European Journal of Mechanics B/Fluids 57 (2016) 129–142

Contents lists available at ScienceDirect

European Journal of Mechanics B/Fluids

journal homepage: www.elsevier.com/locate/ejmflu

Liquid bridge's behavior inside microchannels subject to external pulsatile flow

Majid Ahmadlouydarab [*], Jalel Azaiez, Zhangxin Chen

Department of Chemical and Petroleum Engineering, Schulich School of Engineering, University of Calgary, Calgary, Alberta, Canada T2N 1N4

ARTICLE INFO

Article history:
Received 19 April 2015
Received in revised form
30 September 2015
Accepted 22 December 2015
Available online 6 January 2016

Keywords:
Liquid bridge dynamics
Pulsatile external flow
Microchannel
Three-phase contact line
Diffuse-interface model

ABSTRACT

We report a comprehensive and systematic study on of liquid bridge dynamics inside microchannels subject to external pulsatile flows. A pulsatile body force is applied on both liquid bridge and surrounding fluid to represent a pressure-driven flow. The Cahn–Hilliard diffuse-interface model is used to determine the interfacial evolution and the three phase contact line motion on the solid substrates. Effects of the walls' wettability (θ), pulsatile flow frequency (ω), ratio of oscillation amplitude to the net body force (e), viscosity ratio (R_v), liquid bridge geometrical aspect ratio (W_h), and density ratio (R_d) are analyzed. Results indicate that inertial forces effects on the liquid bridge dynamics are relatively more important under pulsatile flow conditions in comparison with steady state flows with the same net force. However these effects did not result in important qualitative changes. Examination of the effects of the flow frequency revealed that at low ω, the bridge goes through strong deformations that lead to breakup or detachment. A *non-monotonic* variation of the *rupture time* with the flow frequency was found. At higher frequencies large deformations are suppressed if the net flow is not strong. Changes in W_h strongly affect the interfacial deformation and solid–liquid viscous dissipation, and in particular, a *non-monotonic* trend for the variation of the *detachment location* with W_h is observed. Variations in the viscosity ratio R_v change the surrounding fluid resistance against the interfacial deformation, rupturing, detachment, and movement. Depending on the wettability property of the solid walls, changes in R_v result in two opposite effects on the liquid bridge dynamics. Finally any change in e affects the oscillation part of the flow velocity which in turn influences the magnitude of deformation of the liquid bridge. A *non-monotonic* variation of the *detachment time* with e was found. The main reason for the reported non-monotonic behaviors is the out of phase behavior of the three phase contact lines and the external flow field.

1. Introduction

Due to the occurrence of liquid bridges in many conventional and modern applications, their statics and dynamics have been the subject of numerous studies in the past decades. Early studies have been conducted by Haines and Fisher [1,2] where the cohesion between two spherical particles due to the capillary attraction when wetted, was examined. Numerous subsequent studies were carried out to understand the physics behind the liquid bridge behaviors inside pathways. These studies have been reviewed and classified under two categories in [3]. In the first category, the liquid bridge and the studied system are stationary and there is no external flow. For such systems, the main aim is to understand the response of a pinned/held liquid bridge to stretching, squeezing, slipping, spreading, spinning, and oscillation as well as determining the liquid bridge–solid substrate adhesive forces between parallel or tilted plates, spheres and so on [4–15]. In the most recent study in this category, Ru-Quan and Kawaji carried out three-dimensional (3D) numerical simulations to analyze the surface oscillation and flow structures inside a liquid bridge held vertically between solid disks under a horizontal vibration [16]. Their results revealed the existence of transversal vortices inside the 3D liquid bridge. However they did not report the presence of a mean flow which is a common flow feature inside a liquid bridge if an axial vibration with high frequency is applied [17].

In the second category, two subgroups can be identified. In the first group the liquid bridge is not pinned to the solid substrates and an external flow inside the pathway has a constant flow rate [18–21]. An example of studies on such systems is the experimental analysis of water slug formation and motion in millimeter-size gas flow channels by Cheah et al. [22]. It was reported that water emerging from the micro pores with constant

---

[*] Corresponding author.
E-mail address: mahmadlouydarab@ucmerced.edu (M. Ahmadlouydarab).

http://dx.doi.org/10.1016/j.euromechflu.2015.12.007
0997-7546/

flow rate into gas flow channels, forms drops that develop, grow and become liquid bridge and finally slugs. The gas flow causes the slugs to detach and move down the channels. Initially, water flow creates a drop with spherical cap which in turn evolves into corner drop. These drops grow and make the partial liquid bridges, and then as a result of the liquid bridges merged slugs are created. These authors reported that inside the channels with hydrophobic walls and/or with curved walls, small slugs are formed. In the second group, the liquid bridge is pinned on the solid surfaces e.g. between two disks in the presence of an axial external flow with constant or oscillatory flow rate [23–25]. For example, Lowry and Steen [23] studied experimentally the stability of pinned long liquid bridges in the presence of gravity and a constant axial flow against the gravity. Variations of the flow rate, resulted in linear and non-linear effects on the liquid bridge shape.

To the authors' knowledge, no studies except that by Ahmadlouydarab et al. [3] have examined the effects of time-dependent external flows on the behavior and stability of liquid bridges inside confined pathways without any constraint and where the liquid bridge can easily move, fluctuate, deform, rupture and/or detach from the walls. In our previous study [3], we have analyzed the dynamics of the viscous liquid bridge inside microchannels in the presence of a *pure* oscillatory external flow, with a zero net flow rate. It was found that depending on the solid substrate wettability properties and the frequency of the oscillatory flow, liquid bridge behaves in three different ways. It may rupture inside philic microchannels or it may detach from the walls inside the phobic microchannels if the flow oscillation frequency is below a critical value. Increasing the frequency of the flow velocity induces stabilization effects and a behavior approaching that of the stationary system where no rupture or detachment could be observed. This stable behavior is the direct result of weaker deformation of the liquid bridge due to the rapid changes in the flow direction and motion of the contact lines on the solid substrate. Moreover, it was reported that the flow velocity is out of phase with the footprint/throat lengths and that the latter two also show a phase difference. These differences were explained in terms of the motion of the two contact lines on the solid substrates and the deformation of the two fluid–fluid interfaces.

The present study examines the case of pulsatile flows with a non-zero net flow velocity. This corresponds to more realistic cases where the bridge is not static and has to move down the system. In particular we will attempt to understand the physics of the displacement and compare scenarios of constant injection with pulsatile ones that have the same net injection rate as the constant one. To this end, a systematic parametric study of the effects of important factors including the walls' wettability (θ), the external flow frequency (ω), the ratio of the oscillation amplitude to the net body force (e), the viscosity ratio (R_v), the liquid bridge geometrical aspect ratio (W_h), and the density ratio (R_d) has been carried out. The results for the pulsatile flow will be compared with those of an equivalent constant-injection flow as well as with those for oscillatory displacements. It is hoped that this comprehensive study will help optimize the transport of a liquid bridge and control its fate down the system through a judicious choice of the oscillatory flow characteristics. This, together with a better understanding of the dynamics of liquid bridges in confined pathways, will have impact on a wide range of conventional and modern applications that include time-dependent flows encountered in enhanced oil recovery, microfluidics, and lab-on chips devices.

2. Problem setup and methodology

2.1. Computational domain characteristics

The physical domain consists of a 2D horizontal rectilinear microchannel involving a liquid bridge of viscosity μ_1 surrounded by a fluid of viscosity μ_2. An external pulsatile flow driven by a horizontal pressure gradient and with a net direction from left to right is triggered by imposing a body force E^* on both fluids. The top and bottom walls are assumed to have uniform and identical wettability properties, which allows to limit the analysis to only half of the physical domain. The 2D symmetric-planar geometry, with domain length L, height H including the liquid bridge of width W is shown in Fig. 1. For the liquid bridge, two quantitative parameters are defined, namely the solid–liquid interface length hereafter called the footprint length (L_F) and the liquid bridge thickness at the symmetry line that will be referred to as the throat length (L_T). The liquid bridge is assumed to initially have a rectilinear shape. Such a shape is not at equilibrium except for an initial contact angle of 90°. Furthermore it is assumed that both the liquid bridge and the surrounding fluid are initially at rest. This setup can be considered to physically represent a cuboid liquid bridge of width W, height $2H$, and infinite depth, which is trapped inside a microchannel of infinite depth. It is important to choose W in a way that in the absence of an external flow, the liquid bridge neither ruptures nor detaches as a result of the wall wettability at the very early stage. For instance, inside a microchannel with philic walls and based on Eq. (9) presented later, the throat thickness has to be larger than zero. As soon as the system is initiated and the liquid bridge makes contact with the substrate, it adjusts to the local contact angles, deforms, and depending on the applied conditions, it starts to move and may rupture or detach from the microchannel walls. Note that for simplicity, the interfacial development of the liquid bridge in the direction perpendicular to the xy plan (z direction) will not be considered. As a result, the external flow will keep its two dimensional nature, and instabilities such as shark-teeth (printer's instability) and contact line instability which may be seen in three dimensional models are not considered in the present study [26–29]. Overall, considering the existence of two interfaces for the liquid bridge and the out of phase behavior of those two interfaces under external flow [3], a full understanding of the liquid bridge behavior under pulsatile flow conditions would require a comprehensive analysis of the full three-dimensional problem. We do therefore recognize the possible limitation of the present study which is restricted to two-dimensional configurations. In spite of this limitation, the present study which is the first one to analyze liquid bridge motions under pulsatile flow conditions, allowed to reveal and understand new interesting aspects of the physics of the flow.

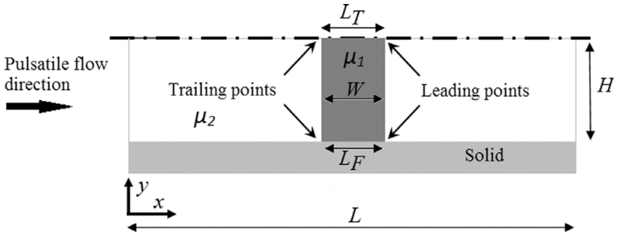

Fig. 1. Schematic of the initial configuration for 2D symmetric-planar computations at a time $t = 0$. As shown, initially W, L_F and L_T are equal.

2.2. Methodology and governing equations

The system is governed by the conservation of mass and momentum; Eqs. (1) and (2). Note that for this micro-sized system, gravitational forces have been neglected. A diffuse-interface formulation with the Cahn–Hilliard model is adopted to handle the three-phase contact lines, solid surface wettability, and deformation and movement of the interfaces. The Cahn–Hilliard diffuse interface method is a suitable technique for capturing the interfacial deformation and regularizing the interfacial jump as