Optimizing Liquid Transport Velocity of Bioinspired Open-type Micro-blade Arrays

Rikima Kuwada and Daisuke Ishii*

Department of Life Science and Applied Chemistry, Graduate School of Engineering, Nagoya Institute of Technology, Gokiso-cho, Showa-ku, Nagoya, Aichi 466-8555, Japan
*ishii.daisuke@nitech.ac.jp

Microfluidic devices are used in many ways, including bioanalysis and chemical synthesis. Nevertheless, these devices have some issues, such as their susceptibility to bubble entrapment and impurities, and their necessity for high pressure to transport liquid as these devices consist of various closed tubes. To solve these problems, we have focused our research on a coastal animal, the wharf roach, which has open-type flow micro-passages composed of micro-blade arrays driven by surface free energy. Inspired by the microstructures, we fabricated a series of flow passages composed of micro-scaled epoxy blades on a silicon wafer through photolithography. The purpose of the present study was to control the liquid transport velocity and understand the liquid film thickness during transport, with the goal of manipulating liquid transport without external forces using the microstructures. The relationship between the interval of the blades and the liquid transport velocity was investigated. Furthermore, the variation of the liquid film thickness ratio with elapsed time was visualized using fluorescent dyes. As a result, we found that the liquid transport velocity was maximized when the blade height was high, and the cross-sectional shape between the two blades was square. Moreover, the interval in the vertical direction was narrow. In addition, it was clear that the liquid film of the water temporarily became thick near the three-phase contact line and the thin water film preceded the uniform thick water film. These findings are important for optimizing liquid transport in open-type microfluidic devices.

Keywords: Bio-inspired, Microstructures, Wetting, Liquid transport

1. Introduction

Recently, microfluidic devices have been paid much attention due to their uses in bioanalysis and chemical synthesis, as these devices can produce laboratory-scale operations, such as solution mixing, separations, reactions, and the detection of substrates. However, currently, some issues have occurred as microfluidic devices require high pressure to transport liquid and are susceptible to bubble entrapment and impurities. This is due to the devices consisting of various closed flow passages. Open channels composed of microstructures have the potential to solve these problems. Many studies on these structures have reported on these applications [1,2], such as liquid-droplet manipulation [3-5], unidirectional liquid transport [6-8], and spontaneous oil/water separation [9,10] through the control of topography and wettability on open-air surfaces. These phenomena have also been observed in nature, and many researchers have been inspired by these biological models. For instance, superhydrophobicity has demonstrated self-cleaning properties on lotus leaves, termed the Lotus effect [11], and is famous for its abilities on biomimetic surfaces composed of microstructures. It has been applied to some paints, roofing materials, and food seals among other materials.

In the present study, Ligia exotica [12], commonly called the “wharf roach”, was used as the biological model. The wharf roach is a marine isopod crustacean that inhabits rocky coasts and...
harbor walls just above the high water mark around the world. It has pairs of legs with open-type flow micro-passages which are driven by surface free energy and transport water spontaneously to its gill for breathing [12]. A scanning electron microscope observation revealed that these water channels are composed of micron-scaled blades arranged in several parallel lines (Fig. 1(a)). Inspired by the microstructures, we fabricated a series of flow passages composed of micro-scaled epoxy blades on the silicon wafer by photolithography (Fig. 1(b)). The previous studies that investigated these microstructures suggested that the transport of various liquids could manipulate the optimization of microstructures and chemical compositions on the surface [13-18].

The purpose of the present study is to control the liquid transport velocity and understand the liquid film thickness during transport, with the goal of manipulating liquid transport without external forces using open-type micro-blade arrays. A series of samples with a stepwise changing line width (LW), pitch interval (PI), and rectangular microchannel arrays (Fig. 1(c)) were used to investigate the difference in the transport velocity due to the presence of the interval of the blades. Furthermore, the variation of the liquid film thickness ratio under elapsed time was visualized using fluorescent dyes. Obara et al. studied the variation of liquid film thickness using olive oil and micropillar arrays and reported that the liquid film became thinner toward the three-phase contact line (TCL) [19]. In this study, we sought to investigate the effects of water transport behavior on the rectangular microchannel arrays and the micro-blade arrays caused by the high surface tension of the water.

2. Experiment
2.1. Fabrication of structures
2.2. Analysis

The fabricated sample was slowly and vertically contacted with a liquid pool using a dip coater (DC4300 (ST-100), AIDEN Co., Ltd.). The liquid spontaneously rose on the sample surface and formed the TCL on its propagating front. The transport behaviors of each sample were recorded using the movie mode on a digital camera (D5200, Nikon Co., Ltd.). The measured position of the TCL \( l \) as a function of time \( t \) (Fig. 3) followed Eq. 3, which was derived by Fries et al. [20].

\[
\Delta p = R \frac{\partial l}{\partial t} + \rho gl + \rho \frac{d(l)}{dt} \tag{1}
\]

\[
l = \frac{\Delta p \frac{1}{R} - \frac{\rho g}{R}}{L} \tag{2}
\]

\[
l = L \left[ 1 + W \left( -e^{-\frac{t}{\tau}} \right) \right] \tag{3}
\]

Per the derivation of Eq. 3, Eq. 2 was obtained by converting the equation of motion for the capillary rise (Eq. 1) used. \( \Delta p \) is the capillary pressure, \( R \) is the resistance constant equal to \( \varepsilon \mu / k \), \( \varepsilon \) is the porosity, \( \mu \) is the viscosity, \( k \) is the permeability, \( \rho \) is the density of the liquid, and \( g \) is the gravitational acceleration. \( L \) is a length constant equal to \( \Delta p / \rho g \), and \( \tau \) is a time constant equal to \( \Delta p R / (\rho g)^2 \). The third term on the right side of Eq. 1 represents the inertial forces, which are negligible in most capillary flows beyond very short time scales. Dropping this term and solving for the velocity \( \langle l \rangle \) produces Eq. 2. In Eq. 3, a function for the height of the rise in terms of time using the W-Lambert function was derived by transforming Eq. 2. \( L \) and \( \tau \) can be obtained by approximating the plot of the position of the TCL \( l \) with respect to time \( t \) through Eq. 3. Then, \( \Delta p \) and \( R \) can be obtained from \( L \) and \( \tau \).

Equation 2 shows that velocity follows the ratio of the capillary pressure to the resistance constant \( \Delta p / R \) when the transport distance is short. We considered that \( \Delta p / R \) was an indicator to evaluate the transport velocity of the sample.

In addition to the above analysis, we conducted an analysis to visualize the variation of the liquid film thickness ratio. Pyranine (trisodium 8-hydroxyypyrene-1,3,6-trisulfonate, Tokyo Chemical Industry Co., Ltd.) was used as a fluorescent dye. In a UV box, which contained a UV lamp (wavelength 352 nm), a pyranine aqueous solution was transported onto the hydrophilic-coated samples. Transport behaviors of each sample were recorded through a sharp cut filter (Y-51, Toshiba Glass Co., Ltd.) in front of the digital camera to remove any UV light. A thickness ratio of the liquid film was determined based on the fluorescent intensity using Image j.

3. Results and Discussion

3.1. The factor of high transport velocity

Figure 4 shows a semilogarithmic graph of the indicator of the transport velocity \( \Delta p / R \) \( (\text{mm}^2/\text{s}) \) plotted to the aspect ratio of the cross-sectional shape situated between the two blades, and \( h/LW \) of the samples, having had different blade heights, are summarized in Table 1. The transport velocity was faster when the blade was higher, and it was the fastest when the cross-sectional shape was square \((h/LW = 1)\) for each blade height.

As shown in Eq. 1, the driving force for the capillary rise is capillary pressure, which is also the Laplace pressure, and Eq. 4 reflects its theorem:

\[
\Delta p = \gamma \left( \frac{1}{r} + \frac{1}{r'} \right) \tag{4}
\]

where \( \gamma \) is the surface tension of a liquid, and \( r \) and \( r' \) are the radius of the curvature of the surface. The Laplace pressure increases as the radius of the curvature decreases. In the case of micro-blade arrays, we considered that the curvature of the gas–liquid interface near the TCL was controlled by the cross-sectional shape, and if the blade height was low and the LW was narrow, the Laplace pressure became large. On the other hand, it was clear that the viscous pressure loss (the first term on the right side of Eq. 1) prevents capillary rise at the beginning of transport when the transport velocity is rapid. According to the
Hagen-Poiseuille law, when the flow path is wide, it is easy for a liquid to pass through the path, since the flow velocity of an incompressible viscous fluid stops at the solid–liquid interface due to viscous resistance [21]. In the case of micro-blade arrays, if the blade height is high and LW is wide, the viscous pressure loss reduces. It is possible that the cross-sectional shape for the fastest transport is a square (h/LW = 1) due to the trade-off between the structure needed to increase the Laplace pressure and the structure needed to reduce the viscous pressure loss. P. J. Ponce de Leon et al. reported that the same tendency exists in the rectangular microchannel arrays and the columnar micropillar arrays [22]. Therefore, it can be seen that the control of the transport velocity through a cross-sectional shape is independent of the control by the PI.

3.2. Various liquid transports

It was investigated that liquids having different surface tension and dynamic viscosity affect the control of the transport velocity. Figure 5 demonstrates the results of the transport velocity on samples $a-24$ to $a-28$ of the three liquids summarized in Table 2. The transport velocity was improved using a liquid with high surface tension and a low dynamic viscosity, such as water, and the cross-sectional shape for the fastest transport was always the square. Therefore, we suggest that the transport velocity was able to be universally controlled by the cross-sectional shape.

3.3. Influence of the pitch interval (PI)

Figure 6 indicates the variation of transport...
velocity when the PI of the samples summarized in Table 3 undergoes a stepwise change. The samples b-1, b-8, and b-15 are the rectangular microchannel arrays (see Fig. 1(c)). In the case of a narrow PI, the transport velocity was fast. It is possible that the structure in which the blades are adjacent to each other in the vertical direction maintains a large curvature at the gas–liquid interface and continually applies the driving force. However, the liquid transport velocity on the micro-blade arrays with a PI of 10 μm was almost the same as that of the rectangular microchannel arrays. The rectangular microchannel arrays can easily maintain a large curvature at the interface. In the case of micro-blade arrays, if the transport is quick and there is enough liquid available near the TCL, the liquid is likely to fill the PI immediately, and quickly recreate the interface with large curvature. Therefore, there is no significant difference between the transport velocities. If a PI is made too narrow to improve the transport velocity, the flow path in the horizontal direction will be blocked, and if there are impurities or defects in the microstructures, the liquid will not be transported by bypassing them. Therefore, the PI should be appropriately spaced so as not to lose the advantage of open-type micro-blade arrays.

3.4. Scale down of blade sizes

We investigated whether the transport velocity could be controlled by the cross-sectional shape and the PI, even if the blade sizes were scaled down. Table 4 shows the scaled-down samples with different blade heights, h/LW, and PI.

![Table 3. Samples with different PI.](image)

![Table 4. Scaled-down samples.](image)

![Fig. 6. Transport velocities plotted to the pitch interval (PI) with different blade heights.](image)

![Fig. 7. Transport velocities plotted to the pitch interval (PI) with different blade height and line width (LW).](image)
Samples \textit{c-1}, \textit{c-7}, and \textit{c-13} are rectangular microchannel arrays. Figure 7 indicates that even when the structure was scaled down, the fastest transport was still possible for the structure with a high blade height, a square cross-section, and a narrow PI. In other words, the transport velocity can be universally controlled even if the size of the structure is on a micrometer scale. However, the only difference in the above experimental results was that the transport velocity of the rectangular microchannel arrays was clearly higher than that of the micro-blade arrays with a PI of 1 μm. We thought that this difference was attributed to the low height of the protrusion. Since the water film became thin due to the low height of the blades, the viscous resistance became large and the transport became slow. Then, sufficient liquid was not supplied near the TCL, PI could not be filled immediately. Therefore, the interface with large curvature could not be recreated quickly.

3.5. Thickness ratio of the liquid film

In order to measure the thickness ratio of the liquid film during high-velocity transport, samples \textit{b-15} (rectangular microchannel arrays) and \textit{b-16} (micro-blade arrays) was used. Figure 8 demonstrates a thickness ratio of the liquid film for each elapsed time, and each graph was made by plotting the thickness ratio of the liquid film obtained from the fluorescence intensity. Zero percent of the thickness ratio was defined as a state without a liquid film, and 100% was defined as liquid film thickness in the position 10 mm above the bottom of the area of microstructures at the end time of the liquid transport. The liquid transport completed by 2 seconds for both samples \textit{b-15} (Fig. 8(a)) and \textit{b-16} (Fig. 8(b)).

Three specific behaviors of water film are shown in Fig. 8. Firstly, in both samples, the thickness ratio slightly increased near the TCL, PI could not be filled immediately. Therefore, the interface with large curvature could not be recreated quickly.

![Graphs showing liquid film thickness ratio over time](image)

**Fig. 8.** Transport distance plotted to liquid film thickness ratio for each elapse time for samples (a) \textit{b-15} and (b) \textit{b-16}.
with high surface tension may have been pumped toward the blade height direction through the Laplace pressure and temporarily wet the upper portion of the blades. This phenomenon caused the water to be pulled closer to the TCL, and the water became able to wet the following blades (Fig. 9).

Secondly, the slope of the decrease of the thickness ratio in the TCL is gentler in the rectangular microchannel arrays (Fig. 8(a)). The long thin liquid film preceding the thick liquid film as shown in Fig. 9(a) was observed. It was thought that the preceding thin liquid film does not fill the flow channel, but quickly rises using the Laplace pressure at the interface formed by wetting the bottom and wall surfaces of the flow channel. Since the Laplace pressure continues to be applied due to the structure without PI, the preceding thin liquid film will be longer.

Thirdly, the ratio remained at approximately 100% of the portion where the ratio slightly increased. The liquid film thickness was uniform.

However, Obara et al. studied a similar experiment using micropillar arrays and olive oil and reported that the liquid film became thinner toward the TCL [19]. Therefore, the behavior of the water film observed in the present experiment can be attributed to the high surface tension of the water and the structure that can transport liquid at a high velocity.

3.6. Obstruction of flow passages

In order to examine the potential capacity for maintaining the function of the flow passages, the microstructures of samples b-15 and b-16 were partially damaged and liquid transport was observed (Fig. 10). In both samples, liquid was transported to the top of the area of microstructures in the unobstructed part of the flow passages by 2 seconds. In the case of the rectangular microchannel arrays, liquid was not transported over the damaged part over time. On the other hand, in the case of micro-blade arrays, the liquid

![Fig. 9. Schematic illustrations of the behavior of the water film near the TCL for samples (a) b-15 and (b) b-16.](image)

![Fig. 10. Transport behavior of partially damaged samples (a) b-15 and (b) b-16.](image)
bypassed the damaged part and filled the entire area by 4 seconds. It is clear that the PI caused horizontal liquid transport. This result suggested that microstructures with PI have the potential capacity to prevent obstruction due to bubble entrapment, impurities and structural damage.

4. Conclusion
We found that the liquid transport velocity of open-type micro-blade arrays inspired by the wharf roach could be controlled by manipulating the cross-sectional shape situated between the two blades and the PI. The transport velocity was the fastest when the blade height was high, the cross-sectional shape was square, and the PI was narrow, and the micro-blade arrays in these conditions transported liquid at the same velocity as the rectangular microchannel arrays. In addition, it was suggested that the transport velocity could be universally controlled by the cross-sectional shape regardless of the surface tension and viscosity of the liquid. In addition, we found that these conditions for faster transport did not change even if the structure was scaled down. Furthermore, it was thought that water with high surface tension on micro-blade arrays was pumped toward the blade height direction by the Laplace pressure, temporarily wet the upper portion of the blades, and was drawn near the TCL. We also found that a thin water film preceded a uniform thick water film. Moreover, it was suggested that the microstructures with PI have the potential capacity to prevent obstruction. In conclusion, the microstructural designs such as sample b-16 are optimal for liquid transport, and these findings are necessary for the design of open-type microfluidic devices that can transport liquid quickly, control the liquid amount efficiently, and prevent obstruction.

Acknowledgements
This study was partly supported by a Grant-in-Aid for Scientific Research (B) (No. 17H03412) from the Japan Society for the Promotion of Science (JSPS). The authors would like to thank Enago (www.enagp.jp) for the English language review.

References
1. C. Ishino, M. Reyssat, E. Reyssat, K. Okumura, and D. Quéré, *Europhys Lett.*, **79** (2007) 56005.
2. M. Hamamoto-Kurosaki and K. Okumura, *Eur. Phys. J. E*, **30** (2009) 283.
3. X. Yang, X. Liu, Y. Lu, J. Song, S. Huang, S. Zhou, Z. Jin, and W. Xu, *J. Phys. Chem. C*, **120** (2016) 7233.
4. J. Seo, S. K. Lee, J. Lee, J. S. Lee, H. Kwon, S. W. Cho, J. H. Ahn, and T. Lee, *Sci. Rep.*, **5** (2015) 12326.
5. T Nishino, H Tanigawa, A Sekiguchi, and H Mayama, *J. Photopolym. Sci. Technol.*, **32** (2019) 383.
6. J. Feng and J. P. Rothstein, *J. Colloid. Interf. Sci.*, **404** (2013) 169.
7. K. H. Chu, R. Xiao, and E. N. Wang, *Nat. Matter.*, **9** (2010) 413.
8. Y. Si, T. Wang, C. Li, C. Yu, N. Li, C. Gao, Z. Dong, and L Jiang, *ACS Nano*, **12** (2018) 9214.
9. K. Li, J. Ju, Z. Xue, J. Ma, L. Feng, S. Gao and L. Jiang, *Nat. Commun.*, **4** (2013) 2276.
10. J. Liu, L. Wang, F. Guo, L. Hou, Y. Chen, J. Liu., N. Wang, Y. Zhao, and L. Jiang, *J. Mater. Chem. A*, **4** (2016) 4365.
11. W. Barthlott and C. Neinhuis, *Planta*, **202** (1997) 1.
12. H. Horiguchi, M. Hironaka, V. B. Meyer-Rochow, and T. Hariyama, *Biol. Bul.*, **213** (2007) 196.
13. D. Ishii, H. Horiguchi, Y. Hirai, H. Yabu, Y. Matsuo, K. Iijiro, K. Tsuji, T. Shimozawa, T. Hariyama, and M. Shimomura, *Sci. Rep.*, **3** (2013) 3024.
14. M. Tani, D. Ishii, S. Ito, T. Hariyama, M. Shimomura, and K. Okumura, *Plos One*, **9** (2014) e96813.
15. M. Tani, R. Kawano, K. Kamiya, and K. Okumura, *Sci. Rep.*, **5** (2015) 10263
16. S. Ito and D. Ishii, *Surf. Interface Anal.*, **48** (2016) 1199.
17. K. Muto, S. Ito, and D. Ishii, *MRS Adv.*, **2** (2017) 1111.
18. K. Muto and D Ishii, *Colloids Surf., A*, **544** (2018) 86.
19. N. Obara and K. Okumura, *Phys. Rev. E*, **86** (2012) 020601.
20. N. Fries and D. Quere, “Capillary transport processes in porous materials—experiment and model”, Göttingen, Germany: Cuvillier Verlag (2010).
21. N. A. Mortensen, F. Okkels, and H. Bruus, *Phys. Rev. E*, **71** (2005) 057301.
22. P. J. Ponce de Leon and L. F. Velásquez-García, *J. Phys. D: Appl. Phys.*, **49** (2016) 055501.