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Historical perspective

A Critical Review of Dynamic Wetting by Complex Fluids: From Newtonian Fluids to Non-Newtonian Fluids and Nanofluids

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ABSTRACT

Dynamic wetting is an important interfacial phenomenon in many industrial applications. There have been many excellent reviews of dynamic wetting, especially on super-hydrophobic surfaces with physical or chemical coatings, porous layers, hybrid micro/nano structures and biomimetic structures. This review summarizes recent research on dynamic wetting from the viewpoint of the fluids rather than the solid surfaces. The reviewed fluids range from simple Newtonian fluids to non-Newtonian fluids and complex nanofluids. The fundamental physical concepts and principles involved in dynamic wetting phenomena are also reviewed. This review focus on recent investigations of dynamic wetting by non-Newtonian fluids, including the latest experimental studies with a thorough review of the best dynamic wetting models for non-Newtonian fluids, to illustrate their successes and limitations. This paper also reports on new results on the still fledgling field of nanofluid wetting kinetics. The challenges of research on nanofluid dynamic wetting is not only due to the lack of nanoscale experimental techniques to probe the complex nanoparticle random motion, but also the lack of multiscale experimental techniques or theories to describe the effects of nanoparticle motion at the nanometer scale (10^{-9} m) on the dynamic wetting taking place at the macroscopic scale (10^{-3} m). This paper describes the various types of nanofluid dynamic wetting behaviors. Two nanoparticle dissipation modes, the bulk dissipation mode and the local dissipation mode, are proposed to resolve the uncertainties related to the various types of dynamic wetting mechanisms reported in the literature.

Contents

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1. Introduction

Dynamic wetting occurs when fluids are spreading over solid surfaces, which is very common in our daily activities and many industrial applications. Dynamic wetting is an essential process in various printing techniques from traditional inkjet printing to more modern nano-printing, 3D-printing or bio-printing, as shown in Fig. 1. The dynamic wetting greatly affects the quality of coating applications which are widely used in automotive, aerospace, marine, and many others industries, as shown in Fig. 2. Energy systems and many other systems involve flows and phase change of the working medium which are both related to the dynamic wetting, especially as the system size is reduced.

Before discussing dynamic wetting by complex fluids, the fundamental principles of dynamic wetting are given to help the readers easily understand the review. For a liquid droplet on an ideal flat solid surface (Fig. 3a), the wettability can be characterized by Young's equation,

$$\cos\theta_{Y} = \frac{\sigma_{SV} - \sigma_{SL}}{\sigma_{LV}}, \tag{1}$$

where σ is the interface tension, θ_Y is Young's equilibrium contact angle, and the subscripts S, L and V denote the solid, liquid and vapor phases. Young's contact angle is a function of the thermodynamic equilibrium of the interfacial energy at the solid-liquid-vapor interface. Hydrophilic surfaces have equilibrium contact angles less than 90°, while hydrophobic surfaces have contact angles larger than 90°. For rough surfaces, the wettability can be characterized by the Wenzel or Cassie-Baxter models shown in Fig. 3b and c. The droplet is assumed to entirely contact all of the rough surface in the Wenzel model, while in the Cassie model, the droplet is assumed to only contact the peaks of the roughness elements and is suspended between the elements.

For the Wenzel model, the equilibrium contact angle is related to the interfacial tensions as,

$$\cos\theta_{W} = \frac{r(\sigma_{SV} - \sigma_{SL})}{\sigma_{LV}} = r\cos\theta_{Y}, \tag{2}$$

where r is the roughness factor, defined as the ratio of entirety contact area to the apparent contact area, as shown in Fig. 3b.

For the Cassie - Baxter model, the wettability is described by,

$$\cos\theta_{CB} = \frac{f_s(\sigma_{SV} - \sigma_{SL})}{\sigma_{LV}} - (1 - f_s), \tag{3}$$

where f_s is the solid-liquid contact function, as shown in Fig. 3c.

Time-dependent dynamic wetting is of great practical interest because fluids are usually used in motion, as shown in Fig. 4. Dynamic wetting is usually characterized by relationships between the dynamic contact angle and the contact line velocity (θ_D-U, or θ_D-Ca, in which Ca is the capillary number) or the spreading radius versus the spreading time (R-t^m, also known as the spreading law). Dynamic wetting can be characterized as forced wetting or spontaneous wetting. Forced wetting is triggered by external forces while in spontaneous wetting, the droplets spreading spontaneously to reduce the contact angle from the initial value to the equilibrium contact angle which corresponds to the lowest system free energy. The capacity for dynamic wetting can be characterized by the spreading coefficient, $S = \sigma_{SL} - \sigma_{SV} - \sigma_{LV}$. The liquid completely wets the surface (complete wetting) when $S > 0$. Partial wetting occurs for $S < 0$.

Dynamic wetting is quite complicated due to the multiple governing forces, the various fluid and solid surface properties and sometimes complex external physical fields, including electrical field, magnetite,

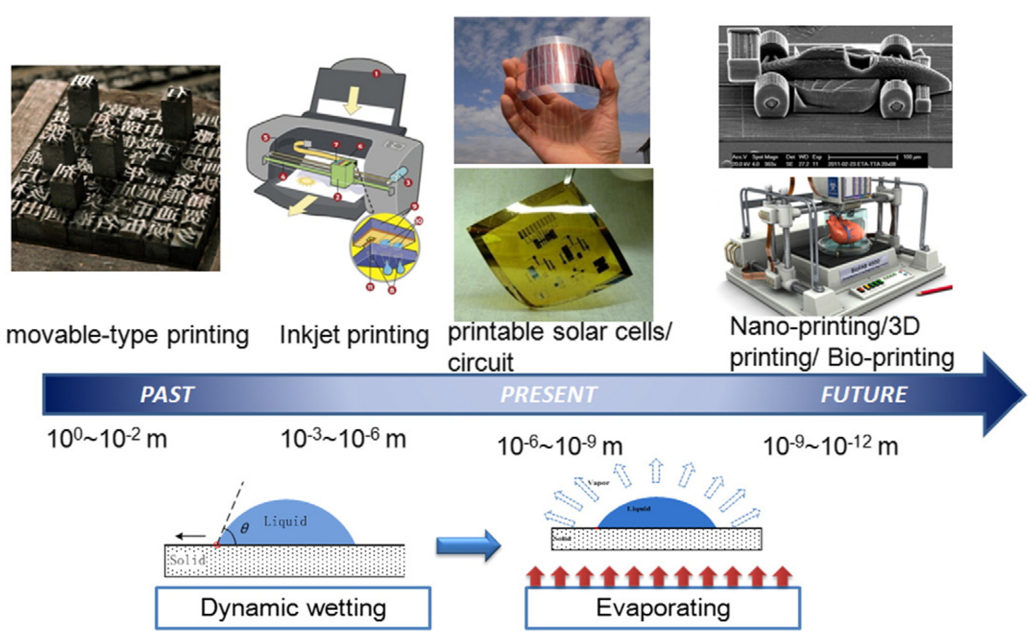

Fig. 1. Dynamic wetting in various printing techniques.