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Analyses of drag on viscoelastic liquid infused bio-inspired patterned surfaces

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ABSTRACT

The villi structures found in intestinal tract, infused with mucus, can attain different configurations by elongation and lashing movements. The present work analyzes the different configurations of villi separately and the associated drag behavior that may aid in movement of food through the tract. Using numerical simulations, the variation of drag in intestinal tract with respect to different configurations, especially the inclination of villi, has been studied, with quasi-steady approximations that consider the villi as solid objects. Extending this intestinal tract surface with villi and mucus, to a normal ridge textured surface infused with a viscoelastic fluid, significant changes in drag, owing to the viscoelastic nature of the infused fluid, have been found. The extent of drag reduction or drag enhancement, which is dependent on texture of the surface, is also found to be contingent on rate of deformation of the viscoelastic fluid along the patterned surface, and the density of ridges or solid fraction. Such control over drag on these surfaces, through Weissenberg number and texture of the surface, indicates the possibility of using viscoelastic liquid infused engineered surfaces for bio-medical and industrial applications.

1. Introduction

Nature uses unique mechanisms to control the drag on different surfaces, enabling it to take complete control over the functions that a surface is intended to do. For instance, from a highly slippery surface with extremely low drag on the surface of a Nepenthes pitcher plant [1] to a highly controlled environment using cilia in trachea with sufficient drag for the mucus to move against gravity [2], nature has utilized similar mechanisms with different adaptations on the surfaces to control drag. Some of the earlier studies associated with nature, regarding drag analyses, starts with the hydrophobicity and self-cleaning activity of the lotus leaf which utilizes nano-scale hair like structures [3,4] to roll the water droplets. This ability to repel water, resulting in a reduced drag [5–7] when water flows over it, stems from the air pockets trapped in-between the textures of hair like structures on the leaf surface. Although the superhydrophobic surfaces have been successfully mimicked by researchers [8–12], they face issues in stabilizing air pockets as they are dependent on relative contact angle of the fluid on the surface, the texture of the surface [13,14], hydraulic pressure [15], etc. Unless these factors are duly considered while fabricating the surfaces, such factors can initiate a shift from a non-wetting Cassie–Baxter state to a completely wetting Wenzel state, where the air pockets are replaced by water [16].

In the case of Nepenthes pitcher plant, the pitcher is lined with a peristome that attracts the insects. Following the peristome is a layer of conductive zone, a waxy layer of the inner wall, which hampers the adhesion of the insect. These surfaces have a texture similar to lotus leaf, but with a liquid, usually rain water, entrapped in the textures that make the surface extremely slippery [17]. Subsequent studies and successful replication of such surfaces [18,19], also called as Slippery Liquid Infused Porous Surfaces (SLIPS), paved a way to progress toward omniphobic surfaces [20] with high pressure stability. Although the drag reduction capabilities of these surfaces have not been ascertained, the SLIPS, compared to superhydrophobic surfaces, have better pressure stability, low droplet roll of angles, etc. that find itself promising for a wide range of applications from anti-biofouling to enhancing dropwise condensation [21–24]. The textures and the fluid infused in these textures characterize such surfaces, and control essential parameters like droplet roll off angles, velocity of the droplets, drag force, etc. [25]. Many aspects like boiling, condensation, heat transfer, omniphobicity, etc. have been studied [26] over a variety of impregnated fluids with different viscosities, surface tensions, etc. with respect to the primary fluid. However, studies performed till date have been employing Newtonian fluids in these surfaces.

Nature, in general, uses liquids that are more often non-Newtonian or viscoelastic, with shear thinning or shear thickening behavior, than Newtonian fluids. Viscoelastic fluids are extensively

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used, especially in biological systems. A short glimpse into the uses of such fluids, like tear film lipid layer, synovial fluid, etc., in the human system, gives a good perspective of the role played by viscoelastic nature of the fluid. For example, the tear film lipid layer in the eye is a viscoelastic shear thinning layer [27]. After a blink, this lipid layer behaves like a stretched spring and slowly moves over to the equilibrium position. This elastic behavior is found to be a significant deterrent on dewetting of the aqueous layers of tear film [28]. Similarly, the synovial fluid found in bone joints of the human body is a viscoleastic shear thinning fluid. Earlier studies claimed that this viscoelastic behavior enabled synovial fluid to act as a hydrodynamic lubricant [29,30]. However, it was later conflicted with boundary lubrication effects [31,32]. Nonetheless, based on these studies, viscoelastic havior of the synovial fluid has a definite contribution to the proper lubrication and functioning of the joints. Mucus, a viscoelastic fluid, running throughout the digestive tract helps in lubricating the movement of the food [33]. Mucus is commonly found infused in-between the villi structures, in the intestinal surfaces [34]. This configuration is similar to SLIPS but possesses an additional parameter, the viscoelastic nature of infused fluid, which has not been studied before.

The present work analyzes the frictional force on intestinal surfaces for different configurations of the villi, with quasi-steady approximations – the villus shape is not affected by chyme motion. Some of the earlier observations have also been considered alongside these analyses. Such observations depict an unresolved behavior in the drag force variation on the intestinal surfaces. To resolve this uncertainty, in the present work, numerical simulations are employed, and the underlying mechanism behind the drag obtained for different configurations of villi is elucidated. Moreover, some of the earlier studies have also realized a modicum of drag reduction in such flows with viscoelastic fluids [35–37] in place of Newtonian fluids. Therefore, with an inspiration from the mucus infused villi surface, we extend our analyses to similar engineered surfaces that can utilize the aforementioned drag reduction even more effectively, due to viscoelastic nature of the fluid. Such surfaces can also be classified under SLIPS, but the infused fluid is viscoelastic in nature, unlike previous studies. Throughout this text, SLIPS, in general, refer to textured surfaces infused with a Newtonian fluid. The remarkable advantage of viscoelastic liquid infused bio-inspired surfaces over SLIPS lies on the significant drag reduction over and above the drag reduction observed in SLIPS, relative to superhydrophobic surfaces. In addition, surfaces can be easily tailor-made to have a higher or lower frictional drag, with the help of viscoelastic nature of the infused fluid, for example, by suitably modifying the concentration of the polymer solution. The resulting polymer solution can be shear-thinning or shear-thickening, and this adds to the versatility of the surface. The viscoelastic nature of the fluid in conjunction with the texture of surface was found to significantly affect the flow pattern, and the deformation encountered by the flow, which in-turn influence the drag on a moving wall. The present work concludes by discussing the relationship between observed drag behavior in the bio-inspired surfaces with deformation rate contours, flow streamlines, etc. for different textured surfaces.

2. Drag on intestinal surfaces

The small intestinal surface of the human digestive system is filled with villi and microvilli to increase the surface area for effective absorption and digestion. They are submerged in mucus, a viscoelastic fluid, which acts like a protective barrier [38]. The finger-like villi projections are 0.5–1 mm long [39]. The mucus coating is 150 μm thick in stomach, and the thickness varies dynamically in small intestine [40]. The villi are covered with absorptive cells that synthesize digestive enzymes and absorb nutrients. They are capable of employing rhythmical, shortening, lengthening, lateral or swaying motion either in single or in groups [41]. The intestinal surface, as a whole, has two types of movements – segmentation and migrating motility complex, a movement similar to peristalsis [39]. The former helps to churn the chyme well to effectively absorb the nutrients through the absorptive cells in villi. The latter helps to push the remaining undigested chyme out of the system. Either of these movements involves rubbing of chyme along the walls of intestine, during which the mucus acts as a lubricant to reduce the friction. Although there have been many studies to determine the frictional coefficient variations with other parameters [42–45], the mechanism behind lubrication effects of mucus in conjunction with the villi has not been established clearly. Alison et al. [43] made an observation, while measuring the frictional coefficients, in which the friction or the drag was always higher during the first run. Whereas, in the subsequent runs, the drag force was found to be lesser, with observable flattening on the tissue surface. On a similar note, Accoto et al. [45] suggests that the lubrication effect of this surface might be from a uniform bending of a group of villi, to squeeze the mucus to stay on top, forcing the chyme to rub over the mucus layer, which lubricates the motion. This indicates that the morphology of intestinal surface, determined by the villi structures, has a significant effect on the friction experienced by the chyme, despite the lubrication effect provided by mucus. It is also known that the villi structures can have shortening, lengthening, lateral or swaying motions, leading to different possible configurations among villi structures in the intestinal surface. Therefore, this work attempts to deduce the behavior of drag force for different configurations of villi structures in the intestinal surface. In reality, the food particle moving over the intestinal surface dynamically changes the villi configuration as it slides; but the intent of the present work is to analyze the drag force separately for different configurations of villi, so the villi are considered as rigid bodies whose shape is not affected by food movement. To analyze the frictional force on such surfaces, we employ validated numerical simulations to predict the shear stress on a moving wall, which acts like the chyme or solid food particle moving over a viscoelastic fluid filled surface, textured with smooth ridges as villi.

3. Numerical simulation setup

3.1. Viscoelastic model

The mucus, a polymeric solution, is viscoelastic in nature. It is modeled with an assumption of no shear thinning, through Oldroyd-B model. The Oldroyd-B model was derived from the kinetic theory of polymers; they are modeled as elastic dumbbells, whose ends are connected by Hookean springs, suspended in a Newtonian solvent. Therefore, this model is suitable for describing the viscoelastic behavior of dilute polymeric solutions [46,47]. The omission of shear thinning effect is inherent with the usage of Oldroyd-B model, since its normal stresses do not decrease with applied strain [48]. It may also lead to an infinite extensional viscosity especially for large Weissenberg numbers [46,49]. The maximum Weissenberg numbers (*We*) reached in the present work are much lesser than the critical value of *We* for planar contractions and flow past a circular cylinder. This is ensured to avoid the infinitely elongated elastic dumbbells and any of its substantial effects [50–52]. Moreover, the present work focuses less on the normal viscoelastic stress than the drag, or shear stress, on moving lid.

The flow of a viscoelastic fluid, a dilute solution of liquid polymer with a polymer viscosity η_p, in a Newtonian liquid solvent of viscosity η_s is governed by the following set of equations that are non-dimensionalized:

$$Re\frac{D\boldsymbol{u}}{Dt} = -\nabla p + \nabla.\boldsymbol{\sigma} \tag{1}$$

$$\nabla.\boldsymbol{u} = 0 \tag{2}$$

$$\boldsymbol{\sigma} = \boldsymbol{T} + 2\mu_s\boldsymbol{D} \tag{3}$$