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The influences of special wetting surfaces on the dynamic behaviors of underwater oil droplet

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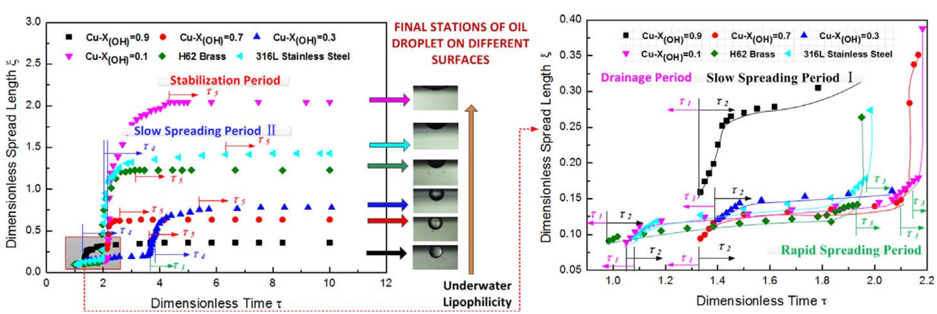
GRAPHICAL ABSTRACT



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ABSTRACT

In this paper, the spread behaviors of the underwater oil droplet on smooth brass substrate and 316L stainless steel (a kind of low-carbon subtype of marine grade stainless steel) substrate were studied from the microscopic view by using high-speed microscopic imaging technology. Chemical modifications were made on the surface of the brass sheet to change the surface properties and the controllable regulation of super-oleophilic–superoleophobic wettability gradient surface was achieved successfully. The behaviors of the spreading length and contact angle of the oil droplet rising to different modified surfaces were observed and measured. Taking the influence of water surrounding the oil droplet into consideration, a quantitative relation among droplet dimensionless spreading length, the droplet impact velocity, droplet size, droplet properties, viscosity of the water and surface wettability was acquired through energy analysis for the spreading behaviors of the oil droplet rising to the surfaces. Then an improved spreading dynamic model was established to describe the spreading behaviors of underwater oil droplets on surfaces with different wetting properties.

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1. Introduction

The wetting coalescence of oil droplets on solid surfaces in the coalescing channel is the key to oil and water efficient separation [1–5]. For oil-wetting surface, oil droplets dispersing in water reach the surface of the substrate under the effect of buoyancy and then an oil film is formed with the wetting adsorption. Afterwards, the subsequent droplets coalesce on the oil film [6]. However, when oil droplets reach the oleophobic surface, they don't spread, but may rebound or break. The dynamic behavior of oil droplets in water on the surface of the coalescence plate is a complex dynamic process involving hydrodynamics, surface physics and many other disciplines. The morphology and movement behaviors of droplets hitting a wall are not only related to the properties of droplets, such as density, viscosity, particle size, surface tension, impact velocity and so on, but also related to the properties of the solid surface of the wall, among which the surface wettability [7–9] has an important impact on droplet spreading behaviors.

At present, there are few studies about the collision and coalescence behaviors of underwater oil droplets rising to the lower surface of the upper plate in small channels. The existing researches are generally aimed at the movement and spreading behaviors of droplets impinging on the wall in the air. In 1996, Pasandideh-Fard et al. [10] studied the influences of surface tension and contact angle of droplets on the spreading behaviors in the wall-impingement process. In 2000, Kang et al. [11] observed the deformation and morphological development of the droplets in the air on the horizontal surface. Later, Rioboo et al. [12,13] carried out an experimental study on the movement of water droplets which impacted on a dry wall in the air. The possible movement patterns of water droplets after impacting on a dry wall were given and analyzed. The results showed that when water droplets impacted on the dry wall with strong wettability at a lower speed, the droplets would spread along the wall and adhere to the wall at the initial stage. When the droplet spreading process did not retract, the maximum dimensionless wetting length ($\xi_{\max} = d_{\max}/d_0$) was 1.25–5. Regardless of the impacting velocity of the droplets, the initial motion patterns of droplets on the dry wall were similar. The relationship between the wetting radius of the droplet and time was approximately $r \sim t^{1/2}$, which was independent of the properties of droplets and walls. Subsequently, different forms of movement would appear due to other factors. Sikalo et al. [14] obtained similar results through experiments. Scheller and Bousfield [15] noted these phenomena as well in their study. They put forward a single step and gained the empirical formula about the maximum dimensionless wetting length of droplets impacting on a dry wall without retraction. The studies above generally ignored the effect of dry wall properties on droplets, and they studied the initial movement of an individual droplet in the air. Nevertheless, a visual experiment was made by Li et al. [16] to study the phenomenon of droplet impingement on the horizontal substrate. They analyzed the parameters that affected the motion behaviors of the droplets on the surface at the later stage. The results showed that the wetting property of the substrate had a great influence on later motion of droplet spreading. Yuan et al. [17] investigated the dynamic spreading of a liquid droplet on micropillar-arrayed surfaces. They pointed out that the energy dissipations raised from both the viscous resistance at mesoscale and the molecular friction at microscale in the triple-phase region. Chen et al. [18] investigated the dynamic polygonal spreading of a droplet on lyophilic pillar-arrayed surfaces. They found that the dynamic processes could be distinguished in two regimes on the varied substrates. When the solid surface area fraction was low, the wetted area of the spreading droplet developed from an initial circle to an octagonal shape; otherwise, the wetted area of the spreading droplet developed from an initial circle, through a square shape, separated to a bilayer structure, and ended up with a rounded octagonal bulk and a square fringe. Then, they theoretically analyzed the scaling law of the anisotropic dynamic spreading based on the molecular kinetic theory, and they demonstrated that the droplets obeyed the same scaling law in distinct spreading patterns. Li et al. [19] studied the special dynamic behaviors of droplets impacting on solid substrates with different wetting properties by using high-speed photography technology. The results suggested that the action mechanism of the droplet and the target substrate, as well as initial conditions (including Weber number, Reynolds number, Capillary number and Ohnesorge number) of the droplet jointly determined the motion of the droplet after impact. However, Rioboo et al. [12] found that the dimensionless parameters, such as *We*, *Re* and *Oh*, etc. cannot reflect the wall roughness and wetting capacity, so it was inappropriate to determine the droplet motion after the droplet impacting on the wall only relied on these parameters or their combinations. The properties of surfaces and the surrounding fluid of the droplet also had an important effect on the moving pattern of droplet on the substrate.

Experimental studies are mostly based on the phenomena, and the results depend on the experimental conditions mostly. It is difficult to unravel the mechanism of droplets motion after impacting on different wetting surfaces through experiments. So many scholars managed to study the impact patterns of droplets in theory. At present, theoretical approaches employ models that attempt to predict the maximum spreading diameter of droplet impingement based on energy balance, momentum balance, and empirical considerations [20–24]. The existing models can be divided into two types. One is based on the Scale Law to get the relationship among the maximum spreading length of droplets on the surfaces, *Re* or *We* [15,24–36]. The other is based on the Energy Conservation to obtain the relationship among the maximum spreading length of droplets on the surfaces, *Re*, *We* and contact angle θ [21–23,37–45]. And the latter includes the interactions between solid wall and liquid. Yuan et al. [17] and Chen et al. [18] theoretically analyzed the scaling law of the anisotropic dynamic spreading based on the molecular kinetic theory, and they demonstrated that the droplets obeyed the same scaling law in distinct spreading patterns. In 1976, based on the conservation of energy before and after collision of droplets on the wall, Jone et al.[33] established the analytic expression of the maximum dimensionless spreading length with related parameters. However, the model cannot accurately describe the experimental phenomena by neglecting the influence of the surface wettability and the viscosity dissipation of the boundary layer on the spreading of droplets [37,42,45]. In 1991, Chandra et al. [37] introduced the viscous dissipative energy into the energy conservation equation. In the model, the spread height h was used as the length dimension of the spreading boundary layer to calculate the velocity gradient of the droplet's spreading; and the static contact angle θ_{static} was used to calculate the interface energy changes in the process of spreading. However, Pasandideh-Fard et al. [22] demonstrated that it was reasonable to use the boundary thickness as the length scale, rather than the droplet spread height. And they pointed out that when the droplet impact velocity is low, it was found the model produced significant errors by using equilibrium contact angle, and they proposed to calculate the surface energy by using the advancing contact angle θ_a. It is noteworthy that although the shape of the droplet in the final state was assumed as a cylindrical disc with height h and diameter $d_{\max}$, the gas-liquid surface energy of the cylindrical side was neglected, and the viscous dissipation term was not calculated carefully, which led to their conclusion that the maximum dimensionless spreading time of the droplet, $\tau^*_{\max} = 8/3$, was inaccurate [42]. Mao et al. [39] improved the Pasandideh-Fard et al-model [22] by modifying the surface energy and viscous dissipation energy. They obtained the analytical formula about spreading length of the droplet with low viscosity and high viscosity. However, part of empirical coefficients were used in the model, limiting universality of the model. In 2005, Chijioke Ukiwe et al. [42] carefully calculated the gas-liquid contact area after spreading based on Pasandideh-Fard et al.'s [22] model. They modified the surface energy by using Young's contact angle θ_Y. However, this model was only suitable for droplet spreading systems with high Reynolds numbers. The model failed in the case of great wettability of the target surface. Later, Vadillo et al. [43]