Study of Role of Adhesive Forces during Liquid-Mediated Contacts Separation

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Abstract

Menisci may form between two solid surfaces with the presence of an ultra-thin liquid film. When separation operation is needed, meniscus and viscous forces contribute to an adhesion leading to stiction, high friction, possible high wear and potential failure of the contact systems, for instance micro-devices, magnetic head disks and diesel fuel injectors. The situation may become more pronounced when the contacting surfaces are ultra-smooth and the normal load is small. In this study, roles of the meniscus and viscous forces during the separation process will be investigated with different liquid properties for flat on flat liquid-mediated contact separation. The factors that influence any change in role of meniscus and viscous forces are studied.

Introduction

Menisci may be formed around the contacting and near contacting asperities due to surface energy effect of a thin liquid film, when liquid is present at the contact interface of two surfaces as shown in Figure 1.A meniscus is formed wherever an asperity touches the liquid. A small amount of liquid at the point of contact between the solid surfaces is called pendular rings. During the formation of menisci, pendular rings are formed on contacting surfaces asperities and liquid bridges are formed on near-contacting asperities. When liquid mediated contact is considered, the formed menisci are the center of interest. The geometric description of the meniscus is the meniscus curve. It is formed between the upper and lower surfaces of the liquid when the two surfaces are brought in contact. The shape of the meniscus is determined by the properties of the liquid and solid. In some cases, the liquid spreads evenly on the surface, and sometimes it forms into tiny droplets. Liquid spreading evenly on the surface with maximizing contact angle is known as hydrophilic phenomenon and liquid forming into a droplet is known as hydrophobic phenomenon. The meniscus is convex for a hydrophobic surface, and it is concave for a hydrophilic surface. Attractive force (meniscus force) acts on the interference for hydrophilic surfaces in contact and repulsive meniscus force for hydrophobic surfaces [1-5]. The angles formed between the meniscus curve and the contact surfaces are called contact angles as shown in Figure 2. The contact angle can be measured through the liquid where a liquid/gas interface meets the solid surface with sessile drop technique. The contact angle is an important indicator of the contacting system. For a multi-phase solid, such as liquid and gas system under certain conditions (i.e. different pressures and temperatures), the equilibrium of the system (represented by the unique contact angles) reflects the strength or energy level of the materials. The formation of the menisci around the contacting and near contacting surface asperities are due to the effect of the surface energy of the liquid film.

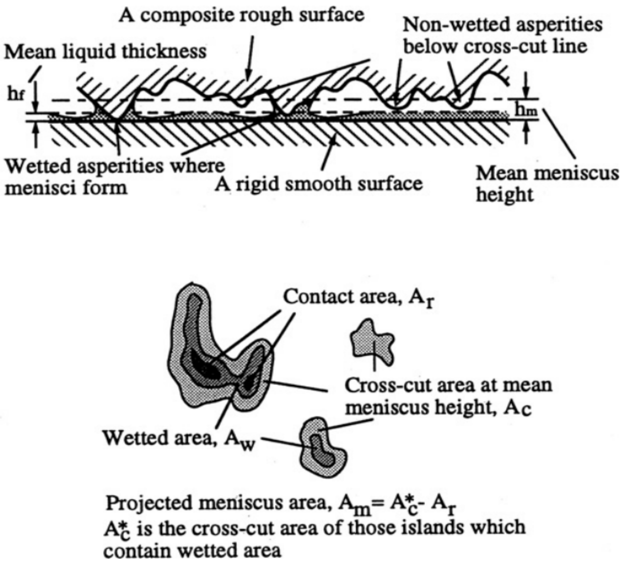

Figure 1: Schematics of formation of menisci between liquid mediated contacts [1, 2, and 3]

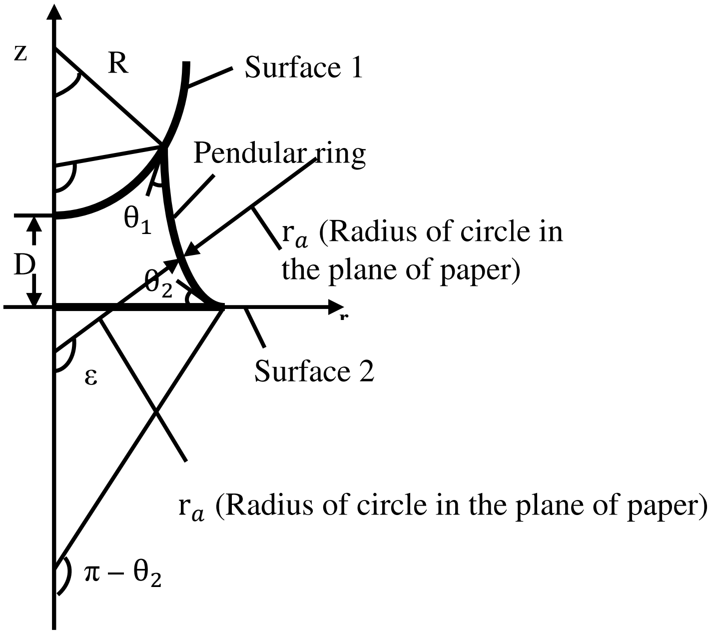

Figure 2: Schematics of meniscus curvature and contact angles at the contact interface of liquid mediated sphere-on-flat contact. [2, 4]

Meniscus and viscous forces are believed to be the major contributors to adhesion during separation of liquid-mediated contact. Many studies have been conducted to study the separation of liquid-mediated contact. Cai and Bushan [5, 6 and 7] developed models (CB model) and studied the separation of two flat-on-flat surfaces and sphere-on-flat surfaces. In CB model, various design parameters, such as contact angle, initial separation height, surface tension and liquid viscosity, have been investigated. More importantly, it has been found that the role of involved meniscus force and viscose force changes when so-called critical meniscus area is reached.

The behaviors of a liquid bridge when compressed and stretched in a quasi-static fashion between two solid surfaces that have contact angle hysteresis (CAH) is studied by H.Chen et al [8].They developed a theoretical model to obtain the profiles of the liquid bridge given a specific separation between the surfaces, where the model is able to correctly predict the behavior of the liquid bridge during a quasi-static compressing/stretching loading cycle in experiments. It has been found that the liquid bridge can have two different profiles at the same separation during one loading and unloading cycle, and more profiles can be obtained during multiple cycles where generated maximum adhesion forces are influenced by contact angle hysteresis (CAH).

When separation of two liquid-mediated contact surfaces is needed, various factors need to be considered in order to characterize the involved forces. The effects of separation distance, initial meniscus height, separation time, and roughness have been studied by S.Cai and B.Bhushan [1, 3 and 5]. Contact angle as one of the major factors in liquid-mediated contact has been studied intensively. The study on adhesion contributed by meniscus and viscous forces during the separation of two hydrophilic smooth surfaces with symmetric and asymmetric contact angles was studied by Cai and Bhusan [3, 5]. In that study, a critical meniscus area (at which meniscus force equals the viscous force) was first identified and defined as the meniscus area at which meniscus and viscous forces change role. It was found that with the increase in separation distance meniscus forces decreases and the integrative viscous force needed to overcome increases. The increase in initial meniscus height for rough surfaces and the increase in surface roughness cause an increase in meniscus force but have an insignificant effect on the viscous force [5]. A three-dimensional model for liquid-mediated adhesion between two rough surfaces is studied by A.Rostami et al by analyzing the effect of liquid surface tension, nominal contact area and external load on the stability of contact interface. It was found that increase in external load causes more interaction between contact surfaces which causes the reduction in the average gap and increase in separation height, and contact area as a result of an increase in tensile force. [9].L.Wang et al investigated an effect of various parameters such as the mass and radius of the sphere, viscosity, surface tension and volume of the liquid during dynamic separation process for two different configurations (sphere from a flat surface and sphere from a sphere surface). It was found that the separation time is longer for sphere-on-sphere for same limitations. Increase in mass leads to a decrease in external force so that the separation time increases. Between two configurations, it has been found that the influence of the mass and radius of the sphere on separation time are much weaker on sphere from sphere separation. Increase in viscosity and surface tension leads to an increase in separation time and it is determined that the influence of the liquid's viscosity and surface tension on separation time are much weaker in sphere on sphere than that for the sphere on flat case [10].

For the separation of two surfaces with formed liquid bridge, an external force larger than the meniscus force is required to initiate the separation process, and higher level force may be needed to overcome the additional viscous force contribution thereafter. It is noticed that meniscus force decreases whereas the integrated viscous force over the separation distance from the initial position increases. This indicates that the role of meniscus and viscous force may be changed during the separation process. This has been numerically verified through the simulation of separation process [1]. Further, the effects of separation distance, initial meniscus height, separation time, contact angle, division of menisci and roughness on meniscus and viscous force were analyzed in the study. The results showed that the viscous force increases with an increase in separation distance. Initial meniscus height is also one of the major factors which affect the magnitude of viscous force during the separation process where the viscous force decreases with an increase in the initial meniscus height. Time taken to break the meniscus during the separation process is the separation time. It is common that the separation time is less than a second or at about microsecond scale. The longer the separation time, the smaller the magnitude of the viscous force, since the viscous force during the separation process is inversely proportional to the separation time [1-6].

During the separation of contact surfaces, the viscosity of the liquid causes an additional attractive force, a rate dependent viscous force. Both the meniscus and viscous force cause an adhesive force during the separation. During the surface contact and when separation operation of two contact surfaces is needed, adhesion due to the meniscus and viscous force is one of the major reliability issues leading to failure or reduction in the consistency of devices such as diesel fuel injectors in operation. The issue becomes more severe when the applied load is small (which is common) for micro or nanoparticle devices. The force required to separate two surfaces is dependent on both meniscus and viscous forces. It has been found that this type of adhesive force is highly dependent on the formed meniscus area (neck cross-section area at a given meniscus height which overlaps the wetted area), separation time, surface tension and viscosity of the liquid. Meniscus force decreases whereas the integrated viscous force (to be overcome) over the separation distance from the initial position increases during the separation process. The roles of the two forces change before the surfaces is separated.

Although the effects on meniscus and viscous force contributing to adhesion during separation of liquid-mediated contact have been studied, the role changes of the contributing forces have not been adequately investigated. It is known that a critical meniscus area determines the role change of the forces. However, questions like how the critical meniscus area changes with the change of the affecting factors, such as liquid properties, need to be answered in order to effectively solve the adhesion caused issues. This paper presents a comprehensive study of the roles of meniscus and viscous force with the critical meniscus area (at which meniscus force equals the viscous force) during liquid-mediated contact separation. The effect on critical meniscus area with change in viscosity and surface tension are studied for flat on flat liquid-mediated contact separation as shown in Figure 3.

Approaches

As part of data collection procedure, already established mathematical model (shown in equations 2 and 4 below) is simulated on MATLAB to analyze the roles of the meniscus and viscous force, considering the liquid properties as Silicon Oil. Figure 3 shows the configuration of the meniscus formed between flat on flat contact surfaces.

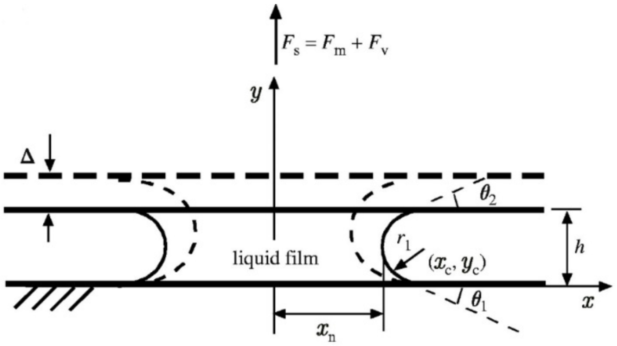

Figure 3: Formation of Liquid bridge with hydrophilic flat on flat liquid-mediated surface contact separation. [1, 2]

- Meniscus Force

The meniscus force on flat on flat contact due to the formation of a meniscus is obtained by integrating the Laplace pressure over the meniscus area and adding the surface tension effect acting on the circumference of the interface [5].

$$F_m = F_L + F_T \quad (1)$$

$$F_m = \pi\chi_n^2 \frac{\gamma}{r_k} + 2\pi\gamma\chi_n \sin\theta_{1,2} \quad (2)$$

Where,
F_s is the external force which is needed to overcome the intrinsic forces contributed by meniscus force.
F_m is the meniscus force.
F_v is the viscous force.
F_L is the attractive force due to Laplace.
F_T is the attractive force due to surface tension.
h is the separation height.
γ is the liquid surface tension.
r_1 is the radii of the meniscus in orthogonal plane.
χ_n is the discrete meniscus radius at time step n.

θ is the contact angle
$\theta_{1,2}$ is the contact angle between solid surface and meniscus for the upper and lower surface respectively.
r_k is the kelvin radius.
x_c, y_c are the center coordinates

The meniscus height is calculated by the following expression:

$$h = r_k\,(\cos\theta_1 + \cos\theta_2) \tag{3}$$

The meniscus force in terms of separation height is:

$$F_m = \frac{\pi\chi_n^2\gamma(\cos\theta_1 + \cos\theta_2)}{h} + 2\pi\gamma\chi_n \sin\theta_{1,2} \tag{4}$$

- <u>Viscous Force</u>

Viscous force occurs due to the presence of viscosity when two surfaces are separated within a short time. Characterization of the viscous force is important in order to estimate the total force needed to separate two liquid-mediated contact surfaces. The equation for viscous force during the separation of flat on flat surfaces has been derived by using Reynolds lubrication equation with a cylinder coordinate system [5].

$$\frac{\partial}{\partial r}\left(rh^3\frac{\partial p}{\partial r}\right) = 12\eta r\frac{dh}{dt} \tag{5}$$

Where η is a kinematic viscosity, h is the separation distance, and r is an arbitrary distance (the same as χ_n as shown in Fig. 3.) in the central plane of the meniscus in the direction of separation.
For the separation of two smooth flat surfaces, the viscous force during the separation of two flat on flat surfaces at given separation height is [4]:

$$F_v = \frac{3\pi\eta\chi_{ni}^4}{4t_s}\left(\frac{1}{h_s^2} - \frac{1}{h_0^2}\right) \tag{6}$$

Where t_s is the time to separate two surfaces, h_s is the break point which is infinite (theoretically) during the separation, and h_o is the initial gap between the two flat surfaces.

Both the meniscus and viscous force is operating inside the meniscus during the separation process in surface contact. So the condition like the asymmetric angles, division meniscus, separation time and height can significantly affect the properties of the meniscus and viscous force during the separation. An external force is required to initiate the separation process. During the break point external force should be larger than total of meniscus and viscous force. Through the contact of the two liquid-mediated surfaces, if the meniscus force is larger than that of the viscous force, the meniscus will break slowly without the application of external forces, however, the time to separate is longer.

Results and Discussions

It is known that larger meniscus area leads to larger meniscus and viscous force. Critical meniscus area (at which meniscus force equals the viscous force) is a function of surface tension, which increases with increase in surface tension. Critical meniscus area and the forces exhibit a nonlinear relationship when the surface tension is changed [2]. In order to establish the relation between viscosity and surface tension with critical meniscus area at which the forces change the role, analysis is performed on silicon oil at room temperature at a viscosity of 0.4860 Ns/m^2 and surface tension of 0.0633 N/m, and a separation time of 1 second with a contact angle of 60^o. Initially, the preliminary value of liquid's viscosity and surface tension at room temperature are inserted in the Eqn. (4) and (6) during flat on flat contact separation and solved numerically. The resulting critical meniscus area, and meniscus and viscous force values are recorded. The simulation gives the values of critical meniscus area at different heights (2nm to 6nm) for corresponding meniscus and viscous forces for different liquid properties. Every time when the different liquid properties value is inserted, simulated program gives the corresponding value of meniscus and viscous forces, and critical meniscus area which is noted for further analysis.

The symbols ●■▲♦○ represent the critical meniscus area values for different viscosities and surface tension values for initial meniscus height which varies from 2nm to 6nm respectively and the highlighted dashes box on left side of the graph represent the initial critical meniscus area for different initial meniscus heights for silicon oil (η_o=0.4860 Ns/m^2 and γ= 0.0633 N/m) at room temperature during flat on flat liquid-mediated contact separation (Refer to Figures. 4, 5, 6 & 7). To study the effect of liquid properties, viscosity value is increased by 5%, 10% ,15% ,20%,25%,30%,35%,40%,50% and 100% (Refer to Figure.4) with its initial value of surface tension constant (0.0633 N/m) and then surface tension value is increased by 5%, 10% ,15% ,20%,25%,30%,35%,40%,50% and 100% (Refer to Figure.5) with its viscosity value constant (0.4860 Ns/m^2). In order to study the effect of viscosity, initial value of liquid properties is taken as silicon oil (η_o=0.4860 Ns/m^2 and γ= 0.0633 N/m). The initial value of surface tension is kept constant as 0.0633N/m while the viscosity value is increased by 5% ,10% and so on with its initial value. Every time the constant surface tension value (0.0633N/m) and result through increased in viscosity value are inserted on the simulated program. For example, increased by 5% of initial viscosity is 0.510 $Ns/m^{2,}$ 10% of initial viscosity is 0.535 Ns/m^2, hence the new liquid properties 0.0633N/m and 0.510Ns/m^2, 0.0633N/m and 0.535 Ns/m^2 and so on are inserted on program separately. And to analyze the effect of surface tension, initial value of liquid properties is also taken as silicon oil (η_o=0.4860 Ns/m^2 and γ= 0.0633 N/m). The initial value of viscosity is kept constant as 0.4860 Ns/m^2 however the surface tension value is increased by 5% ,10% and so on with its initial value. Every time the constant viscosity value (0.4860 Ns/m^2) and result by increased surface tension value are inserted on the simulated program. For example, increased by 5%

of initial surface tension is 0.0665 N/m˙ 10% of initial viscosity is 0.0696 N/m, hence the new liquid properties 0.0665N/m and 0.4860Ns/m^2, 0.0696N/m and 0.4860 Ns/m^2 and so on are inserted on program separately. Table 1 shows the corresponding increased value of viscosity and surface tension with its initial. This different viscosity and surface tension values are used for meniscus and viscous force calculation and the critical meniscus area are recorded for different initial height. Figures 4 and 5 show the increasing viscosity and surface tension value on x- axis and corresponding critical meniscus area on the y-axis.

Figure 4. shows the effect of liquid viscosity on critical meniscus area during flat on flat liquid-mediated contact separation. It shows the effect of increasing viscosity of the liquid with constant surface tension. It is observed that initial meniscus height and viscosity of the liquid have a significant effect on the critical meniscus area. The results show that with the contact angles of Θ_1 and Θ_2 as 60^o, any increase in the initial meniscus heights leads to a larger critical meniscus area for the same viscosity. This is because a larger initial meniscus height leads to a much faster decrease in viscous force compared to the meniscus force so a larger meniscus area is needed for the viscous force to become comparable to the meniscus force. The ratio of the increase of critical meniscus area for increasing viscosity is always same for 2nm to 3nm, 3nm to 4nm, 4nm to 5nm and 5nm to 6nm separation heights. The result shows that changing of critical area from 5nm to 6nm has a higher ratio followed by 4nm to 5nm, 3nm to 4nm and 2nm to 3nm. It is observed that critical meniscus area decreases with increase in viscosity. The decrease in critical meniscus area results in a decrease in meniscus force. From Figure 4, we can also observe that the change in the critical meniscus area from 2nm to 6nm initial separation is almost constant as viscosity increases.

Table 1 : Viscosity and surface tension after increasing with its initial value at room temperature

Initial Viscosity and Surface Tension at Room Temperature for Silicon Oil	η_o= 0.4860 Ns/m^2	γ_o = 0.0633 N/m
Increased Percentage with Initial value	Viscosity (Ns/m^2)	Surface tension(N/m)
5%	0.510	0.0665
10%	0.535	0.0696
15%	0.559	0.0728
20%	0.583	0.0760
25%	0.608	0.0791
30%	0.632	0.0823
35%	0.656	0.0855
40%	0.680	0.0886
50%	0.729	0.0950
100%	0.972	0.1266

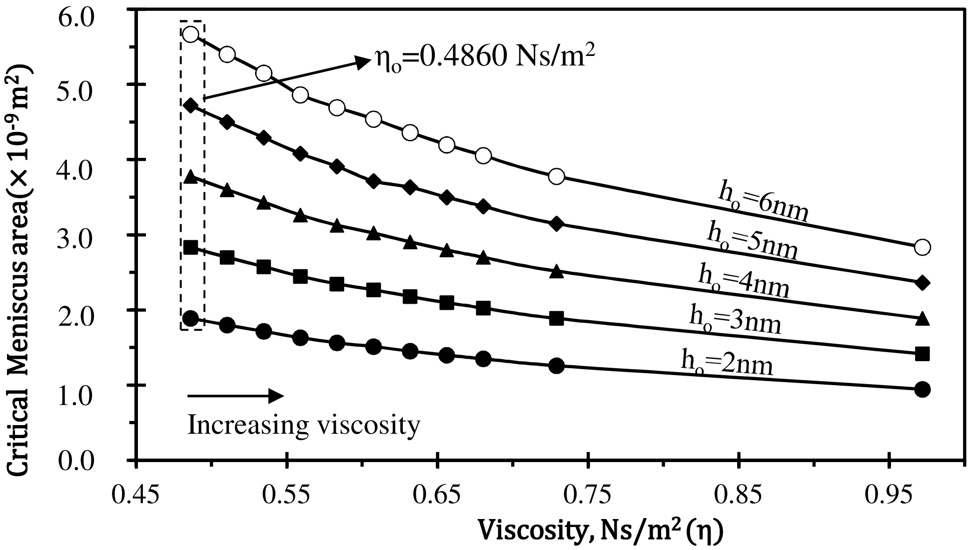

Figure 4: Dimensional relationship between viscosity and critical meniscus area at contact angles $\theta_1 = \theta_2 = 60^o$, constant γ with 0.0633 N/m (Silicon Oil) for separation time =1s, Note: $\eta_o = 0.4860$ Ns/m^{2,} Initial meniscus area= 8.50×10^{-10}m^2

To study the effect of surface tension, the liquid viscosity value ($\eta_o = 0.4860$ Ns/m^2) at room temperature is kept constant and the surface tension is increased (shown in Table 1). Figure.5 shows the effect of liquid surface tension on critical meniscus area during flat on flat liquid mediated contact separation. It is observed that initial meniscus height and surface tension of the liquid have a significant effect on the critical meniscus area. The results also show that with the contact angles of Θ_1 and Θ_2 as 60^o, an increase in the initial meniscus heights leads to a larger critical meniscus area for same surface tension. This is because a larger initial meniscus height leads to a much faster decrease in viscous force compared to the meniscus force. So a larger meniscus area is needed for the viscous force to become comparable to the meniscus force. The ratio of the increase of critical meniscus area for increasing surface tension is also always same for 2nm to 3nm, 3nm to 4nm, 4nm to 5nm and 5nm to 6nm separation heights. The result shows that changing of critical meniscus area from 5nm to 6nm has higher value followed by 4nm to 5nm, 3nm to 4nm and 2nm to 3nm, same as viscosity analysis in Figure 4. It is observed that critical meniscus area moves to a higher value with the increase in surface tension. From the Figure 5, one can also conclude that the change in the critical area from 2nm to 6nm initial separation is constant as surface tension increases.

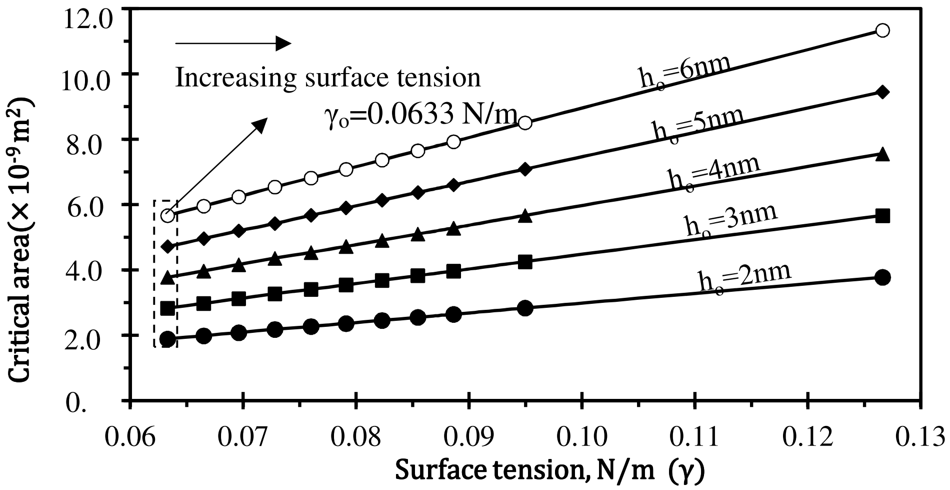

Figure 5: Relationship between surface tension and critical area with contact angles $\theta_1 = \theta_2 = 60^o$, Constant η with.4860 Ns/m^2 (Silicon Oil) for separation time=1s, Note: γ_o=0.0633 N/m

The relationship between meniscus and viscous force with critical meniscus area and the corresponding effects of viscosity and separation height is shown in Figure 6. It is observed that critical meniscus area decreases with the increase in liquid viscosity for the cases where the surface tension is constant with constant initial meniscus height. This is due to the most rapid increase in viscous force when the viscosity of the liquid is higher. Thus viscous force can dominate at smaller critical meniscus area. It is also noticed that the lower initial meniscus height has a smaller critical meniscus area. In addition, the rate of decrease in critical meniscus area is also smaller for a lower initial meniscus height when the liquid viscosity is increased.

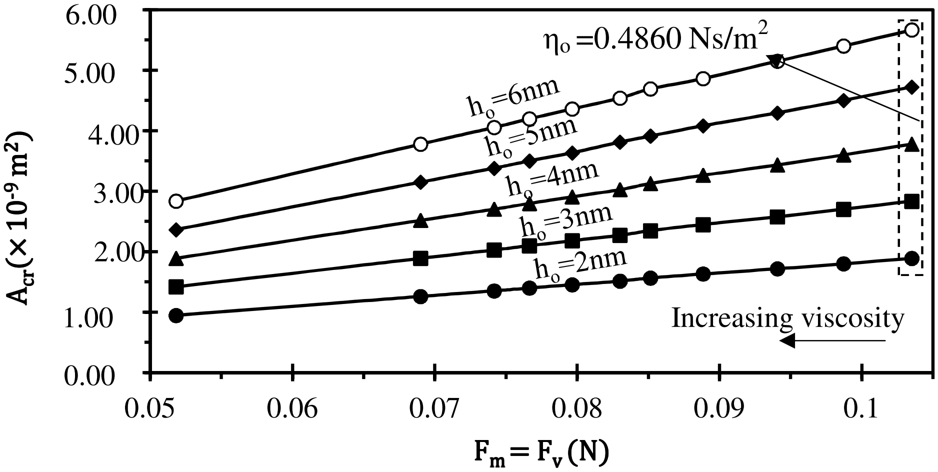

Figure 6: Relationship between meniscus force and critical area with contact angles θ_1= θ_2=60^o, constant η (0.4860 Ns/m^2) for separation time = 1s, Note: γ_o=0.0633 N/m (Silicon Oil) [2]

The relationship between meniscus and viscous forces as a function of critical meniscus area with the effect of surface tension and separation height is presented in Figure 7. The figure shows the effects of initial meniscus height and surface tension on the critical meniscus area in a dimensional analysis. It is observed that for a constant initial meniscus height, the critical meniscus area (at which meniscus force equals the viscous force) increases with the increase in liquid surface tension. The lower initial meniscus height has a smaller critical meniscus area. In addition, the rate of increase in critical meniscus area is also smaller for a lower initial meniscus height. This confirms the observation made previously. These observations indicate that viscous force may be likely to take a dominant role when initial meniscus height is smaller.

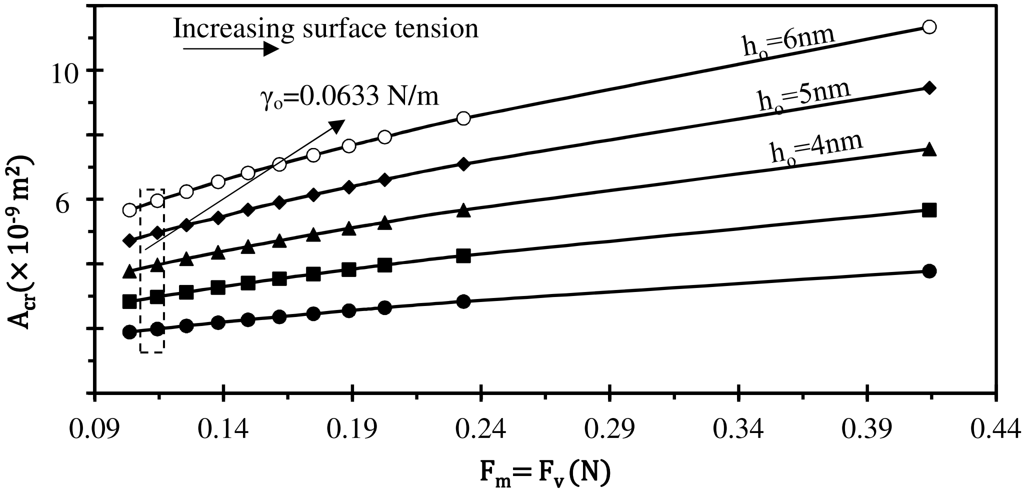

Figure 7: Relationship between meniscus force and critical area with contact angles θ_1= θ_2=60^o, constant η (0.4860 Ns/m^2) for separation time = 1s, Note: γ_o=0.0633 N/m (Silicon Oil) [2]

Conclusion

This work presents a study of critical meniscus area at which meniscus and viscous forces change roles during flat on flat liquid-mediated contact separation. It was observed that the critical meniscus area depends upon contact configurations such as viscosity, surface tension, and separation height.

For the same separation time, initial meniscus height, change in viscosity and surface tension of the liquid have a significant effect on the critical meniscus area. Critical meniscus area decreases at a higher rate for the higher separation height (i.e.= 6nm) followed by decreasing initial separation (5nm, 4nm, 3nm and 2nm). Also, it is observed that critical meniscus area decreases as the viscosity increases. The change in the critical meniscus area from 2nm to 6nm initial separation height is almost constant as viscosity increases. With the increase in surface tension, critical meniscus area increases and the change in critical meniscus area from 2nm to 6nm initial separation is nearly constant. Critical meniscus area always increases with increase in initial separation for fixed viscosity or surface tension. For a fixed initial separation, critical meniscus area decreases with an increase in viscosity, but increases with an increase in surface tension.

The increase or decrease in meniscus and viscous force during liquid-mediated contact separation are significantly affected by changes in meniscus area. These two types of forces are comparable when the critical meniscus area is reached. The dominant of either meniscus force or viscous force depend on the size of critical meniscus area.

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Biographies

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