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Enhancement of meniscus pump by multiple particles

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Abstract

We numerically investigate the behavior of a droplet spreading on a smooth substrate with multiple obstacles. As experimental works have indicated, the macroscopic contact line, or three-phase boundary line, of a droplet exhibits a significant deformation resulting in a local acceleration by successive interactions with an array of tiny obstacles settled on the substrate (Mu *et al.*, Langmuir 35, 2019). We focus on the menisci formation and resultant pressure and velocity fields inside a liquid film in a two-spherical-particle system to realize an optimal design of the effective liquid transport phenomenon. Special attention is paid to the meniscus formation around the second particle, which influences the liquid supply related to the pressure difference around the first particle as a function of the distance between the two particles.

Introduction

Wetting is ubiquitous in nature, and nature exploits wetting. For example, lotus leaves repel water droplets owing to their microstructures,¹ and certain insects move freely on a water surface by deforming the free surface with their feet.² Wetting characteristics have been applied to numerous industrial products such as inkjet printing³ and self-cleaning.⁴ In particular, to improve industrial equipment such as heat pipes⁵ and “lab on a chip devices”,⁶ which are designed to efficiently transport liquids, it is essential to have a physical understanding of the spreading of liquids on solid surfaces and to control this efficiently.

Liquid spreading is evaluated by monitoring the behavior of a contact line (CL), which is a three-phase interface on a solid surface. In particular, a visually confirmed CL is known as a macroscopic contact line (M-CL). Several studies have confirmed that the correlation between the spreading radius R and spreading time t of liquid film on a smooth horizontal substrate can be expressed as $R \sim t^a$. The exponent a depends on the dominant force acting on the liquid film; the exponent becomes $a = 1/10$ in a surface-tension dominant regime,⁷ and $a = 1/8$ in a gravity dominant regime.⁸ In particular, the exponent becomes $a = 1/7$ when surface tension is dominant in two-dimensional spreading where the liquid film spreads

in only one direction.⁷

The spreading of liquid film on a rough substrate has also been investigated. Cazabat and Cohen Stuart⁹ conducted a series of experiments on liquid spreading on a hydrophilic rough glass surface and determined that the presence of the roughness made the liquid film more susceptible to spreading on the substrate. In recent years, a number of studies have been conducted on the phenomenon where water droplets deposit on a superhydrophilic surface where numerous cylinders and prismatic structures are arranged, and the liquid erodes into gaps between the structures (hemiwicking).^{10–15} Courbin et al.¹⁰ demonstrated that a water droplet on a superhydrophilic surface changes its shape to polygons such as a square or octagon in the process of spreading. Several studies have attributed this phenomenon to the complex microscopic behavior of the liquid between the rows of individual columns (zip-ping).^{11,14} Based on the above results, Kim et al.¹⁵ constructed a scaling law to estimate the hemiwicking velocity on a rough substrate for different pillar arrangements by both macroscopic and microscopic approaches. They described the correlation from the equilibrium equations of capillary driving force and viscous drag force generated between the structure and liquid film. Thus, to understand macroscopic liquid behavior, it is important to understand the microscopic, that is, the influence of individual structures on the spread of the liquid film.

Recently, the microscopic dynamics of the interaction among the spherical particles on a horizontal substrate and liquid in the M-CL was investigated.^{16,17} Mu et al.¹⁷ demonstrated that the interaction between a spreading liquid film and single spherical particle on a horizontal substrate induced the rapid acceleration of the liquid in the vicinity of the M-CL. These acceleration phenomena are thought to be caused by the curvature of the meniscus formed around the spherical particles. Nakamura et al.¹⁸ numerically reproduced the acceleration phenomena in a single particle system and focused on the pressure distribution inside the meniscus formed around the particle. Consequently, the pressure difference between the upstream and downstream meniscus around the particle was found to be the main factor

driving the liquid as a ‘pump’.

Furthermore, Mu et al.^{19,20} confirmed that the direction of the liquid transport can be controlled by the successive arrangement of microstructures. In the experiment, the meniscus formation process in the interaction between the individual structures and liquid film is observed in detail, and the effect of the meniscus shape formed around the structure on the acceleration phenomenon is illustrated. To realize the adequate and effective design for a liquid transport system, it is of great importance and indispensable quantitative discussion on the correlation among the alignment of the structures, the menisci shape and the resultant pressure and velocity fields in the liquid film. In the present study, we investigate the menisci formation and resultant liquid behaviors and M-CL acceleration in a two-spherical-particle system.

Method

To conduct the present numerical simulations, the open source software for computational fluid dynamics, OpenFoam ® ver. 5.0, is used. The free-surface modelling technique of the volume of fluid²¹ is used to track the gas-liquid two-phase flow. The governing equations set in the simulations are the (1) continuity equation of incompressible fluid, (2) Navier–Stokes equation, and (3) advection equation of volume function α .

$$\nabla \cdot U = 0 \quad (1)$$

$$\frac{\partial \rho U}{\partial t} + \nabla \cdot (\rho U U) = -\nabla p + \nabla \cdot \tau + \rho g + F_{SV} \quad (2)$$

$$\frac{\partial \alpha}{\partial t} + \nabla \cdot (\alpha U) + \nabla \cdot (U_r \alpha (1 - \alpha)) = 0, \quad (3)$$

where U , p , τ , F_{SV} , and U_r represent the velocity, pressure, viscous stress, force induced by the interfacial tension, and relative velocity between the liquid and gas ($U_g - U_l$), respectively. U_r is called the compression velocity and used to counteract the numerical diffusion. When

the entire cell is occupied by the liquid or gas, the volume function α of the liquid phase takes values of one or zero, respectively. When it denotes the presence of an interface in the cell, α takes values in between these values. Solving the advection equation allows the tracking of the position and shape of the interface. We define the $\alpha = 0.5$ isosurface as the interface of the liquid film. The stress due to the interfacial tension is described by $F_{SV} = \gamma \kappa \mathbf{n} = \gamma \kappa \nabla \alpha / \|\nabla \alpha\|$ by the continuum surface force method,²² where κ and $\mathbf{n}$ are the curvature of the interface and normal vector of the interface pointing to the gas phase, respectively.

The computational domain is schematically indicated in Fig. 1. The length and grid number of the domain are $(L_x, L_y, L_z) = (300+L, 80, 150) \mu\text{m}$ and $(N_x, N_y, N_z) = (L_x/2, L_y/2, L_z/2)$, respectively. The distance between the two particles is denoted by L , and eight cases of numerical simulations are performed by varying $L = 62.5, 75, 87.5, 100, 112.5, 125, 137.5$, and 150 . The origin of the coordinates $(0, 0, 0) \mu\text{m}$ is set to the edge of the computational domain on the substrate. The bottom plane $(x, y = 0, z)$ represents the substrate, imposing no-slip and no-penetration conditions. The top plane $(x, y = L_y, z)$ and side walls $(x, y, z = 0); (x, y, z = L_z)$ are set to the mirror boundaries. Two spherical solid boundaries representing particles of diameter $D_p = 50 \mu\text{m}$ are positioned at the substrate $(x_p^{(1)}, y_p^{(1)}, z_p^{(1)}) = (150, 25, 0)$, and $(x_p^{(2)}, y_p^{(2)}, z_p^{(2)}) = (150 + L, 25, 0) \mu\text{m}$. In the present simulations, we employ the mirror boundary system to reduce the numerical cost. The wettability of the substrate and particles are defined in terms of the contact angles $\theta_s = 5^\circ$ and $\theta_p = 20^\circ$, respectively. The advancing and receding contact angles for the substrate and particles are set to be 0° and 10° , and 10° and 30° , respectively. We set the physical properties of the liquid and gas to those of the 2-cSt silicone oil and air used in the experiments; the surface tension, density, and kinematic viscosity of the liquid are $\sigma = 1.83 \times 10^{-2} \text{ N/m}$, $\rho_l = 873 \text{ kg/m}^3$, and $\nu_l = 2.0 \times 10^{-6} \text{ m}^2/\text{s}$, respectively. The $\rho_g = 1 \text{ kg/m}^3$ and $\nu_g = 1.48 \times 10^{-5} \text{ m}^2/\text{s}$, respectively. At time $t = 0 \text{ s}$, the liquid film begins to flow into the computational domain under the condition of $P_{\text{inlet}} = 0$, $U_{\text{inlet}} = 0$ gradient from an inlet of height $h_{\text{inlet}} = 20 \mu\text{m}$ at the

$x = 0$ boundary. The capillary number of the M-CL on the substrate immediately before the interaction with the particles in this numerical simulation corresponds to $Ca = 3.01 \times 10^{-4}$. This value of Ca , greater than that in the experiment ($Ca \sim 10^{-6}$),¹⁷ is employed to reduce the numerical cost. Note that the particles are fixed to the substrate and do not move in the present simulations, whereas the particles were not fixed to the substrate and were attracted toward the bulk of the droplet when the Ca surpassed a certain value in the experiments.¹⁶ In the present simulation, we focus on the interfacial shape and resultant pressure and velocity fields around the particles, and do not consider the particle motions observed in the experiments. The gravitational acceleration is set to be constant at $g = 9.81 \text{ m/s}^2$.

Figure 1: Computational domain of spreading liquid film on horizontal substrate with two particles.

Results and discussion

Figure 2 shows the numerical results of the spreading distance X_{CL} and M-CL velocity U_{CL} on the substrate with and without particles. The spreading distance X_{CL} is defined as the M-CL position along the line of $(x, y = 0, z = z_p)$ and U_{CL} is evaluated by the central differences

of X_{CL} . As indicated in Fig. 2, the simulations correctly reproduced the liquid film spreads of Tanner's law in the case of two-dimensional spreading $X_{CL} \propto t^{1/7}$ and $U_{CL} \propto t^{-6/7}$ on the flat substrate without particles. Conversely, the presence of particles significantly changed the liquid film spreading. After the liquid film contacted the first particle, the M-CL velocity increased and achieved a maximum value $\max(U_1)$, and then gradually decreased as can be observed in the experiments for a single-particle system.^{17,19,20} Then, the liquid film subsequently contacted the second particle and accelerated and decelerated again. The maximum M-CL velocity after contact with the second particle, $\max(U_2)$, was greater than $\max(U_1)$. It was determined that $\max(U_2)$ tended to decrease as the distance between the two particles L increased for $L = 75, 100$, and 125 . This M-CL acceleration phenomenon by interaction with two particles agrees with that observed in the experiments.^{19,20} The ratio $\max(U_2)/\max(U_1)$ is discussed again later with Fig. 6.

Figure 2: Temporal variations of (a) CL position X_{CL} and (b) velocity U_{CL} on substrates for $L = 75, 100$, and 125 . CL position is derived on line $(x, y = 0, z = z_p)$ passing under particle foot on substrate. Note that CL position is not well defined in gray area, where CL is traveling around particle foot.

We investigated in detail what occurred within the meniscus formed around the two particles based on our numerical simulations. Figure 3 illustrates the variation of the liquid film behavior after interaction with the second particle for $L = 75, 100$, and 125 as shown in Fig. 2. The liquid film driven by the interaction with the first particle contacted with and built up around the second particle. Then, a meniscus with a negative curvature of the interface formed, bridging between the two particles. At the initial stage of the meniscus formation around the second particle (i.e., immediately after the liquid film contacted the second particle), the velocity on the meniscus surface exhibited an increase at the contact part locally ($t = t_i$ ms). The smaller the distance between the particles L , the greater the interface velocity at the region concerned. Furthermore, regardless of L , as the liquid film built up around the second particle, the M-CL on the substrate spread forward ($t = t_i + 10.0$ ms), and then decelerated ($t = t_i + 20.0$ ms).

Figure 3: Meniscus formation and resulting acceleration around second particle in side view by simulation in case of $L = 75, 100$, and 125 . Vectors indicate velocity on meniscus surface. The time at the initial stage of meniscus formation around second particle is defined as $t = t_i$.

To discuss the details of its time evolution, the interface shape of the liquid film in the $x-y$ section at $(x, y, z) = (x, y, z_p)$ is shown in Fig. 4. As the liquid film builds up around the second particle, the M-CL on the substrate is driven forward, and the meniscus curvature decreases monotonically. The inset displays a comparison of the M-CL angular position

φ_{CL} around the first particle due to the difference in the distance between the particles L . Regardless of the value of L , after contact with the second particle, the value of φ_{CL} increases and then converges around $\varphi_{CL} = 120^\circ$, which is greater than the maximum value in the case of single particle system (around $\varphi_{CL} = 100^\circ$).¹⁸ This higher position is realized owing to the meniscus bridge between the two particles. Moreover, at $L = 75$ and 100 , φ_{CL} decreases marginally and then increases immediately after the contact with the second particle. Conversely, no decrease occurs for $L = 125$. This result indicates that the behavior of the liquid film around the particles depends on the distance between the particles.

Figure 4: Temporal variation of meniscus profile around particles on plane at $z = z_p$ under $L = 100 \mu\text{m}$. Red dash profile corresponds to meniscus surface at $t = 0.029$ s. Time interval between profiles is 0.0002 s. Inset illustrates temporal variations of angular position φ_{CL} of meniscus front on first particle in case of $L = 75, 100$, and $125 \mu\text{m}$.

In the simulation of the single particle system, the pressure difference inside the meniscus between the upstream and downstream sides has an important role in the acceleration phenomenon.¹⁸ We also monitored the temporal variation of the pressure distribution in the meniscus around the particles during its formation process. As indicated in Fig. 5(a), the pressure inside the meniscus around the second particle is less than the atmospheric pressure at the initial stage ($t = 28.4$ ms). Note that this indicates the results under the same condition as in Fig. 4. As the liquid film builds around the second particle, the pressure inside the meniscus increases towards the atmospheric pressure because of the diminishing curvature caused by the ongoing advancement of the M-CL ($t = 28.4$ to 30.0). Simultaneously, the pressure difference between the upstream and downstream sides is generated inside

the meniscus at the particle foot ($t = 29.2$ ms), and eventually diminishes ($t = 30.0$ ms). Such trends are similar to the results in the single-particle system¹⁸ and can be explained by the correlation between the shape of the interface and pressure difference at the gas-liquid interface based on the Young-Laplace equation.

Figure 5: (a) Temporal variation of pressure around particle on plane at $z = z_p$ under $L = 100$ μm . (b)1–3 Temporal variations of pressure difference between upstream (at x_u as shown in (a)) and downstream (x_d) sides in meniscus, and CL velocity U_{CL} under the condition of $L = 75$ (frame (b)-1), 100 (frame (b)-2), and 125 μm (frame (b)-3). Monitoring points inside meniscus on upstream and downstream sides are defined as $x_u^{(1)}$ [μm] = (130, 1, 0), $x_d^{(1)}$ [μm] = (170, 1, 0); $x_u^{(2)}$ [μm] = (150 + L - 20, 1, 0), $x_d^{(2)}$ [μm] = (150 + L + 20, 1, 0), respectively. Position of CL on the substrate cannot be well defined in the gray area.

The time evolution of the pressure difference inside the meniscus on the upstream and downstream sides, and the M-CL velocity are shown in Fig. 5(b). In this case, around the i th particle ($i = 1, 2$), the pressures $p_u^{(i)}$ and $p_d^{(i)}$ are extracted at $\mathbf{x}_u^{(i)}$ and $\mathbf{x}_d^{(i)}$, corresponding to $(x^{(i)}, y^{(i)}, z^{(i)}) = (x_p^{(i)} \pm 20\mu\text{m}, 1\mu\text{m}, z_p^{(i)})$ as shown in Fig. 5(a). The subscripts u and

d indicate the upstream and downstream, respectively. We define $\Delta p^{(i)} = p_u^{(i)} - p_d^{(i)}$ as the pressure difference between the upstream and downstream sides of the meniscus around each particle. We describe the correlation between the $\Delta p^{(i)}$ and U_{CL} shown in the panels (b) and the induced phenomena for different L . As indicated in the bottom panel of Fig. 5(b)-1, the pressure difference between the upstream and downstream inside the meniscus around the first particle, $\Delta p^{(1)}$, rapidly decreases when the meniscus begins to form on the upstream side of the particle; then, as the meniscus forms around the particle foot and reaches the downstream side, $\Delta p^{(1)}$ becomes positive and achieves a maximum value $\max(\Delta p_1^{(1)})$ as indicated at (I). Such correlation is obtained by considering the volume function $\alpha_{up}^{(i)}$ and $\alpha_{down}^{(i)}$ at the monitoring points $x_{up}^{(i)}$ and $x_{down}^{(i)}$ in the upper panel in Fig. 5 (b). It is indicated, for instance, that the advancing CL has reached the downstream evaluation point of the first particle $x_{down}^{(1)}$ at $t = 14.5$ ms. Before that instant, the pressure $p^{(down)}$ at $x = x_{down}^{(1)}$ corresponds to the ambient gas pressure and thus the time trace of Δp carries the signature of $p^{(up)}$. This pressure decreases when the meniscus starts to form on the upstream side of the particle, producing the minimum in the Δp trace. Then, as the meniscus forms around the particle foot and reaches $x_{down}^{(1)}$, Δp becomes positive and reaches the maximum. This is due to the asymmetric nature of the meniscus, which displays a greater curvature on the downstream side. Similar trend is found for the second particle as well. As described later, the j th peak in the pressure difference around the i th particle is defined as $\max(\Delta p_j^{(i)})$. The M-CL velocity on the substrate reaches the maximum value $\max(U_1)$ marginally thereafter. This is similar to the single particle system.¹⁸ An acceleration phenomenon similar to that around the first particle is observed around the second particle, and the M-CL velocity achieves $\max(U_2)$ immediately after the pressure difference $\Delta p^{(2)}$ reaches the maximum value $\max(\Delta p_1^{(2)})$ as indicated at (II). Comparing (I) and (II), it can be observed that the value of $\max(\Delta p_1^{(2)})$ is greater than that of $\max(\Delta p_1^{(1)})$, which causes $\max(U_2)$ to be greater than $\max(U_1)$. Moreover, when the pressure difference $\Delta p^{(2)}$ achieves the maximum value, $\max(\Delta p_1^{(2)})$, as indicated at (II), a pressure difference emerges again around the first particle,

and the second peak $\max(\Delta p_2^{(1)})$ is realized as indicated at (III). For $L = 75, 100$, and 125 , $\max(\Delta p_2^{(1)})$ and $\max(\Delta p_1^{(2)})$ become greater as L decreases. As we illustrate $\max(\Delta p_2^{(1)})$ affects the liquid film behavior around the first particle as shown in the inset in Fig. 4, such variations of $\Delta p_1^{(2)}$ and $\Delta p_2^{(1)}$ make φ_{CL} decrease immediately after the interaction between the liquid film and the second particle under the condition of small distance between particles, that is, $L = 75$ and 100 .

Figure 6: Relation between maximum CL velocity and pressure difference inside meniscus due to difference in interparticle distance. $\max(U_2)/\max(U_1)$ is ratio of maximum CL velocity after contact with second particle after contact with first particle. $\max(\Delta p_1^{(2)})$ and $\max(\Delta p_2^{(1)})$ are maximum pressure differences around second particle and second peaks of pressure difference around first particle, respectively.

To understand in detail how the difference of the distance between particles L influences the liquid film behavior, the ratio of the maximum M-CL velocity after contact with the first and second particles, $\max(U_2)/\max(U_1)$, and the peak of the pressure difference, $\max(\Delta p_j^{(i)})$, are shown in Fig. 6. This indicates that the maximum M-CL velocity ratio

$\max(U_2)/\max(U_1)$ decreases monotonically by increasing L for $L \geq 75$. This is consistent with the experiment using multiple pillars.²⁰ Conversely, $\max(U_2)/\max(U_1)$ for $L = 67.5$ decreases for $L = 75$. Thus, the maximum M-CL velocity $\max(U_2)$ is not necessarily greater as L decreases, and a threshold exists at approximately $L = 75$ in the present simulations. For the pressure difference around the particles, we can observe that the maximum pressure difference $\max(\Delta p_1^{(2)})$ increases as L decreases, achieves a peak near $100 < L < 87.5$, and then decreases as L further decreases. Conversely, $\max(\Delta p_2^{(1)})$ increases monotonically with decreasing L . In the majority of cases, $\max(\Delta p_2^{(1)})$ is greater than $\max(\Delta p_1^{(2)})$; however, this relation is reversed at $L = 67.5$. It can be noted that the variations of $\max(U_2)/\max(U_1)$ and $\max(\Delta p_2^{(1)})$ are not completely consistent against L . That is, the M-CL velocity after contact with the second particle is not always influenced only by the pressure difference around the second particle, $\Delta p^{(2)}$. One of the reasons that $\max(\Delta p_1^{(2)})$ peaks at approximately $100 < L < 87.5$ is considered to be the effect of $\Delta p^{(1)}$. As shown in Fig. 5(b)-2 and (b)-3, in the case of $L = 100$ and 125, the pressure difference around the first particle, $\Delta p^{(1)}$, converges to zero once achieving the maximum pressure difference $\max(\Delta p_1^{(1)})$, and then exhibits the second $\max \Delta p_1^{(2)}$ after the interaction between M-CL and the second particle. For $L = 75$ (Fig. 5(b)), conversely, $\Delta p^{(1)}$ achieves $\max(\Delta p_1^{(1)})$, and then reaches $\max(\Delta p_1^{(2)})$ without converging to 0. The convergence of $\Delta p^{(1)}$ to zero means that there exists a sufficient period to drive the liquid from the upstream side to the downstream side of the first particle owing to the pressure difference, and the meniscus around the first particle has temporarily completed its role as a pump. For $L = 75$, before sufficient liquid is supplied to the downstream side of the first particle, the second particle and M-CL come into contact with each other. It is thought that because of $\Delta p^{(1)}$, a sufficient pressure difference does not occur around the second particle.

To this point in this document, we have focused on the M-CL behavior in the x direction (stream-wise direction) on the substrate and in the y direction (parallel to the normal direction to the substrate) around the particles. Now, we focus on the M-CL behavior in the

Figure 7: Temporal variation of CL profile on substrate observed from above for $L = 100 \mu\text{m}$. Red dot and green dash profiles correspond to CL at $t = 0.017 \text{ s}$ and 0.029 s , respectively, and time interval between profiles is 0.0002 s . Velocity vector at position with greatest CL velocity on profile at each time, i.e., $\max(U_{\text{CL}}(z))$ is shown.

z direction (span-wise direction) on the substrate to explain the effect of multiple particles on the liquid film behavior. Figure 7 shows the temporal variations of the M-CL profile on the substrate observed from above. The M-CL advances with a straight shape perpendicular to the x direction until it contacts the first particle. After contact with the first particle, the M-CL around the particle foot on the substrate proceeds locally and the M-CL shape is significantly distorted (red dot). This is because the liquid is supplied from the rear to the front of the first particle by the pressure difference $\Delta p^{(1)}$ inside the meniscus around the first particle, and the M-CL near the first particle is driven forward owing to the pump effect. Subsequently, until contact with the second particle, as time elapses, the heavily distorted M-CL shape gradually changes to a linear shape. This is because the dominant force driving the liquid inside the film changes from the pressure difference within the meniscus to the interfacial tension acting on the interface with the curvature. The vectors on the M-CL illustrate velocity vectors whose absolute value is the greatest along the M-CL at each instant. Immediately after contact with the particle, the velocity near the particle foot becomes the greatest, and then the position of the greatest velocity shifts outward. It was found that the largest velocity was induced at a position along the M-CL with a negative curvature. Simi-

larly, after the M-CL contacts the second particle, the M-CL near the particle foot advances (green dashed line) by the pressure difference inside the meniscus around the particle, and then spreads such that the M-CL shape becomes a straight line. It should be noted that the velocity becomes the largest near the side of the calculation region after contact with the second particle for a period because the calculation region in the z direction is not sufficient in the present simulation. In experiments,^{19,20} it was also observed that the liquid film on the substrate became elongated in the main flow direction. This was because the liquid was transported in the main direction owing to a series of accelerations by the microstructures arranged continuously, and the spreading in the span direction was suppressed. That is, the spreading of the liquid film depends on the balance between the pressure driving around the particles and the interfacial tension along the M-CL. When the distance between the structures is less than a certain value, the liquid is driven continuously by the pressure difference between the particles, which enables an efficient liquid supply in the main flow direction.

Concluding Remarks

We conducted a series of three-dimensional numerical simulations addressing the behavior of a droplet spreading on a smooth substrate with multiple obstacles. We successfully reproduced a local acceleration of the macroscopic contact line of a droplet after successive interactions with spherical particles settled on the substrate. Special attention was paid to the menisci formation and resultant pressure and velocity fields inside the liquid film in a two-spherical-particle system. To realize an optimal design of the effective liquid transport phenomenon, we focused on the meniscus formation around the second particle, which influences the liquid supply owing to the pressure difference around the first particle as a function of the distance between the particles. It was indicated that an effective liquid supply inside the film was achieved by successive formation of the menisci, which had an important role as a pump. The pumping effect was enhanced by aligning the second particle closer than

the distance threshold between the particles.

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Graphical TOC Entry