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Simplified dynamical model for optical response of electrofluidic displays ☆

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ABSTRACT

In this work we analyze the switching behavior of an electro-fluidic pixel in separate stages. For 'on' switching we consider the motion leading to oil film rupture (initiation stage), fast oil-dewetting and a slower droplet rearrangement stage. For 'off' switching we consider fast oil wetting and surface reforming to the flat (dark) state. A dynamic model derived from an overall energy balance analysis has been employed to describe the optical response inside an electrofluidic display (EFD) pixel for the oil dewetting and wetting stages. By comparison with the experimental electro–optic response data, the accuracy and shortcomings of this model can be illuminated. The optical response asymmetry between on and off-switching and optical response delay during the on-switching process are well described and explained. In addition, the liquid film reforming dynamics and electrohydrodynamic instability analysis are used to estimate the oil film rupture and film reforming times very well. This study provides a straightforward approach to describe the complicated electrofluidic switching dynamics inside an EFD pixel, which may guide the further optimization of EFD device design and driving schemes.

1. Introduction

Interest in electrofluidic displays (EFD), also known as electrowetting displays (EWD), has rapidly grown in the past decade due to its promising properties, such as 'paper-like' reading experience [1], high-speed switching [2] and mechanical flexibility [3]. Generally, the electro–optic behavior of EFD is achieved by controlling the motion of the immiscible water and oil fluids in confined pixels [4]. A physical model proposed by Roques-Carmes [5] has been successfully applied in predicting the equilibrium electro-optic behavior of EFD. However, in a real situation, the dynamic behavior which may lead to unique defect phenomena, such as oil dewetting patterns, oil overflow, and non-closing which are even more critical to EFD performance [6]. A full understanding of the interfacial and geometry dependent fluid motion and its optical dynamics [7] is necessary for optimizing driving waveform [8], and consequently the electro-optical performance of the device.

Ku et al. [9] were first to attempt the modelling and simulation of the micro-fluidic movement in EWD systems. They proposed a 3D model based on the volume of the fluid-continuum surface force to describe the dynamic fluid behavior inside a pixel. An ANSYS FLUENT simulation was first adopted in predicting the fluid behavior with different electrode designs. However, the change in contact angle resulting from the EW effect was overlooked in the model, which reduces the applicability of the simulation results. Hsieh et al. [10] attempted more rigorous 3D modeling aiming at accurate prediction of the fluid dynamics during the electro-optic switching process. By coupling the electrohydrodynamic (EHD) force deduced from the Maxwell stress tensor with the laminar phase field of the oil–water dual phase, the fluid motion of a complete EFD switch process and its corresponding electro-optic performance are successfully simulated. Based on the VOF method, Roghair et al. [11] provided a EWD system modeling tool implemented in the OpenFOAM framework. They solved the electrohydrodynamic equations by incorporating Gauss's law and a charge transport equation to the Navier–Stokes equations of fluid flow. In their work, the interaction of a fluid–fluid interface with an applied electric field is successfully simulated, thus yielding a good

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description of fluid motion in a pixel. Recently, Tang et al. [12] developed an electro-capillary wave model for a fuller understanding of the behavior of water/oil interfaces subject to confinement by the pixel wall for the EFD system. This work provided convincing empirical evidence and a theoretical description for the existence of discretized modes in a confined electro-capillary fluidic system, which in practice can describe the voltage dependent oil film rupture process during pixel on-switching. The models above show significant progress in understanding the physics governing dynamic phenomena which influence EFD. However, contact-line friction, dynamics of the three-phase line and contact-angle hysteresis are still among the phenomena posing significant challenges to EW-based electrohydrodynamic modeling work.

Here, instead of developing a full simulation we choose to divide the switching behavior of an EFD pixel into separate stages based on our detailed experimental observations, and we outline the minimum models required to satisfactorily describe the process that characterizes each phase.

The stages that we observe to occur in the switching behavior are the following (see Fig. 1): Prior to an on-switch, the oil film is considered to be flat and confined by pixel walls. After voltage application an undulation in the oil film occurs that can grow all the way down to the fluoropolymer substrate, which we call the 'initiation stage.' The wavelength selection of this process is described in [12]. When the oil thickness becomes very small, the oil film ruptures and further development of the on-state consists of lateral motion of the oil droplets. This is called the 'oil-dewetting' stage. During the oil dewetting stage the contact angle of the drops has not achieved the Lipmann condition yet, so on the contact line we have a net force. The Lippmann condition is the equilibrium condition for the contact angle under application of an electric field normal to the substrate. As soon as we reach the Lipmann condition oil motion need not completely stop. Instead a rearrangement of oil can take place within the pixel between different pockets of oil which we will loosely call droplets. These different droplets of oil are connected by channels of oil that are along the pixel walls. Through these channels the exchange of oil between the droplets can take place. We call this the 'rearrangement' stage. This stage is essentially a coarsening process where large (low pressure) pockets of oil grow at the expense of small (high pressure) pockets.

For the reverse process, the off-switching (Fig. 2), we firstly observe that the oil droplets spontaneously start increasing their contact area because the electric force on the contact line ceases to keep the droplets in place. This stage is called 'oil wetting'. When the contact line of these pending droplets meet, they merge and the oil film will fully cover the fluoropolymer surface. This is called the 'coalescence stage' which is assumed to be quite fast and will not be quantified in this paper. However, after the drops have merged, the film will not yet be flat. The process that follows is a reforming of a film that flows to a flat or, more precisely, it's equilibrium state, since in practice one may have underfilled (or overfilled) a pixel.

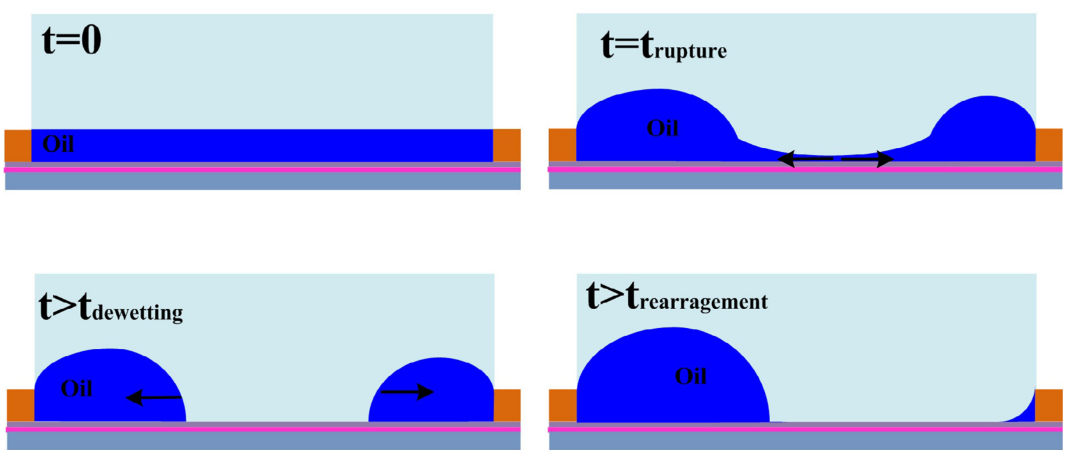

Fig. 1. Stages in the on switching of an EFD pixel.

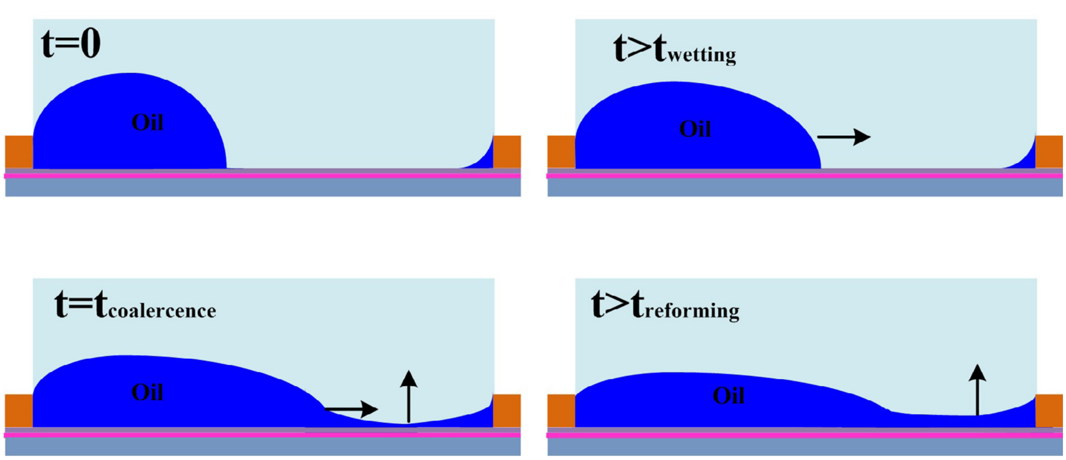

Fig. 2. Stages in the off-switching process.