



Historical perspective

Electrokinetic transport in liquid foams



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ARTICLE INFO

MSC:
00-01
99-00

ABSTRACT

Investigating electrokinetic transport in a liquid foam is at the confluence of two well developed research areas. On one hand, the study of electrokinetic flows (i.e. surface-driven flows generated close to a charged interface) is fairly well understood in regards the solid/liquid interface. On the other hand, the flow of liquid in a 3D deformable network, i.e a foam, under a volume force such as gravity has been thoroughly studied over the past decade. The overlapping zone of these two frameworks is of great interest for both communities as it gives rise to challenging new questions such as: what is the importance of the nature of the charged interface, created by mobile and soluble surfactants in the case of foam, on electrokinetic transport? How does a foam behave when submitted to a surface-driven flow? Can we compensate a volume-driven flow, i.e. gravity, by a surface-driven flow, i.e. electroosmosis? In this review, we will explore these questions on three different scales: a surfactant laden interface, a foam film and a macroscopic foam.

1. Introduction

Liquid foams are ubiquitous in our everyday life, and are instrumental to many industrial applications, such as in cosmetics, food engineering, pharmaceuticals, firefighting, or oil recovery [1]. Liquid foams are also key to new green applications, for instance in the building industry [2], or for decontamination and depollution [3]. Recently, new high-tech uses of liquid foams have been proposed, in particular as new photonic and phononic crystals, soft and low-cost alternatives to solid-state lab-on-chip devices, or as bioengineering systems (for a review see Ref. [4]). Last but not least, liquid foams can be encountered in nature, whether they are used for their special properties (e.g. frog and fish bubble nests, Fig. 1) or must be dealt with (residual dirt in ponds and sea).

A major weakness of liquid foams is their uncontrollable lifetime (being limited or very long) and their inhomogeneity due to the gravitational drainage of the liquid in the foam [1,5]. Among possible strategies to control the stability and homogeneity of liquid foams, it was recently suggested that one could use an external switch to increase their lifetime or to destroy them on demand, the switch being light actuation, temperature or magnetic field [6–10]. Another way to oppose gravity-induced drainage in a foam made of ionic surfactants would be to use electrical actuation, generating so-called electrokinetic flows [11]. As an introduction, we will first present the fundamentals of electrokinetic (EK) effects and then describe the specific structure of a liquid foam. These two points are indeed crucial to review the observations of EK transport in this specific media.

1.1. Electrokinetic effects

Electrokinetic flows belong to a wider class of phenomena referred to as electrokinetic (EK) effects, which cover all possible couplings between different types of transport, i.e. when a thermodynamic gradient of a certain type (pressure, electric potential, solute concentration, temperature, etc.) induces a flux of a different type (flow, electric or solute current, heat flux, etc.) [13–16]. The most used and studied EK effects couple hydrodynamic and electrical transport (Fig. 2): electroosmosis — flow induced by a gradient of electric potential, and streaming current — electric current induced by a pressure gradient [11,17].

In these types of coupled effects, symmetrical terms are equal according to Onsager reciprocal relations [18]. For instance, electroosmosis and a streaming current are both quantified by the so-called zeta-potential ζ (Fig. 2).

EK effects fundamentally arise from the presence of interfaces, precisely from the specific behavior of the liquid close to interfaces. In aqueous electrolytes, EK effects originate from the presence of a nanometric charged layer of liquid close to interfaces, the electrical double layer (EDL) [11]. The amplitude of EK effects has long been exclusively related to the static, structural properties of the interface: in particular, the zeta-potential is traditionally associated with the surface electric potential, i.e. to the pure electrostatic properties of the interface. However, this standard picture has been increasingly challenged thanks to the development of powerful experimental and numerical tools to probe interfacial hydrodynamics down to the nanoscale during

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<http://dx.doi.org/10.1016/j.cis.2017.06.005>



Fig. 1. Left: frogs construct a bubble nest in order to protect their eggs from predators. Right: Male betta blows an assembly of bubbles to attract females and to keep their eggs on the water's surface [12].

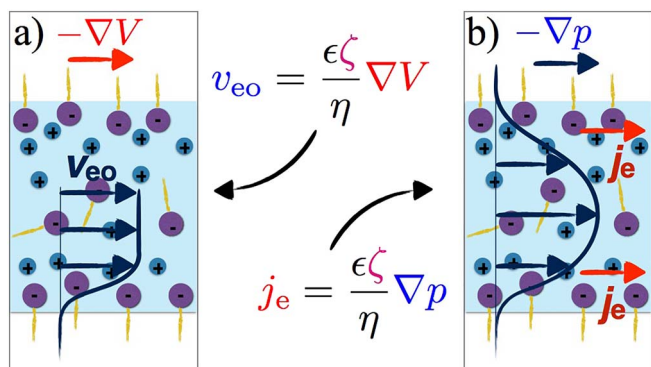


Fig. 2. Electrokinetic coupling between hydrodynamic and electrical transport in a foam film: (a) electroosmosis, the flow induced by a gradient of electric potential; (b) streaming current, the electrical current induced by a pressure gradient. Both effects are quantified by the zeta-potential, which relates the density of electrical current j_e to the pressure gradient ∇p , and the electroosmotic velocity v_{eo} to the gradient of electric potential ∇V . In the formulae, ϵ and η are the bulk dielectric permittivity and shear viscosity of the liquid, respectively.

the last decades. In particular, Muller et al. suggested that liquid/solid slip could amplify the zeta-potential close to hydrophobic surfaces [19] and this effect was confirmed both numerically [20] and experimentally [21,22].

The study of EK effects started in the colloid science community as a crucial characterization tool [11]. EK have also been increasingly used in the micro and nanofluidic communities to manipulate liquids and particles [23,24], and in the recent years for applications in energy conversion [25–27]. Following intensive experimental and numerical work, EK effects in solid-state fluidic systems are now relatively well-understood [16].

1.2. Liquid foam structure

However, EK effects are much more difficult to describe in complex systems such as liquid foams. In particular, liquid foams are multiscale systems, and specific EK effects due to the complex hydrodynamic boundary conditions or liquid foam deformability arise at the different scales of the foam. Indeed a liquid foam consists of liquid soap films (thickness δ : 10–100 nm) whose interfaces are covered by surfactant molecules (molecular scale: 100 pm). Liquid films merge three by three at 120° in connecting liquid channels discovered by Plateau and therefore called “Plateau” borders (thickness or radius of curvature r_c around 10 μm, length L around 10–1000 μm). The Plateau borders are connected four by four in the so-called nodes of the foam structure. These different elements are reported in Fig. 3.

Studying EK transport at each scale of the foam represents a number of challenges. For instance, the surfactant-laden liquid–vapor interface

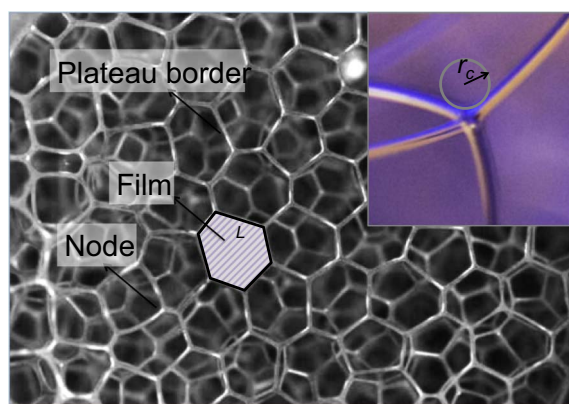


Fig. 3. Picture underlying the multiscale structure of a liquid foam (adapted from Ref. [28]). Three soap films are connecting at 120° along liquid channels called Plateau borders of length L and radius of curvature r_c , and four Plateau borders are merging in a node. L here is 2 mm.

is much more complex than the liquid–solid ones: indeed, the surface charge is carried by ionic surfactants, which are mobile, penetrate inside the liquid, and can display complex collective behaviors (clustering, surface elasticity/viscosity [29]). Standard models of EK effects may fail to describe the electrostatic and hydrodynamic behavior of these complex interfaces. On a larger scale, liquid channels in the foam (foam films and Plateau borders) are flexible and can react to the flow and to variations of surface charge, salt concentration, temperature, etc. Such couplings could induce complex non-linear behaviors, which need to be described.

In this article, we will review how the challenge of understanding and optimizing EK effects in liquid foams is currently tackled both by experimental and numerical approaches, to which we add recent results of our own on. To this end, we will focus on the most-often used EK effects coupling electric and hydrodynamic transport, and in particular on electroosmosis. This review will be organized following the different scales of the system, spanning from the smallest scale of the liquid–vapor interfaces to the macroscopic foam. Through a personal selection of recent works, this article represents our view of the current state-of-the-art. We refer the interested reader to complementary reviews for more information on EK effects [13,17], and in particular, on their application in microfluidics and nanofluidics [14–16,23].

2. Zeta-potential near an interface

The role of surfactants at the liquid/gas interface has long been studied since the discovery of soap. Pliny the Elder in the 1st century already reported different consequences of impurity adsorption at liquid/gas interfaces such as curious wave damping behind a boat [30].

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