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Tribology of thin wetting films between bubble and moving solid surface

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ABSTRACT

This work shows a successful example of coupling of theory and experiment to study the tribology of bubble rubbing on solid surface. Such kind of investigation is reported for the first time in the literature. A theory about wetting film intercalated between bubble and moving solid surface was developed, thus deriving the non-linear evolution differential equation which accounted for the friction slip coefficient at the solid surface. The stationary 3D film thickness profile, which appears to be a solution of the differential equation, for each particular speed of motion of the solid surface was derived by means of special procedure and unique interferometric experimental setup. This allowed us to determine the 3D map of the lift pressure within the wetting film, the friction force per unit area and the friction coefficient of rubbing at different speeds of motion of the solid surface. Thus, we observed interesting tribological details about the rubbing of the bubble on the solid surface like for example:

1. A regime of mixed friction between dry and lubricated friction exists in the range of 6–170 $\mu\text{m/s}$, beyond which the rubbing between the bubble and solid becomes completely lubricated and passes through the maximum;
2. The friction coefficient of rubbing has high values at very small speeds of solid's motion and reduces substantially with the increase of the speed of the solid motion until reaching small values, which change insignificantly with the further increase of the speed of the solid.

Despite the numerous studies on the motion of bubble/droplet in close proximity to solid wall in the literature, the present investigation appears to be a step ahead in this area as far as we were able to derive 3D maps of the bubble close to the solid surface, which makes the investigation more profound.

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1. Introduction

The origin of the science of friction dates back to five centuries from the pioneering works of Leonardo da Vinci [1]. Later on

Amontons [2], Euler [3] and Coulomb [4] had established the fundamental laws of the dry friction between sliding solid bodies. Subsequently, the dry contact between elastic bodies was investigated by Hertz [5], who laid the foundations of the contact mechanics. Reynolds [6] found out that a liquid layer, intercalated between two solid surfaces in relative motion toward each other, becomes a lubricator. Thus, he had developed the hydrodynamic

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lubrication theory, which found many fields of application [7–11]. With the advancement of technology, friction is studied on micro- and nano-levels [12,13] indicating elastic and plastic deformations of the surface asperities during the sliding process. The classical work of Hertz [5] on the friction between sliding elastic surfaces was further developed in the middle of the previous century [14,15], while the contribution of adhesion between elastic bodies in contact was accounted for in the Johnson–Kendall–Roberts (JKR) theory [16] and the Derjaguin–Muller–Toporov (DMP) theory [17]. The term tribology was suggested by Jost [18] as “the science and technology of interacting surfaces in relative motion and practices related to”. Upon bringing the scaling of the investigations on sliding surfaces to nano- and sub-nano dimensions [8,19,20], the term nano-tribology appeared as well. At present knowledge about nano-tribology is exploited for designing micro- and nano-electromechanical systems (MEMS/NEMS), self-lubricating and biologically inspired surfaces [21]. The tribological studies mentioned above were focused on sliding solid phases in dry or lubricated contact.

Thin wetting film is a nano-layer lubricating the friction between the bubble and the solid surface when they are in relative motion against each other. In addition, the thin layer is squeezed, due to the load force pressing the bubble toward the solid surface. The resulting liquid outflow is laminar and its hydrodynamics obeys the lubrication approximation [6,22–26]. The theoretical problem is even more complicated as far as the bubble surface is deformable and an additional slip on the solid surface could also exist. To investigate the dynamic interaction between bubble and solid surface, the displacement of bubbles and the change of their shape in capillaries full with water [27] were measured. Moreover, the motion of bubbles/droplets at low [28,29] and moderate [30] Reynolds and Bond [29,31–33] numbers at inclined surfaces was intensively studied thus reporting that the bubbles/droplets can slip, slide or roll over the surface depending on their Bond number. Usually, the equation of Young–Laplace with correction for the buoyancy/gravitational force is solved along with the Navier–Stokes equation in lubrication approximation at a variety of different Bond numbers. Another way to study the tribology of bubbles is by AFM (see e.g. Ref. [34]) via measuring the lateral friction force of a very small bubble attached to an AFM cantilever close to a solid surface moving with a certain speed. However, the distance between the bubble and the solid surface cannot be measured precisely due to the deformation of the bubble and strong inhomogeneity of the wetting film.

Another series of works [35–38] study the rubbing of elastomeric ball on solid surface reporting about the existence of critical speed, at which the ball starts hydroplaning thus forming a liquid film between the ball and the solid surface. The AFM can study on the rubbing of the ball provided very valuable insights into the phenomena. Hence we decided to use the interferometry to study the rubbing of bubbles on moving solid surface and build up a unique experimental setup [39]. Meanwhile the interferometry has been used to study thin wetting films since the earliest works of Derjaguin and Kussakov [40,41] in 1939. Since that time there are many works on wetting films studying: their dimpling [42], electrostatic interactions between their surfaces (e.g. Refs. [43–45]), their stability on hydrophobized surface (e.g. Refs. [46–49]), the effect of surfactants on their behavior (e.g. Refs. [50,51]), etc. However, in all of these studies the solid surface, on which the wetting film was situated, remained immovable. It is common in the real case for the bubble and solid to be in relative motion against each other. Such realistic applications motivated us to apply the interferometry to the wetting films on moving solid surface.

This work presents a theory based on our experimental results. Such combination of theory and experiment on bubble rubbing on solid surface through wetting films is now reported for first time in the literature.

2. Literature studies on the motion of bubble in close proximity to solid walls

Bubble, located in horizontal hydrophilic tube filled with polar liquid (e.g. water), forms thin wetting film with the walls of the tube. When a pressure gradient across the tube is set up, the liquid and the bubble start moving across the tube in the same direction (see Fig. 1). The first studies on such a moving bubble in enough narrow tube allowing neglecting the gravitation force and at small Reynolds numbers belong to Fairbrother and Stubbs [52], who established that the speed U_B of the bubble exceeds the average speed U_L of the moving liquid. They suggested an empirical correlation for the relative bubble drifts velocity given by

$$\frac{U_B - U_L}{U_L} = 1.0\sqrt{Ca}, \quad (1)$$

where $Ca = \mu U_B / \sigma$ is the capillary number, μ is the viscosity of the liquid and σ is the surface tension of the air/liquid interface. Eq. (1) is valid for $10^{-3} < Ca < 1.5 \times 10^{-2}$. Bretherton [27], who is recognized as the pioneer in this field, conducted detailed studies on the same system and analytically arrived at an expression, confirmed by the his experimental data:

$$\frac{U_B - U_L}{U_L} = 2.683Ca^{2/3}. \quad (2)$$

Eq. (2) is valid for $8 \times 10^{-5} < Ca < 10^{-3}$. Moreover, Bretherton [27] assumed constant film thickness between the bubble and wall, thus solving the hydrodynamic problem analytically (see Fig. 3) arriving at expressions for the film thickness:

$$h = 1.338rCa^{2/3}, \quad (3)$$

where r is the radius of the tube. Unfortunately Eq. (3) has not been experimentally verified in the literature in contrast to Eq. (2). In a former work of ours [39] we have studied interferometrically wetting film between bubble and moving solid surface. Comparison between the theoretical prediction of Eq. (3) and our experimental data from Ref. [39] is presented in Fig. 3. One can see satisfactory coincidence between the experiment and the theory at speeds larger than $100 \mu\text{m/s}$. However, significant discrepancy at speeds smaller than $100 \mu\text{m/s}$ exists. According to Karakashev et al. [39] one can see substantial strong dependence of the film thickness on the speed of motion U at $U < 22 \mu\text{m/s}$. This dependence becomes weaker at $U > 60 \mu\text{m/s}$, however the coincidence between

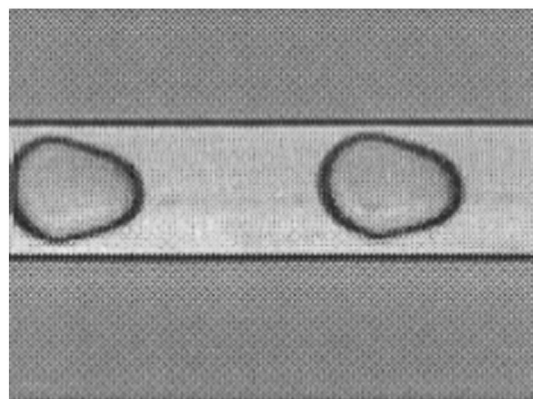


Fig. 1. Snapshot of moving bubbles in aqueous flow in a tube – $U_{\text{bubble}} = 31 \text{ cm/s}$, $U_{\text{water}} = 23.5 \text{ cm/s}$.

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