Modelling Capillary Bridges on Liquid-Infused Surfaces

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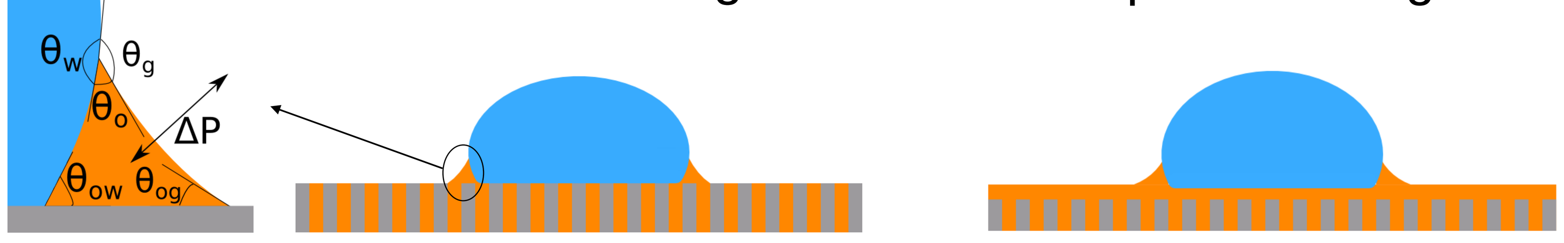
Liquid-Infused Surfaces (LIS)

Inspired by the Nepenthes pitcher plant, LIS are porous materials infused with a lubricant liquid[1]. Such surfaces have been demonstrated to possess very slippery properties. This has stimulated research into potential applications in areas such as drag reduction, self-cleaning and anti-frost surfaces[2].

Modelling Droplets on LIS

To model the displacement of a (water) droplet resting on an (oily) LIS, one can define six independent parameters, θ_o, θ_w, θ_{ow}, θ_{og}, ΔP, V_w. The angles θ_o, θ_w, θ_g, are the Neumann angles related to the surface tensions of the liquids involved. The angles θ_{ow}, θ_{og}, are the surface contact angles. The oil-gas pressure difference is given by $\Delta P = \Delta P_{og} = P_o - P_g$, and V_w is the volume of the water droplet. There are two wetting configurations which become important when defining the energy. There is the partial wetting case, where $\theta_{ow}, \theta_{og} > 0^o$; and the complete wetting case, where $\theta_{ow}, \theta_{og} = 0^o$, in which case a thin lubricating layer will form on the surface.

Partial Wetting — Complete Wetting



To define the **energy** of the system E_{total}, different considerations must be made for partial wetting ($\theta_{ow}, \theta_{og} > 0^o$) and complete wetting ($\theta_{ow}, \theta_{og} = 0^o$).

Partial Wetting

$$E_{total} = E_{liquid} + E_{solid}$$

Complete Wetting

$$E_{total} = E_{liquid} + E_{disj}$$

$$E_{liquid} = A_{wg}\gamma_{wg} + A_{ow}\gamma_{ow} + A_{og}\gamma_{og} - \Delta P_{wg}V_w - \Delta P_{og}V_o$$

$$E_{disj} = \frac{B}{12\pi y^2} \qquad E_{solid} = A_{ws}\gamma_{ow}\cos\theta_{ow} - (A_{ws} + A_{os})\gamma_{og}\cos\theta_{og}$$

The **force** is then given by the derivative: $F = \frac{\mathrm{d}E_{total}}{\mathrm{dh}}$

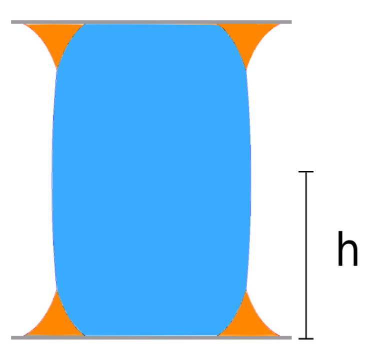
To allow for comparisons with the binary case, (binary being the case with no lubricant) the apparent contact angle[3], θ_{app}, was used, which can also be interpreted as a material parameter of the system.

$$\cos\theta_{app} = -\cos\theta_{ow}\frac{\sin\theta_g}{\sin\theta_o} + \cos\theta_{og}\frac{\sin\theta_w}{\sin\theta_o}$$
$$= \cos\theta_{wg}$$

Studying Capillarity Properties

The parallel displacement of droplets on LIS, i.e. how they slip across the surface have been studied extensively.

However the displacement of droplets in the perpendicular direction have had relatively limited study. Our research will model a capillary bridge of water between two LIS plates to understand how this differs with the binary case. From this the capillary force can be determined along with the breaking separation h_{max} between the plates.

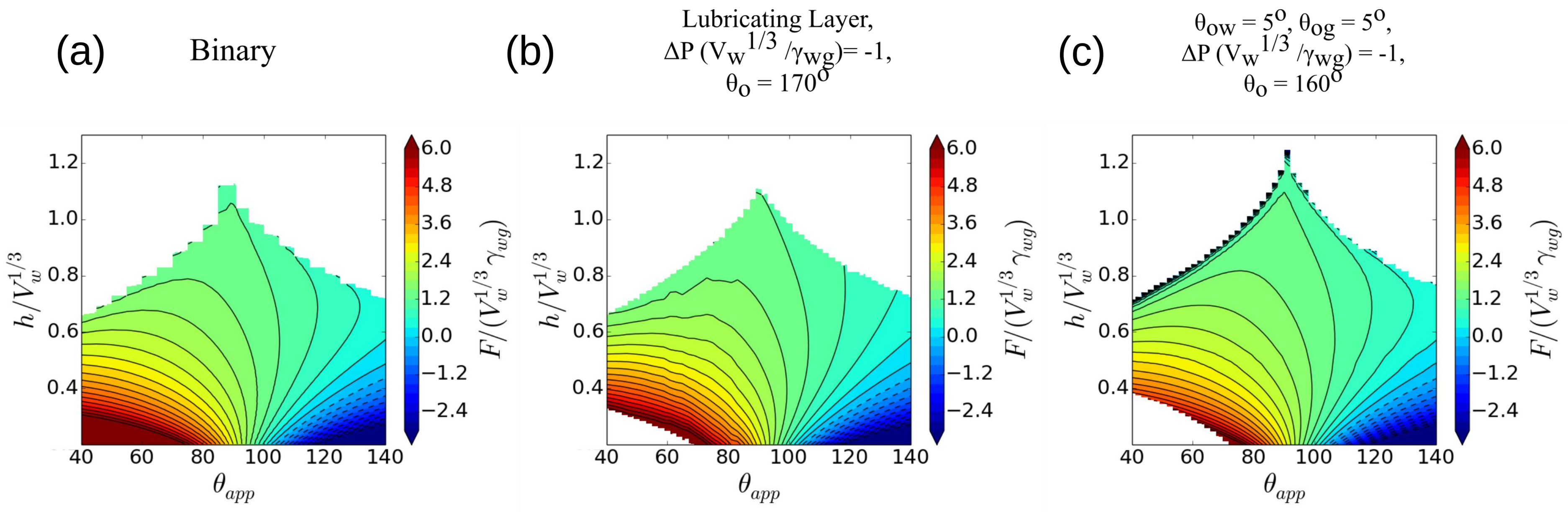


LIS Capillary Bridge

Are LIS stickier than smooth surfaces?

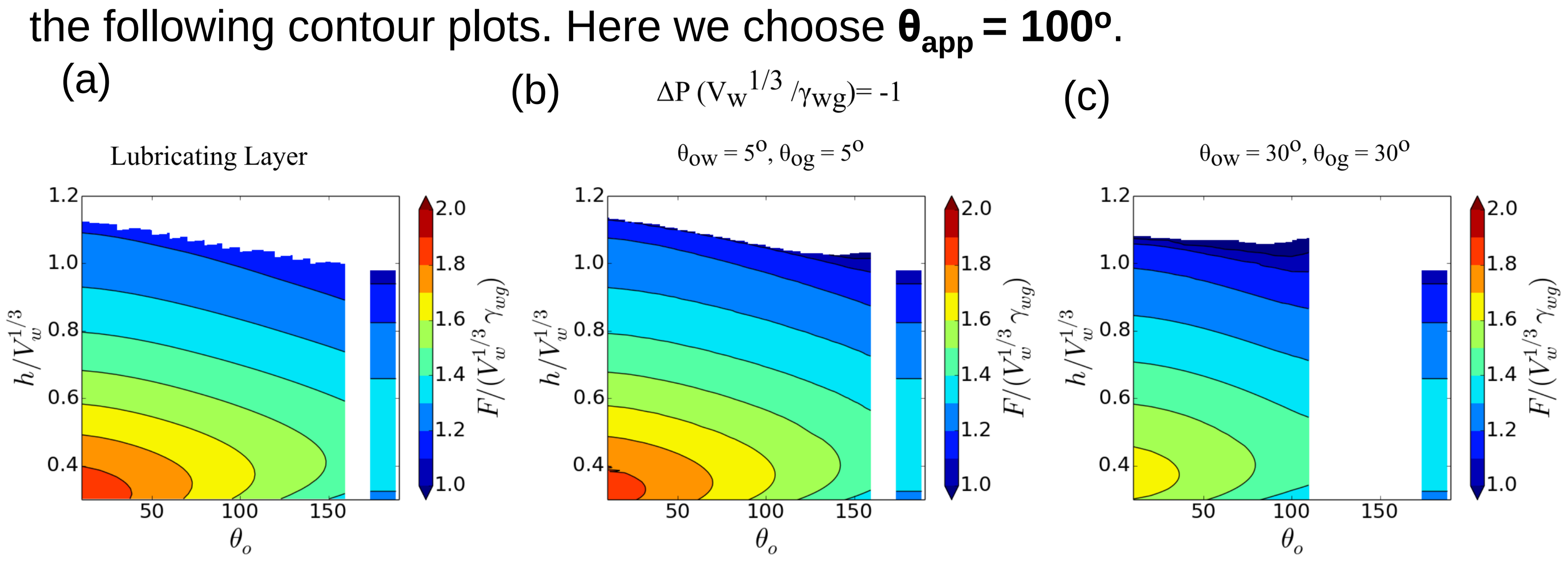
One question which can be asked is whether LIS are stickier than normal smooth surfaces. To answer such a question one must define 'stickiness'. For our research this will be related to the capillary force between the plates and the breaking separation h_{max}, which can be taken to represent the range of the capillary force.

Results

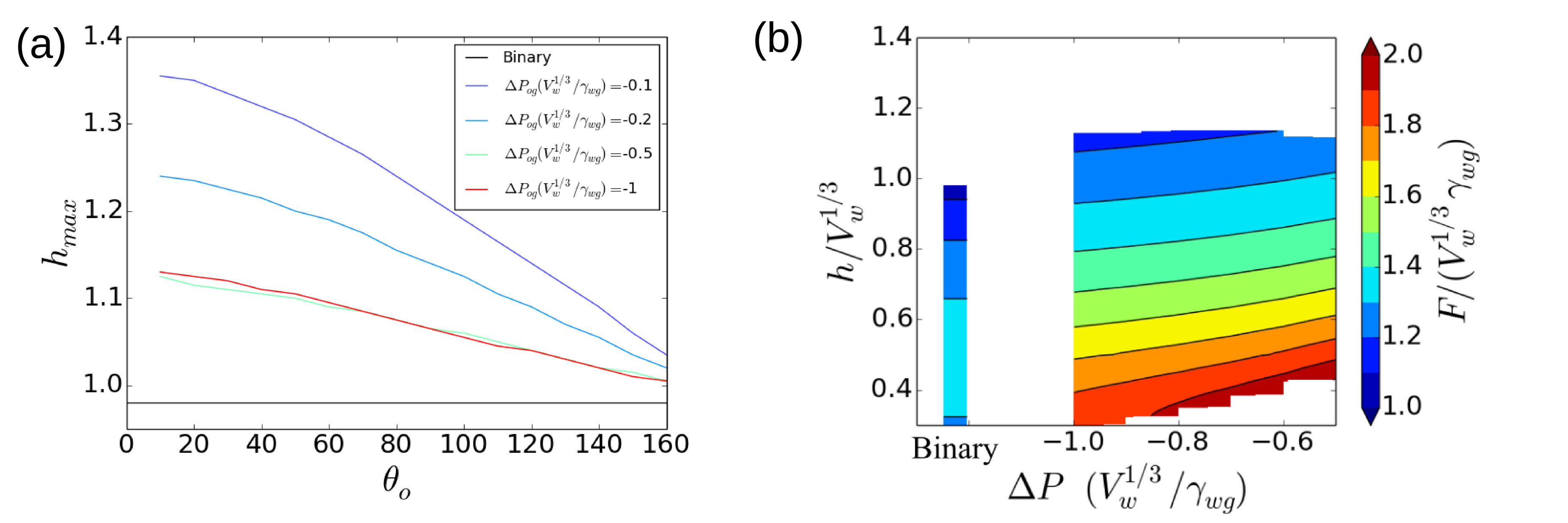


The above are force contour plots for the cases of (a) binary, (b) lubricating layer, and (c) small contact angle. The plots (b) and (c) are chosen with large θ_o as this should be close to the binary case, so these results serve as a benchmark and highlight the similarities. At $\theta_{app} < 90^o$ the force becomes increasingly attractive at smaller distances, where as for $\theta_{app} > 90^o$ they become less attractive and eventually repulsive.

If one takes a closer look at the effect of varying θ_o on the force, we obtain the following contour plots. Here we choose $\boldsymbol{\theta_{app} = 100^o}$.



From the above it can be observed that decreasing θ_o increases the force. However by increasing the contact angles θ_{ow}, θ_{og} the force is found to decrease instead. This is not surprising as it reflects weaker wetting of the surface.



The above demonstrate the effect of varying the pressure difference. Plot (a) shows there is an increase in the breaking separation provided ΔP is small enough. Finally plot (b) shows that the smaller the ΔP the greater the force.

Conclusion

- LIS are indeed stickier than smooth surfaces
- The lower the surface tension of the oil (i.e. the smaller the θ_o) the stickier the system becomes
- The smaller the pressure difference, ΔP, the stickier the system becomes
- Decreasing the wetting angles θ_{ow}, θ_{og} will increase the capillary force

References

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