Disjoining Pressure of Water in Nanochannels

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ABSTRACT: The disjoining pressure of water was estimated from wicking experiments in 1D silicon dioxide nanochannels of heights of 59, 87, 124, and 1015 nm. The disjoining pressure was found to be as high as $\sim 1.5$ MPa while exponentially decreasing with increasing channel height. Such a relation resulting from the curve fitting of experimentally derived data was implemented and validated in computational fluid dynamics. The implementation was then used to simulate bubble nucleation in a water-filled 59 nm nanochannel to determine the nucleation temperature. Simultaneously, experiments were conducted by nucleating a bubble in a similar 58 nm nanochannel by laser heating. The measured nucleation temperature was found to be in excellent agreement with the simulation, thus independently validating the disjoining pressure relation developed in this work. The methodology implemented here integrates experimental nanoscale physics into continuum simulations thus enabling numerical study of various phenomena where disjoining pressure plays an important role.

KEYWORDS: nanochannel, water, disjoining pressure, wicking, nucleation, capillary pressure

A nanoscale thin liquid film on a surface can have properties significantly different from those of its bulk form. At such short distances, intermolecular interactions with surface atoms can dominate and define new equilibrium positions/velocities of liquid atoms; as these fundamental parameters are statistically averaged to estimate thermodynamic properties, substantial changes in density, pressure, surface tension, viscosity, and so on can occur. Distances up to which a surface can affect liquid properties depends on the atomic composition: If either atom is nonpolar, then the presence of only weak and short-range van der Waal's force limits such changes to $<5$ nm, however, if both atoms are polar, then strong and long-range electrostatic forces can alter properties up to tens to hundreds of nanometers from the surface. The latter scenario often occurs in practical situations involving water on various surfaces.

In this work, we focus on the pressure of nanoscale water films. The thermodynamic equilibrium of liquid/air inside the nanochannels is dependent on several parameters including van der Waals forces, electrostatic forces, and structural forces; thus, it represents a Gibbsian composite system. Here, we use disjoining pressure as the major variable governing the alteration in nanoscale liquid film, which also lays the foundation for advancing research on liquid–vapor phase-change heat transfer to develop future thermal management devices. The pressure in such thin films is expected to be reduced based on the modified Young–Laplace equation. Such a reduction, defined as disjoining pressure, plays a fundamental role in a wide range of engineering and natural systems involving bubbles, transpiration, emulsions, and membranes. The theoretical determination of disjoining pressure of water on surfaces using extended DLVO theory requires fitted constants as the structural forces are usually unknown, and the surface potential cannot be measured directly for deionized (DI) water. However, numerical simulations such as molecular dynamics are currently insufficient to computationally simulate large domains and accurately capture the intermolecular forces of water over larger distances. Likewise, the experimental estimation of sub-100 nm liquid films has been severely limited to nonpolar films on solid surfaces primarily due to the evaporative and fluidic nature of nanoscale water films. Here, we overcome these experimental challenges by characterizing water’s wicking behavior in 1D silicon dioxide (SiO$_2$) nanochannels of varying height, estimating the disjoining pressure of water from experimental data, and applying these disjoining pressure values in computational fluid dynamics (CFD) wicking and bubble nucleation simulations.

Figure 1a shows the sketch of a typical sample used in our experiments. The nanochannels are 2 cm long and 10 μm wide, with a 10 μm spacing between two adjacent channels.
Wicking experiments for each channel height were conducted at least four times to ensure repeatability.

The wicking distance \( L \) variation with time \( t \) is plotted in Figure 2; \( L \) is found to be proportional to \( t^{1/2} \) for all channel heights as predicted by the analytical solution of the Navier–Stokes equation for a high aspect ratio (height \( \ll \) width) rectangular cross section channel:32

\[
L = \frac{h^2 [1 - 0.63 (h/w)] \Sigma P}{6 \mu} t^{1/2} \approx \sqrt{\frac{h^5 \Sigma P}{6 \mu}} \cdot t^{1/2} = C \cdot t^{1/2}
\]

where \( h \) and \( w \) are the height and width of the nanochannel, respectively; \( \mu \) is the fluid dynamic viscosity; and \( \Sigma P \) is the total pressure difference driving the wicking. The value of constant \( C \) (i.e., the slope in Figure 2) is obtained from the linear curve fitting of experimental data in Figure 2 for the highest \( R^2 \) value, and \( C \) increases with increasing channel height as expected. During the wicking process, two types of menisci were observed: regular-curved-shaped and wedge-shaped (insets in Figure 2). In the 1015 nm channel, the meniscus was always of a regular curve shape as it moved in the entire channel length (∼2 cm). However, in the 59 and 87 nm channels, the regular curve meniscus occurred only within the first few hundreds of micrometers from the entrance. Beyond this initial distance, water was seen to flow faster at the corners forming the wedge-shaped meniscus, which also led to air or vapor being momentarily trapped within the wicking liquid front.33 Meanwhile, the 124 nm channel was transitional as both types of menisci simultaneously coexisted in neighboring channels even at lengths far away from entrance (∼1.5 cm).

The most common mechanism of wicking in nanochannels is attributed to capillary pressure.34–37 If wicking is only driven by capillary pressure i.e., \( \Sigma P = \rho g \approx \sigma \cos \theta / h \) where \( \sigma \) is the surface tension and \( \theta \) is the contact angle, then eq 1 can be simplified to the widely used Washburn equation for capillary filling:38

\[
L = \frac{\rho g \cos \theta}{3 \mu} t^{1/2}
\]

Although the linear dependence of wicking distance on \( t^{1/2} \) holds at nanoscale, Washburn equation is inconsistent in predicting the experimental wicking rate. Other published literature on wicking in rectangular cross section nanochannels include a similar observation33,39–42 and explained this inconsistency, primarily due to electro-viscous effect32–45 or
geometrical effect. However, these effects do not explain our observed deviation (please refer to the Supporting Information for a detailed explanation). Furthermore, a common major flaw in these prior studies is the contact angle $\theta$ used in eq 2. We should not inherently assume a uniform contact angle $^{33,42,48-50}$ of the meniscus due to the channel’s high aspect ratio (width is $\sim 10 \mu m$ for all channels, while height varies from 0.059 to 1.015 $\mu m$). Thus, due to the rectangular cross section of the channel, we define two separate contact angles $\theta_{top}$ and $\theta_{side}$ of the meniscus corresponding to the top and side views, respectively (Figure 3a).

Figure 3b plots the change in $\theta_{top}$ for the 59 and 87 nm channel heights along with their respective wicking rates during the initial time period when the meniscus is regular curve shape (please see the Supporting Information for $\theta_{top}$ estimation from optical microscope images). The experimental data presents two unique findings: (1) Despite as much as 50% fluctuation in the values of $\cos \theta_{top}$ the wicking distance $L$ is still proportional to $t^{1/2}$ (Figure 3b); (2) The fitting curve slopes of 0.96 and 1.25 mm/s$^{1/2}$ for 59 and 87 nm channels, respectively, during the initial wicking period (Figure 3b) are in good agreement with the slopes for the entire wicking curve shape to a wedge shape. These observations imply that capillary pressure, which is strongly dependent on the meniscus shape, does not govern the wicking phenomenon in smaller channel heights of 59 and 87 nm. Instead, the disjoining pressure must be the driving force as most or all of the water in these nanochannels interact with the solid surface due to the small height. The opposite holds true for the larger channel height of 1015 nm where only the steady regular curve shape meniscus occurs implying that capillary pressure drives wicking, as merely a small fraction of the total water will be affected by the surface. In the transitional 124 nm channel, both disjoining and capillary pressures are important. The importance of both pressures at this channel height also alludes to the idea that the effect of SiO$_2$ surface on water (i.e., disjoining pressure) starts to diminish at distances beyond $h/2 \sim 60 \text{ nm}$ from the surface, and is in good agreement with published studies$^{6,7}$ which found the distance to be $\sim 50 \text{ nm}$ using nuclear magnetic resonance. Next, we use the experimental data to calculate disjoining pressure in the nanochannels.

Disjoining pressure is theoretically known to continuously decrease with increasing distance from the surface. However, as we only have four channel heights, disjoining pressure $P_d$ averaged over half the channel height is estimated from experimental data using eq 1 and $\Sigma P = P_d + P_c$, the combination of which can be rearranged into

$$P_d = \Sigma P - P_c = \frac{6 \mu C^2}{h^2} - 2N\left(\frac{\cos \theta_{side}}{h} + \frac{\cos \theta_{top}}{w}\right) \quad (3)$$

where $C$ is the slope (from Figure 2) of the wicking rate and $\theta_{top}$ is obtained from top view images as mentioned earlier. It should be noted here that although properties of water ($\mu$ and $\sigma$) in such confined channels will be different from the bulk we still assume bulk properties as per the norm in literature$^{40-43,46}$ and due to the fact that such properties have not yet been directly measured in experiments; in fact, the disjoining pressure term is introduced in the modified Young–Laplace equation$^{15,30}$ to account for the lack of such properties at these scales. Thus, in eq 3, all parameters are experimentally known except $\theta_{side}$. However, as the heights of the channels are at nanoscale, it is not possible to experimentally measure $\theta_{side}$. Considering the published experimental finding that water molecules on a glass surface are highly ordered up to distances

Figure 4. (a) Estimated average disjoining pressure $P_d$ of water in silicon dioxide nanochannels for various water film thickness $\delta$ based on nanochannel height $h$, and the corresponding exponentially fitted curve with $R^2 = 0.9718$. The gray region represents the 50% confidence bounds. (b) Comparison of experimental wicking rate with that from CFD simulations where average disjoining pressure data of (a) is integrated into the simulations. (c) Sketch (center) of bubble nucleation in 59 nm nanochannel with experimental image (top left) of the bubble and corresponding measured temperature distribution (bottom left); phase contour plots from CFD simulation of bubble nucleation in nanochannel (top right) with the corresponding temperature distribution (bottom right). The colored bubble image was converted to gray scale and its contrast was enhanced using MATLAB functions.

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of 50 nm normal to the surface6,7 (i.e., channel heights of up to 100 nm in our case), we use molecular dynamics simulations to quantitatively study the effect of liquid structuring on contact angle by simulating wicking of liquid argon in a hydrophilic nanochannel of two different heights (please see the Supporting Information for simulation details and results).

For the smaller channel height where liquid structuring is prominent, θside is determined to be ~90°, whereas the larger channel height with mostly bulk liquid resulted in a θside value of ~45°. Thus, using the same analogy for water in our SiO$_2$ nanochannels, we assume θside = 90° for the smaller height channels (59 and 87 nm) and θside = θtop = 39.6° for the larger channel heights (1015 nm) in eq 3 to estimate $\overline{P}_d$ (Figure 4a).

For the transitional channel with a height of 124 nm, θside would be between 90° and θtop; hence, we take the average of the upper and lower $\overline{P}_d$ values based on this range of θside while simultaneously showing the limits (Figure 4a). Please see the Supporting Information for the values of $\overline{P}_d$ and $P_d$ for each channel height. Thus, the $\overline{P}_d$ of water in silicon dioxide nanochannels is found to exponentially decrease with increasing water film thickness $\delta$ (Figure 4a) which is equivalent to half the channel height, $h$/2. We choose the exponential relation as polar molecules exhibit dominant electrostatic interaction as compared to power law function when only van der Waals interaction is present.21 Such a relation can be expressed as

$$\overline{P}_d = A e^{-b\delta}$$  \hspace{1cm} (4)

where $A = (4.25 \pm 1.06) \times 10^6$ Pa and $b = 0.035 \pm 0.007$ nm$^{-1}$. The values of constants $A$ and $b$ are obtained from curve fitting the experimental data of Figure 4a with coefficient of determination of 0.9718, and the gray region shows the range of 50% confidence bounds.

Next, we implement eq 4 in the commercial CFD software ANSYS Fluent52 to show the applicability of experimentally derived $\overline{P}_d$ values into continuum simulations. Similar to the experiments, we simulate wicking of water in 59 and 1015 nm channels (please see the Supporting Information for details) using a laminar multiphase volume of fluids (VOF) method.53 As the driving force of the wicking is $\Sigma P = \overline{P}_d + P_a + P_t$ is achieved through continuous surface force (CSF) modeling along with wall adhesion, and $\overline{P}_d$ is invoked by a user-defined function (udf). The different $\overline{P}_d$ and $\overline{P}_d$ values in the 59 nm channel are implemented by assigning the corresponding contact angles to the side walls and top/bottom walls of the channel, respectively. Wicking rates are found to be in good agreement with experimental data in both channels (Figure 4b) demonstrating successful implementation of the disjoining pressure model in CFD. Such an integration captures nanoscale physics in continuum simulations while including the effects of disjoining pressure in various phenomena such as phase change, transpiration, etc.

In order to quantitatively and independently validate the disjoining pressure expression (eq 4), we performed experiments and continuum simulations of bubble nucleation inside a silicon dioxide nanochannel and compared the nucleation temperature values. For the simulations, we first developed an expression55 for the local disjoining pressure $P_d$ as a function of the distance $x$ from surface, $P_d = 5.765 e^{-0.142x}$, from the average disjoining pressure equation (eq 4) and implemented the expression in ANSYS Fluent as a user-defined function (similar to the implementation mentioned above which resulted in Figure 4b). We simulated bubble nucleation in water confined in a 59 nm height nanochannel by applying a localized heating source with constant heat flux (Figure 4c). Initially, the nanochannel domain was completely filled with water at 300 K. A constant heat flux was then supplied at the specified spot of the bottom surface which increased the liquid temperature inside the domain (please refer to the Supporting Information for details of CFD simulation). The bubble nucleation temperature was determined to be 126.0 °C in the CFD simulation (Figure 4c). Due to the disjoining pressure effect, the liquid pressure in such nanochannel is higher17,56 than the bulk liquid pressure, thus requiring a higher temperature to nucleate a bubble in water-filled nanochannel than in bulk water. To validate the CFD simulation result, nanochannels of 58 nm in height were fabricated with multiple layers buried underneath the nanochannel; the layers assist in absorbing an incident laser beam and heating the surface to nucleate a bubble.11,12 A typical bubble nucleation process in a 103 nm height nanochannel is shown in Video S1 as it provides a much better contrast and visualization than nucleation in the 58 nm nanochannel (for which MATLAB processing was required as shown in Figure 4c). The nucleation temperature in the nanochannel was measured directly using infrared (IR) camera with a 4× objective and was found to be 123.9 ± 3.0 °C (Figure 4c, please see the Supporting Information for the details of experiments), in excellent agreement with CFD simulations. Thus, the obtained disjoining pressure expression (eq 4) is independently validated and can be further utilized to explore transport phenomena in various nanofluidic applications.

To summarize, we report a fundamental study of estimating disjoining pressure of water in silicon-dioxide nanochannels through experiments of wicking in channels with heights of 59, 87, 124, and 1015 nm. Disjoining pressure is found to be the primary driving force of wicking in smaller height nanochannels, while capillary pressure dictates wicking in the larger height nanochannel. The average disjoining pressure of water exponentially decreased with increasing film thickness, and a relation is derived by curve fitting the experimental data. The disjoining pressure relation is implemented in CFD simulations and is shown to capture the experimental wicking behavior. Such an implementation is then used to simulate bubble nucleation in a water-filled nanochannel with a height of 59 nm. Simultaneously, nanochannels with a height of 58 nm were fabricated, and bubble nucleation was achieved inside the water-filled nanochannel by laser heating. The bubble nucleation temperature measured in experiments was found to be in excellent agreement with that obtained from CFD simulations, thus independently verifying the disjoining pressure model developed in our work.

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**ASSOCIATED CONTENT**

**Supporting Information**

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.nanolett.1c02726.

Additional details on sample fabrication, wicking rate in nanochannels, dynamic contact angle, MD simulation, disjoining pressure calculation, CFD simulation of wicking, and nucleation temperature of water in nanochannel (PDF)

Video S1: bubble nucleation inside nanochannel (MP4)
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Notes
The authors declare no competing financial interest.

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REFERENCES

(1) Thompson, W. H. Perspective: Dynamics of confined liquids. J. Chem. Phys. 2018, 149 (17), 170901.
(2) Allen, M. P.; Tildesley, D. J. Computer Simulation of Liquids, 2nd ed.; Oxford University Press, 2017.
(3) Sumith, Y. D.; Maroo, S. C. Surface-Heating Algorithm for Water at Nanoscale. J. Phys. Chem. Lett. 2015, 6 (18), 3765–3769.
(4) Hu, H.; Weinberger, C. R.; Sun, Y. Effect of Nanostructures on the Meniscus Shape and Disjoining Pressure of Ultrathin Liquid Film. Nano Lett. 2014, 14 (12), 7131–7137.
(5) Mancinelli, R.; Imberti, S.; Soper, A. K.; Liu, K. H.; Mou, C. Y.; Bruni, F.; Ricci, M. A. Multiscale Approach to the Structural Study of Water Confined in MCM41. J. Phys. Chem. B 2009, 113 (50), 16169–16177.
(6) Tsukahara, T.; Hibara, A.; Ikeda, Y.; Kitamori, T. NMR study of water molecules confined in extended nanoscale. Angew. Chem., Int. Ed. 2007, 46 (7), 1180–1183.
(7) Tsukahara, T.; Mizutani, W.; Masutani, K.; Kitamori, T. NMR Studies of Structure and Dynamics of Liquid Molecules Confined in Extended Nanoscale. J. Phys. Chem. B 2009, 113 (31), 10808–10816.
(8) Elliott, J. A. W. Gibbsian Surface Thermodynamics. J. Phys. Chem. B 2020, 124 (48), 10859–10878.
(9) Chatterjee, A.; Plawsky, J. L.; Wayner, P. C. Disjoining pressure and capillarity in the constrained vapor bubble heat transfer system. Adv. Colloid Interface Sci. 2011, 168 (1–2), 40–49.
(10) Denquin, B. V.; Churaev, N. V. On the question of determining the concept of disjoining pressure and its role in the equilibrium and flow of thin films. J. Colloid Interface Sci. 1978, 66 (3), 389–398.
(11) Zou, A.; Chanana, A.; Agrawal, A.; Wayner, P. C.; Jr; Maroo, S. C. Steady State Vapor Bubble in Pool Boiling. Sci. Rep. 2016, 6, 20240.
(12) Zou, A.; Gupta, M.; Maroo, S. C. Origin, Evolution, and Movement of Microlayer in Pool Boiling. J. Phys. Chem. Lett. 2018, 9 (14), 3863–3869.
(13) Son, G.; Dhir, V. K.; Ramanujapu, N. Dynamics and Heat Transfer Associated With a Single Bubble During Nucleate Boiling on a Horizontal Surface. J. Heat Transfer 1999, 121 (3), 623–631.
(14) Wayner, P. C., Jr. Intermolecular forces in phase-change heat transfer: 1998 Kern award review. AIChE J. 1999, 45 (10), 2055–2068.
(15) Panchamgam, S. S.; Chatterjee, A.; Plawsky, J. L.; Wayner, P. C. Comprehensive experimental and theoretical study of fluid flow and heat transfer in a microscopic evaporating meniscus in a miniature heat exchanger. Int. J. Heat Mass Transfer 2008, 51 (21), 5368–5379.
(16) Koch, G. W.; Sillet, S. C.; Jennings, G. M.; Davis, S. D. The limits to tree height. Nature 2004, 428 (6985), 851–854.
(17) Zou, A.; Gupta, M.; Maroo, S. C. Transpiration Mechanism in Confined Nanopores. J. Phys. Chem. Lett. 2020, 11 (9), 3637–3641.
(18) Stubenrauch, C.; von Kitzing, R. Disjoining pressure in thin liquid foam and emulsion films - new concepts and perspectives. J. Phys.: Condens. Matter 2003, 15 (27), R1197–R1232.
(19) Taylor, S. D.; Czarnecki, J.; Masliah, J. Disjoining pressure isotherms of water-in-bitumen emulsion films. J. Colloid Interface Sci. 2002, 252 (1), 149–160.
(20) Binks, B. P.; Cho, W. G.; Fletcher, P. D. I. Disjoining pressure isotherms for oil-water-oil emulsion films. Langmuir 1997, 13 (26), 7180–7185.
(21) Yoon, R. H.; Aksoy, B. S. Hydrophobic forces in thin water films stabilized by dodecylammonium chloride. J. Colloid Interface Sci. 1999, 211 (1), 1–10.
(22) Dimitrova, T. D.; Leal-Calderon, F.; Gurkov, T. D.; Campbell, B. Disjoining pressure vs thickness isotherms of thin emulsion films stabilized by proteins. Langmuir 2001, 17 (26), 8069–8077.
(23) Exerowa, D.; Kaschiev, D.; Platikanov, D. Stability and Permeability of Amphiphile Bilayers. Adv. Colloid Interface Sci. 1992, 40, 201–256.
(24) Sedev, R.; Exerowa, D. DLVO and non-DLVO surface forces in foam films from amphiphilic block copolymers. Adv. Colloid Interface Sci. 1999, 83 (1–3), 111–136.
(25) Huereu, A.; Valignat, M. P.; Maggs, A. C.; Theodoly, O.; Jullien, M. C. Laplace pressure based disjoining pressure isotherm in non symmetric conditions. Appl. Phys. Lett. 2017, 111 (22), 221601.
(26) Pan, L.; Jung, S.; Yoon, R. H. Effect of hydrophobicity on the stability of the wetting films of water formed on gold surfaces. J. Colloid Interface Sci. 2011, 361 (1), 321–330.
(27) Tokunaga, T. K. DLVO-Based Estimates of Adsorbed Water FilmThicknesses in Geologic CO2 Reservoirs. Langmuir 2012, 28 (21), 8001–8009.
(28) Shi, C.; Cui, X.; Xie, L.; Liu, Q. X.; Chan, D. Y. C.; Israelachvili, J. N.; Zeng, H. B. Measuring Forces and Spatiotemporal Evolution of Thin Water Films between an Air Bubble and Solid Surfaces of Different Hydrophobicity. ACS Nano 2015, 9 (1), 95–104.
(29) Shi, C.; Chan, D. Y. C.; Liu, Q. X.; Zeng, H. B. Probing the Hydrophobic Interaction between Air Bubbles and Partially Hydrophobic Surfaces Using Atomic Force Microscopy. J. Phys. Chem. C 2014, 118 (43), 25000–25008.
(30) Panchamgam, S. S.; Plawsky, J. L.; Wayner, P. C. Experimental evaluation of Marangoni shear in the contact line region of an evaporating 99+% pure octane meniscus. J. Heat Transfer 2007, 129 (11), 1476–1485.
(31) Dasgupta, S.; Plawsky, J. L.; Wayner, P. C., Jr Interfacial force field characterization in a constrained vapor bubble thermosyphon. AIChE J. 1995, 41 (9), 2140–2149.
(32) Rapp, B. E. Microfluidics: Modelling, Mechanics and Mathematics. In Microfluidics: Modelling, Mechanics and Mathematics; Rapp, B. E., Ed.; Elsevier: Oxford, 2017; pp 351–370.
(33) Yang, M.; Cao, B. Y.; Wang, W.; Yun, H. M.; Chen, B. M. Experimental study on capillary filling in nanochannels. Chem. Phys. Lett. 2016, 662, 137–140.
(34) van Honschoten, J. W.; Brunets, N.; Tas, N. R. Capillarity at the nanoscale. *Chem. Soc. Rev.* 2010, 39 (3), 1096−1114.

(35) Poudel, S.; Zou, A.; Maroo, S. C. Droplet Evaporation on Porous Nanochannels for High Heat Flux Dissipation. *ACS Appl. Mater. Interfaces* 2021, 13 (1), 1853−1860.

(36) Poudel, S.; Zou, A.; Maroo, S. C. Evaporation Dynamics in Buried Nanochannels with Micropores. *Langmuir* 2020, 36 (27), 7801−7807.

(37) Poudel, S.; Zou, A.; Maroo, S. C. Wicking in Cross-Connected Buried Nanochannels. *J. Phys. Chem. C* 2019, 123 (38), 23529−23534.

(38) Washburn, E. W. The dynamics of capillary flow. *Phys. Rev.* 1921, 17 (3), 273−283.

(39) Phan, V. N.; Joseph, P.; Djeghlaf, L.; Allouch, A. E. D.; Bourrier, D.; Abgrall, P.; Gué, A.-M.; Yang, C.; Nguyen, N. T. Capillary Filling in Nanochannels—Modeling, Fabrication, and Experiments. *Heat Transfer Eng.* 2011, 32 (7−8), 624−635.

(40) Tas, N. R.; Haneveld, J.; Jansen, H. V.; Elwenspoek, M.; van den Berg, A. Capillary filling speed of water in nanochannels. *Appl. Phys. Lett.* 2004, 85 (15), 3274−3276.

(41) Haneveld, J.; Tas, N. R.; Brunets, N.; Jansen, H. V.; Elwenspoek, M. Capillary filling of sub-10 nm nanochannels. *J. Appl. Phys.* 2008, 104 (1), 014309.

(42) Mozaffari, S.; Tchoukov, P.; Mozaffari, A.; Atlas, J.; Czarnecki, J.; Nazemifard, N. Capillary driven flow in nanochannels - Application to heavy oil rheology studies. *Colloids Surf., A* 2017, 513, 178−187.

(43) Phan, V. N.; Yang, C.; Nguyen, N. T. Capillary Filling in Nanochannels. *Icmm* 2009, 2009, 907−915.

(44) Ren, C. L.; Li, D. Q. Improved understanding of the effect of electrical double layer on pressure-driven flow in microchannels. *Anal. Chim. Acta* 2005, 531 (1), 15−23.

(45) Yang, C.; Li, D. Q. Electrokinetic effects on pressure-driven liquid flows in rectangular microchannels. *J. Colloid Interface Sci.* 1997, 194 (1), 95−107.

(46) Tas, N. R.; Mela, P.; Kramer, T.; Berenschot, J. W.; van den Berg, A. Capillarity induced negative pressure of water plugs in nanochannels. *Nano Lett.* 2003, 3 (11), 1537−1540.

(47) Tas, N. R.; Escalante, M.; van Honschoten, J. W.; Jansen, H. V.; Elwenspoek, M. Capillary Negative Pressure Measured by Nanochannel Collapse. *Langmuir* 2010, 26 (3), 1473−1476.

(48) Ye, Z. R.; Li, S. B.; Wang, C.; Shen, R.; Wen, W. J. Capillary flow control in nanochannels via hybrid surface. *RSC Adv.* 2016, 6 (4), 2774−2777.

(49) Han, A.; Mondin, G.; Hegelbach, N. G.; de Rooij, N. F.; Stauffer, U. Filling kinetics of liquids in nanochannels as narrow as 27 nm by capillary force. *J. Colloid Interface Sci.* 2006, 293 (1), 151−157.

(50) Yang, D.; Krasowska, M.; Priest, C.; Popescu, M. N.; Ralston, J. Dynamics of Capillary-Driven Flow in Open Microchannels. *J. Phys. Chem. C* 2011, 115 (38), 18761−18769.

(51) Carey, V. P.; Wemhoff, A. P. Disjoining pressure effects in ultra-thin liquid films in micropassages - Comparison of thermodynamic theory with predictions of molecular dynamics simulations. *J. Heat Transfer* 2006, 128 (12), 1276−1284.

(52) Fluent, A. ANSYS Fluent, release 14; Academic Research, 2015.

(53) Hirt, C. W.; Nichols, B. D. Volume of Fluid (Vof) Method for the Dynamics of Free Boundaries. *J. Comput. Phys.* 1981, 39 (1), 201−225.

(54) Brackbill, J. U.; Kothe, D. B.; Zemach, C. A Continuum Method for Modeling Surface-Tension. *J. Comput. Phys.* 1992, 100 (2), 335−354.

(55) Poudel, S.; Zou, A.; Maroo, S. C. Inclusion of Near-Surface Disjoining Pressure Effect in Continuum Simulations. *arXiv (Fluid Dynamics)*, May 18, 2021, 2105.08483, ver. 1. [https://arxiv.org/pdf/2105.08483v1](https://arxiv.org/pdf/2105.08483v1) (accessed August 25, 2021).

(56) Zou, A.; Maroo, S. C. Nano-confinement effects on liquid pressure. *Phys. Fluids* 2021, 33 (4), 042007.