Slippery Coatings for Highly Viscous Complex Fluids on Solid Surfaces

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Surface science has grown as an interdisciplinary area of research where physics meets chemistry meets biology to understand the fundamentals behind it as well as to develop advancematerials and devices for the betterment of humankind. In recent years, interfacial science for various liquid-solid and liquid-liquid interfaces has especially gained attention due to a variety of phenomenon governed by them, for example, wetting, lubrication, printing, adhesion, friction, and erosion. Controlling the equilibrium behaviour of liquid drops on a solid or liquid surface is probably the most important question in interfacial science. Physical properties of involved liquid and solid and the interaction between the two determine the equilibrium behaviour of the liquid.

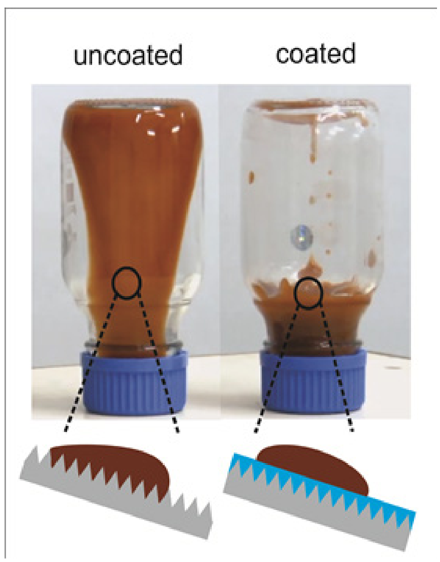
Wetting physics, that encompasses various exciting physical phenomena, is a rapidly growing field of modern physics. French physicist Prof. PG de Gennes, who received the Nobel Prize in Physics, to demonstrate ordering in liquids (liquid crystals), worked extensively on surface science including wetting of solid and liquid surfaces. He was fascinated on seeing tremendous applications of wetting physics,, for example, water drops on windshields of cars and window panes, non-wetting behaviour of leaves of various plants, and breaking of a liquid jet into drops. He observed that small sized water drops move effortlessly on non-wetting surfaces forming complete spherical shape. Later, physicists investigated that hierarchical surface roughness and low surface energy coating are responsible for non-wetting characteristics of these surfaces. Even though these surfaces show excellent non-wetting and repelling behaviour for water drops, they do not depict similar

* Ms. Meenaxi Sharma, Ph.D. Scholar from Indian Institute of Technology, Kanpur, is pursuing her research on "Statics and Dynamics of Aqueous Drops on Lubricating Fluid Coated Slippery Surfaces." Her popular science story entitled "Slippery Coatings for Highly Viscous Complex Fluids on Solid Surfaces" has been selected for AWSAR Award.

characteristics for highly viscous and complex fluids, for example, food items, bio-materials, paints, which is also required in many applications. Hence, it is equally important and demanding to develop surfaces where highly viscous and complex fluids can also move like water drops.

In nature, we have *Nepenthes* pitcher plants, which act as slippery surface for a variety of materials. In a pitcher plant, inner walls consist of microstructures and water/nectar from environment gets locked forming a lubricating layer. If an insect gets trapped inside a pitcher plant, it cannot escape as it slips due to the lubricating layer. Mimicking the *Nepenthes* pitcher plant structure, research group of Prof. Joanna Aizenberg from Harvard University fabricated Slippery Lubricant Infused Porous Surfaces (SLIPS) in 2011. She used functionalized porous structures of a hydrophobic polymer, polytetrafluoroethylene(Teflon),and infused them with silicone oil, which acts as a lubricating layer. Upon tilting such surfaces by only few degrees, various liquid drops slipped effortlessly as if the surface was frictionless. Following this development, many research groups started working in this area to understand various fundamental aspects along with potential commercial applications.

Our research group at the Department of Physics, Indian Institute of Technology Kanpur, has also been actively working on this topic since last 5 years. We have successfully fabricated such slippery surfaces on a variety of smooth and rough solid surfaces including metals, polymers, and ceramics. Based on thermodynamics, there are few conditions that need to be fulfilled for successful fabrication and stable behaviour of slippery surfaces. An ideal slippery surface should offer zero friction to every possible slipping fluid and the surfaces we prepared in our laboratory are very close to ideal in terms of the friction offered to a variety of slipping fluids. We used smooth or rough solid surfaces of metals, glass and ceramics, modified their surface chemistry appropriately



and subsequently coated them with a thin lubricating film of silicone oil. We used variety of liquids (immiscible with the lubricating oil) to study their slipping behaviour, for example, water, alcohols, alkenes, complex fluids like tomato ketchup, honey, nail paint, and wall paint. All these simple and complex liquids show excellent slipping behaviour on the fabricated slippery surfaces. Hence, they can be very useful in many applications where almost frictionless motion of a liquid is required.

We all know how difficult it is to take out tomato ketchup from a ketchup bottle. We have to apply a lot of thrust and force to bring the ketchup out of the bottle. Also, quite a lot of ketchup is wasted as it cannot be taken out of the bottle completely. The main reason behind this is the stickiness and highly viscous nature of the ketchup. We thought that lubricant based slippery surfaces can also be used for complex fluids like tomato ketchup and many more. Hence, we prepared a slippery coating on the inner wall of a glass bottle. We filled the glass bottle with slippery coating with tomato ketchup and compared its behavior to a normal bottle. The adjacent figure shows slipping behaviour of tomato ketchup on uncoated (left one) and slippery coated (right one) glass bottles. It is clear that the ketchup gets stuck on the sidewalls of uncoated bottle whereas it slips completely on the bottle coated with the slippery coating. The schematics in the bottom of the figure show zoom-in image of uncoated and coated surface of the bottles. Large surface roughness on inner wall of a glass bottle prevents smooth motion of ketchup. Whereas glass bottles coated with a lubricating fluid presents almost no friction to ketchup and the ketchup moves very easily and comes out of the bottle effortlessly.

There are numerous other applications of such slippery surfaces e.g. enhanced condensation, anti-icing, anti-fouling, anti-fogging, self-cleaning, self-healing etc. Lubricating fluid coated slippery surfaces show enhanced condensation which is very useful in heat transfer applications. Self-healing is another excellent property of slippery surfaces. Due to fluidic nature of lubricating oil, the surface heals automatically upon some physical damage like scratching or rubbing. Such surfaces also demonstrate excellent anti-icing behavior as ice condensation is reduced on them. Even if small amount of ice gets deposited on a slippery surface, the adhesion of ice will not be very strong and it can be easily removed by blowing them. Self-cleaning is another very important application where slippery surfaces can be used extensively. Due to the low surface friction, dust particles or impurity won't stay longer and can be removed when a liquid slips through the surface.

So it is clear that lubricating fluid coated slippery surfaces, inspired by *Nepenthes* pitcher plants, are excellent candidate to demonstrate almost frictionless motion for variety of slipping liquids. I have been working in this research area from fundamental as well as application point of view since last 4 years. Our group has published about 10 research articles in this area along with one patent.