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SYMPOSIUM

Surface-Tension Phenomena in Organismal Biology: An Introduction to the Symposium

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From the symposium "Shaking, Dripping, and Drinking: Surface Tension Phenomena in Organismal Biology" presented at the annual meeting of the Society for Integrative and Comparative Biology, January 3–7, 2014 at Austin, Texas.

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Synopsis Flows driven by surface tension are both ubiquitous and diverse, involving the drinking of birds and bees, the flow of xylem in plants, the impact of raindrops on animals, respiration in humans, and the transmission of diseases in plants and animals, including humans. The fundamental physical principles underlying such flows provide a unifying framework to interpret the adaptations of the microorganisms, animals, and plants that rely upon them. The symposium on "Surface-Tension Phenomena in Organismal Biology" assembled an interdisciplinary group of researchers to address a large spectrum of topics, all articulated around the role of surface tension in shaping biology, health, and ecology. The contributions to the symposium and the papers in this issue are meant to be a starting point for novices to familiarize themselves with the fundamentals of flows driven by surface tension; to understand how they can play a governing role in many settings in organismal biology; and how such understanding of nature's use of surface tension can, in turn, inspire humans to innovate.

Introduction

Surface-tension phenomena are ubiquitous in organismal biology, although the subject has not yet received a unified treatment. Among plants, surface tension governs the flow of xylem fluid in trees, the ejection of spores via Buller's drop in fungi (Money 1998) or the dispersal of seeds through the splash of raindrops (Amador et al. 2013). Among insects, surface tension is exploited in drinking or adhesion through drops of fluid at the end of their feet (Federle et al. 2002). Among microbes, surface tension enables surface-active microorganisms and pathogens to disperse via drops and bubbles (e.g., Bourouiba et al. 2012, 2014; Traverso et al. 2013). Such dispersion can be beneficial, as in the case of life-promoting biomaterial in the surf zone (Bourouiba and Bush 2013), or deleterious, as in the case of disease-inducing pathogens in confined environments (e.g., Bourouiba et al. 2014). In human lungs, surfactants lower surface tension, thereby facilitating breathing (Notter 2000), while water-walking insects exploit surface tension in maintaining water-repellency (Bush et al. 2007). Although these organisms, scales, and applications are disparate; they share common fundamental physical mechanisms.

For readable discussions of the role of surface tension in biology, we refer the reader to reviews by Bush et al. (2007) and Bush and Hu (2006); for an overview of surface tension in general, we refer the reader to de Gennes et al. (2003).

Let us begin by discussing the origin of surface and interfacial tensions. We refer to surface tension when considering a boundary between a fluid and a gas (e.g., water and air) while we refer to interfacial tension when considering the boundary between two bulks of immiscible fluids (e.g., oil and water). Surface or interfacial tension is a force per unit length or energy per unit area, which originates from the difference between the intermolecular forces acting at the interface (fluid–fluid or gas–fluid) and those acting in the fluid-bulk (de

Gennes et al. 2003). In the bulk, a molecule has more similar neighbors with which to bind than does a molecule at the interface. As a result, the molecule in the bulk is energetically more stable than its homolog at the interface. Surface tension is a measure of the energetic differential between the bulk and the interface. Additional creation of surface area coincides with a higher energy state for a given fluid-bulk; thus, a general principle of minimization of the surface energy governs most small bodies of fluid. For example, a small fluid-bulk evolves into a sphere, as observed for raindrops during storms or in the kitchen tap when producing a jet of sufficiently low rate of flow.

Nevertheless, the story of surface tension is not so simple. Indeed, various hydrodynamic instabilities involve surface or interfacial tension as a key player; but it does not always play the same role. In certain configurations, surface tension can contribute to the destabilization of an interface, favoring its break-up (fragmentation) into smaller volumes of fluid such as filaments or droplets. In other configurations, surface tension stabilizes the interface, resisting its break-up (e.g., Levich and Krylov 1969; Villermaux 2007). Moreover, surface tension is affected by changes in the temperature and chemical composition of the fluid. Gradients of surface tension can create flows restricted to the surface, referred to as Marangoni flows. Surface-active components, referred to as surfactants, can modify surface tension by being particularly suited to bind with the molecules of the interface. Such surfactants can then lower the energy associated with the surface area and facilitate the creation of more surface area or cause break-up. Transport of drops and bubbles, their surface properties, sizes, mixing properties, or longevity, can all be modified greatly by the presence of surfactants on their interfaces (Bush et al. 2007). Biological, health, and ecological fluids commonly involve surfactants that can induce a rich interfacial dynamics (Israelachvili 2011).

Traditionally, surface tension and the physics at the interface have received little treatment in textbooks of either classical biology or fluid dynamics, but a realization of their importance is growing. This increasing interest is now culminating in the creation of funding programs and avenues that allow beginning scientists to train and address complex biological, ecological, and health problems, by joining fundamental and interdisciplinary approaches. The organization of this symposium was one particular result of such movement. The participating speakers described a broad range of biological or health-driven topics, all centered on the fundamental role of surface tension. The goal of the symposium was to allow a broad audience to understand how the techniques of physical mathematics, such as scaling analysis, calculus, and differential equations describing fluid dynamics, as well as high-speed videography and image-processing techniques can apply to solve interdisciplinary problems in biology and health. A survey of the key topics of the talks presented is organized below per theme.

Surface tension and the spread of disease: pathogen-bearing drops and bubbles

Bourouiba discussed the interplay between interfacial flows and pathogen transport leading to indoor transmission of diseases. The dynamics leading to the creation of pathogen-bearing droplets from contaminated fluids were discussed in various contexts, including violent sneezing (Bourouiba et al. 2014) and the bursting of contaminated bubbles (Bourouiba and Bush 2013; Walls et al. 2014, this issue). Reversely, the influence of pathogens on the process of fragmentation of fluids was also discussed (Bourouiba 2014). Fluid dynamics was used to determine the patterns of contamination for various infectious diseases.

Gilet and Bourouiba (2014, this issue) discussed aspects of the fragmentation of fluids in the context of rain-induced foliar transmission of disease within a plant, or between plants. In this particular case, the interaction between fluids and leaves was found to be key in governing the type of fragmentation leading to the creation and ejection of droplets bearing foliar pathogens. The identified modes of fragmentation determined the pattern of foliar transmission expected in agricultural plant fields.

Surface tension and suction pressure in human physiology

Levy et al. (2014, this issue) discussed models for the spreading dynamics of surfactants on thin viscous films in the context of lung dynamics. Surfactants are known to lower the surface tension in the alveolar fluids found in the lungs, which induces coupled motion of the surfactant and the underlying fluid. The connections to problems in the lungs of premature infants, which lack such surfactant, were discussed.

Maki and Ross (2014, this issue) discussed the flow of the post-lens tear fluid (fluid under a contact lens) in response to the suction pressure generated by a contact lens. Although surfactants and surface tension play a role in the tear fluid, in this case the suction pressure is not created by interfacial tension but rather by the elastic tension in a contact lens. Models of the suction pressure can help us understand the problems caused by extended wearing of soft contact lenses, as well as the associated corneal complications, some resulting in loss of vision.

Nature-inspired designs: from cells and seeds to insects and plants

Chen and Lee (2014) focused on various microfluidic systems aiming at mimicking nature, for example, red blood cells, with the aim of encapsulating and transporting various biomaterials. Droplets were controlled for use as vehicles for trapping and transportation. Walls et al. (2014, this issue) discussed another interfacial dynamic concerned with bubbles, and their drainage, in the presence of particulates, a topic relevant for applications from bioreactors to mixing in the surf zone of the ocean.

Jung et al. (2014) focused on the revolving dynamics of *Pelargonium* seeds, which have developed an optimal strategy of propulsion and burial in response to changing environmental conditions such as humidity and soil. Burton et al. (2014, this issue) illustrated how insects exploit surface tension and Marangoni flows for propulsion and floating and how understanding such mechanisms can lead to innovation in unexpected domains: such as gastronomy! Indeed, innovative, bio-inspired patented accessories were presented to the audience. These included a floral pipette inspired by a floating flower and a self-propelled, edible alcohol-holding boat inspired by the Marangoni flows used by insects for propulsion.

Mayser and Barthlott (2014, this issue) focused on the intriguing superhydrophobic surface of the water fern. Such a surface is able to retain air underwater for months, thanks to its microstructure. Understanding how its hairy surface relates to the optimization of retention of air underwater has a myriad of industrial applications. Also intriguing was the nontrivial interplay between such incredible retentive ability and the impacts of raindrops of increasing intensity. Bird et al. (2014) discussed the physical forces involved in the dynamics of the impacts of droplets on surfaces. Here too, nature was an inspiration. The micro-textures of leaves, such as those of the lotus, or the larger-scaled textures of butterfly wings, were used as inspiration and illustration of how surfaces could be designed to control the dynamics of the impact of droplets on surfaces. In particular, efficient methods were found that reduce the time of residence of droplets impacting engineered surfaces.

Locomotion and transport at the interface

Prakash and Mukundarajan (2014) highlighted the finding of a new mode of insect "flight" using an initially puzzling use of surface tension. Water-lily beetles were found to flap their wings while remaining attached to the fluid's interface, thereby using flapping to propel themselves over the interface or to glide rather than fly. Interfacial capillary-gravity waves were discussed as playing a key role in this newly discovered mode of propulsion. Stark et al. (2014, this issue) discussed the role played by the gecko in maintaining its adhesion despite the infiltration of moisture between its toe pads and the target surface. An air plastron, located around its adhesive toe pads, expels water at the interface, thus illustrating an unexpected link between hydrophobicity and adhesion.

Hu et al. (2014) surveyed a large range of biological applications illustrating how ejections of fluids and droplets can be used by animals and insects (see Dickerson and Hu 2014). Accumulation of rain and dew require efficient ejections or drainage even of the tiniest droplets, a feat especially difficult for small insects or when dealing with small droplets. The frequency of shaking by mammals was found to achieve optimal ejection of droplets (Dickerson et al. 2012), while a law of urination (another mode of clearing fluid, after all) was found to follow scaling laws consistent with the balance of hydrodynamic forces.

Although birds use aerodynamics to fly, Ortega-Jimenez and Dudley (2012) focused on the inconvenience to which they are subjected by hydrodynamics. In particular, interfacial flows via wetting and via the impacts of raindrops can challenge their flight dramatically. Hummingbirds' flight was examined experimentally while increasing intensities of precipitations. Interestingly, the birds were found to perform what Dickerson et al. (2012) reported in mammals: a head shake, but now in flight!

Summary

The talks presented at the symposium and the accompanying articles in this volume reflect the breadth of the research at the intersections of flows driven by surface tension in relation to health, biology, and ecology. The tools used to tackle the questions discussed ranged from mathematical physics and physical experiments to computational tools.

The talks and discussions at the symposium, and the contributions to this volume, show exciting new directions in biology and in health-driven problems involving surface tension. The lively exchanges among junior and senior scientists have the potential to define new interdisciplinary questions and novel approaches to solve current problems ranging from the transmission of pathogens to the flights of mosquitoes in rain.

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