_{owc}/k_{wwc} is 1.1 with $r = 90 \mu m$. Since the typical pore radius is around several μm , this result suggests that k_{owc}/k_{wwc} of actual porous media might be higher than 1.1.

Such findings are useful to understand the displacement of trapped oil and two-phase flow in porous media. In two-phase flow, the driving force of the trapped oil is determined by the balance of pressure drop over porous media and capillary pressure that occurs at the interface of the two fluids. This study indicates that pressure drop is influenced by fluid slip under the OWC. Therefore, fluid slip under the OWC is one of the factors which control the displacement behavior of oil in two-phase flow. In addition, the results of the velocity profiles in single-phase flow will contribute to validate the results of microscopic scale experiments in two-phase flow in porous media.

Fig. 10 Experimental (Exp.) and the Numerical (Num.) Results of the Velocity Profiles along (a) Line 1, (b) Line 2, (c) Line 3 and (d) Line 4

5. Conclusions

The present study experimentally investigated the effect of slip, which depends on the wettability, on flow in porous media. Water-wet and oil-wet microchannels with 30° and 96° contact angles, respectively, were prepared. The flow in the porous area of the microchannel was observed by the μ -PIV technique and validated by a numerical simulation. Both the experimental and the numerical results showed that the difference in the velocity profiles with the wettabilities was approximately under 2.4 %. The effect of the slip on permeability was derived from pressure gradients calculated by the numerical simulations. The permeability under the oil-wet condition was 20 % higher than that under the water-wet condition. This finding provides the criterion of the slip impact on velocity profiles and the permeability of single-phase flow in porous media

under the oil-wet condition. The present results will contribute to the verification of data when extending the investigation to two-phase flow for understanding the slip impacts on oil displacement behavior.

Acknowledgment

This work is supported by JX Nippon Oil & Gas Exploration Corporation. The authors are thankful to COMSOL Inc. for the software license.

Nomenclatures

d	: diameter of cylinders	[μm]
dT	: time between laser pulses	[ms]
dp/dx	: pressure gradient	[Pa/m]
h	: model depth	[μm]
k	: absolute permeability	[m^2]
$\mathbf{n}$	: normal vector	[-]
N	: size of interrogation window	[pixels]

p	: pressure	[Pa]
r	: equivalent capillary radius	[μm]
s	: length between cylinders	[μm]
$\mathbf{u}$	: velocity field	[m/s]
$\mathbf{u}_{ }$	: velocity field tangential to surfaces	[m/s]
U	: surface flow velocity	[m/s]
<Greeks>		
β	: slip length	[μm]
θ	: contact angle	[$^{\circ}$]
μ	: viscosity	[$\text{Pa}\cdot\text{s}$]
ρ	: fluid density	[g/cm^3]
ϕ	: porosity	[-]
<Subscripts>		
OWC	: oil-wet condition	
WWC	: water-wet condition	

References

- 1) Bear, J., "Dynamics of fluids in porous media," American Elsevier Pub. Co., New York (1972), p. 1.
- 2) Lauga, E., Brenner, M. P., Stone, H. A., "Handbook of Experimental Fluid Dynamics," eds. by Tropea, C., Yarin, A., Foss, J. F., Springer, New York (2007), p. 1219.
- 3) Schnell, E., *J. Appl. Phys.*, **27**, (10), 1149 (1956).
- 4) Churaev, N. V., Sobolev, V. D., Somov, A. N., *J. Colloid Interface Sci.*, **97**, (2), 574 (1984).
- 5) Lee, H. B., Yeo, I. W., Lee, K. K., *Geophys. Res. Lett.*, **34**, (19), 1 (2007).
- 6) Tretheway, D. C., Meinhart, C., *Phys. Fluids*, **14**, (3), 9 (2002).
- 7) Joseph, P., Tabeling, P., *Phys. Rev. E*, **71**, (3), 1 (2005).
- 8) Tsai, P., Peters, A. M., Pirat, C., Wessling, M., Lammertink, R. G. H., Lohse, D., *Physics of Fluids*, **21**, (11), 1 (2009).
- 9) Chun, M.-S., Lee, S., *Colloids Surf. A*, **267**, (1), 86 (2005).
- 10) Lauga, E., Stone, H., *J. Fluid Mech.*, **489**, 55 (2003).
- 11) Eddington, D. T., Puccinelli, J. P., Beebe, D. J., *Sens. Actuator B-Chem.*, **114**, (1), 170 (2006).
- 12) Wang, C. Y., *Fluid Dyn. Res.*, **32**, (5), 233 (2003).
- 13) Meinhart, C. D., Santiago, J. G., *Exp. Fluids*, **27**, (5), 414 (1999).
- 14) Rossi, M., Segura, R., Cierpka, C., Kähler, C. J., *Exp. Fluids*, **52**, (4), 1063 (2012).
- 15) Raffel, M., Willert, C., Wereley, S., Kompenhans, J., "Particle image velocimetry A practical guide, 2nd edition," Springer, New York (2008), p. 40.
- 16) Shah, R. K., London, A. L., Irvine, T. F., Hartnett, J. P., "Laminar Flow Forced Convection in Ducts," eds. by Irvine, T. F., Hartnett, J. P., Academic Press, Inc., New York (1978), p. 196.
- 17) Tamayol, A., Khosla, A., Gray, B. L., Bahrami, M., *Int. J. Heat Mass Transfer*, **55**, (15-16), 3900 (2012).
- 18) Santiago, G. J., Wereley, T. S., Meinhart, D. C., Beebe, J. D., Adrian, J. R., *Exp. Fluids*, **25**, (4), 316 (1998).
- 19) COMSOL Multiphysics 5.3a User's Guid, COMSOL Inc., Stockholm, Sweden (2017).
- 20) Huang, D. M., Sendner, C., Horinek, D., Netz, R. R., Bocquet, L., *Phys. Rev. Lett.*, **101**, (22), 1 (2008).
- 21) Berg, S., Cense, A. W., Hofman, J. P., Smits, R. M. M., *Transp. Porous Med.*, **74**, (3), 275 (2008).
- 22) Dullien, F. A. L., "Porous Media Fluid Transport and Pore Structure," Academic Press, Inc., New York (1979), p. 179.

要 旨

表面濡れ性が孔隙内流動へ及ぼす影響評価

大中 温^{†1)}, Afshin GOHARZADEH^{†2)}, 佐藤 光三^{†1)}

^{†1)} 東京大学大学院工学系研究科システム創成学専攻, 113-8656 東京都文京区本郷7丁目3番1号

^{†2)} Dept. of Mechanical Engineering, Khalifa University of Science and Technology, Petroleum Institute, P.O. Box 2533, Abu Dhabi, UAE

異なる表面濡れ性を持つ孔隙内を流動する粘性流へ壁面滑りが与える影響を、マイクロ粒子画像流速計測 (micro-particle image velocimetry: μ -PIV) 法を用いた実験で検証した。実験ではポリジメチルシロキサン (PDMS) で作成した深さ 100 μm の透明なマイクロチャネル内の流動を可視化した。マイクロチャネル内には直径 180 μm の円柱を並べて配置し、孔隙とした。O₂ プラズマ処理によってマイクロチャネル表面の濡れ性を改変し、水濡れおよび油濡れの試料を準備した。測定した速

度は数値計算結果と比較を行った。結果、実験および数値計算ともに濡れ性による速度分布の差は、流路中央付近において 2.4 % 以下であった。また、数値計算の評価では絶対浸透率に関する油濡れ条件での水濡れ条件に対する比率は 1.2 であった。本結果では油濡れ条件下で、壁面滑りが孔隙内の 1 相流動の速度分布および浸透率にもたらす影響の程度を示している。本結果は 2 相流における油の置換挙動の理解に関する研究を行う際のデータの妥当性評価への活用も期待できる。