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Vibration-driven mass transfer and dynamic wetting

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Abstract

This review is devoted to the physical mechanisms enabling dynamic wetting effects following the transport of mass in droplets and films that are exposed to external mechanical vibrations. The essential nonlinear nature of the transport mechanisms is emphasized. Specifically, we discuss the transport of mass and dynamic wetting effects due to (a) the innate nonlinearity of the conservation equations governing the flow of liquid and (b) the nonlinear motion of the three phase contact line. Special attention is payed to the contribution of high frequency mechanical vibrations to dynamic wetting, observed in the course of the past decade, as well as to parametric resonance and its catalytic contribution to vibration-driven mass transfer.

1. Introduction

The spreading dynamics of a thin film of liquid over a solid substrate is significant in many areas of science and engineering, from manipulating water solutions on microfluidic platforms [1–3] and cooling of electronic systems [4, 5], to desalinating sea water [6] and manufacturing [7–9]. The interest in vibration-driven flows in droplets and films is additionally fueled by the recent advances in surface acoustic wave (SAW) microfluidics [10, 11]. Surface waves were successfully employed for the manipulation of droplets, flow control, mixing, and particle alignment. However, despite numerous applications one observes a deficiency in robust theoretical models for vibration-driven fluidic systems. In this review we particularly focus on the physical phenomena enabling vibration-driven mass transfer and corresponding dynamic wetting effects as well as on the theoretical modeling of these phenomena.

The study of the mass transfer driven by external vibrations goes back to Chladni and Faraday that looked at the acoustic streaming generated from vibrating cords in the 18th and 19th centuries, respectively [12]. Two general research directions emerged in this field since then: (a) the investigation of the eigenmodes of the oscillatory mechanical deformation of fluid bodies and related parametric instabilities [13, 14], and (b) the investigation of the streaming phenomenon, that is, of the steady mass transfer generated by vibration [15, 16]. The investigation of the eigenmodes is typically concerned with the dynamics in the vicinity of mechanical parametric resonance, while streaming is traditionally considered away from resonance. The connection between dynamic wetting, mass transfer, and mechanical resonance was established by Daniel, Chaudhury, and de Gennes, who have shown that mechanical parametric resonance may contribute to the vibration-driven transport of droplets [17]. Nowadays, it is apparent that vibration-driven mass transfer is a cumulative product of a number of natural phenomena, including parametric and acoustic resonances. The present review is an attempt to bridge between the different mechanisms of mass transfer and their contribution to dynamic wetting.

2. Low-frequency vibration-driven dynamic wetting

The theme connecting the different studies reported here is that the external excitation frequency is of the same order of magnitude as the basic (lower) natural frequencies supporting mechanical resonance in the investigated system. To the best of our knowledge, the first systematic study on the dynamics of sessile droplets atop a vibrating substrate was conducted by Daniel *et al.* [17]. In particular, they have established that substrate oscillations may sustain quasi-steady transport of droplets. A similar transport process was observed by Brunet *et al.* [18, 19], who have investigated the motion of droplets supported by a vertically vibrating inclined plate and observed two regimes of transport: sliding and climbing, corresponding to the droplets moving down and up the incline, respectively. An example for the dynamics of a climbing drop is given in figure 1. Later on, Noblin *et al.* have observed the transport of droplets on a plate simultaneously sub-

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