G Model
COLSUA-19092; No. of Pages 6

Colloids and Surfaces A: Physicochem. Eng. Aspects xxx (2014) xxx–xxx

Contents lists available at ScienceDirect

Colloids and Surfaces A: Physicochemical and Engineering Aspects

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

High frequency oscillatory flow in micro channels

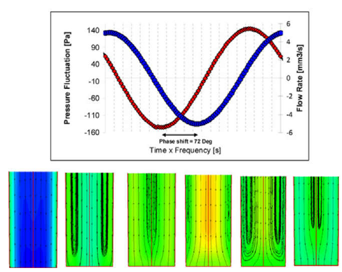
M. Karbaschi[a,b,*], A. Javadi[a,c], D. Bastani[b], R. Miller[a]

[a] Max Planck Institute of Colloids and Interfaces, Potsdam, Germany
[b] Sharif University of Technology, Tehran, Iran
[c] University of Tehran, Tehran, Iran

HIGHLIGHTS

- Measurements of pressure amplitude and phase shift during a high frequency oscillatory flow have been performed.
- A complex velocity field is formed in narrow micro-channels during liquid oscillations.
- A phase shift is observed between the maximum instant liquid flow rate and the maximum pressure loss.
- CFD simulations describe the flow field of the oscillatory flow in micro-channels.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 5 January 2014
Received in revised form 13 March 2014
Accepted 20 March 2014
Available online xxx

Keywords:
Oscillatory flow in microchannel
Velocity profile and pressure loss
Hydrodynamic relaxation time
Transient parabolic to complex flow pattern
Oscillating drop and bubble
Interfacial rheology

ABSTRACT

This paper deals with computational and experimental studies on the oscillatory flow at high frequencies up to 100 Hz performed with the Oscillating Drop and Bubble Analyzer (ODBA) setup based on the capillary pressure technique. The CFD results are validated considering pressure amplitude experimental data. The simulated results of phase shift between the generated oscillatory flow and the consequent pressure amplitudes show also good agreement with the experimental data. In absence of any compressibility and viscoelasticity effects and assumptions, a complex velocity field during oscillation is the main reason for the observation of a phase shift. The results of velocity profiles at the moment of maximum instant flow rate illustrate a transient of the regular parabolic laminar flow inside the tip at low frequencies to a complex flow profile at intermediate and high frequencies. For the moment of maximum pressure amplitude a complex shape with triple maximum/minimum velocity regions is observed. The evolution of the velocity profile shape depends significantly on the frequency and capillary tip size, however, not by the volume amplitude. The results are in good correlation with the concept of the hydrodynamic relaxation time, however, the presented approach reveals more details. The creation of a double parabolic-like flow inside the tip, which can be defined as fluid flow through much smaller tubes or channels is the main reason for observing a maximum pressure loss with a certain phase shift to the maximum instant liquid flow rate.

1. Introduction

Recently, the strong increase in microfluidic research is motivated by the growing micro fabrication technologies and arising demands of micro scaled drivers for special industrial and fundamental applications. Example for such applications are the

* Corresponding author at: Max Planck Institute of Colloids and Interfaces, Am Mühlenberg 1, D14476, Potsdam/Golm, Germany. Tel.: +49 331 567 9259; fax: +49 331 567 9202.
E-mail address: mohsen.karbaschi@mpikg.mpg.de (M. Karbaschi).

http://dx.doi.org/10.1016/j.colsurfa.2014.03.062
0927-7757/

Please cite this article in press as: M. Karbaschi, et al., High frequency oscillatory flow in micro channels, Colloids Surf. A: Physicochem. Eng. Aspects (2014), http://dx.doi.org/10.1016/j.colsurfa.2014.03.062

formation of micro-drops for manipulating small amounts of fluids, especially for biotechnological purposes, the micro capillary devices applied in mono dispersed double emulsion generators, drop and bubble oscillation on a capillary tip for interfacial rheology measurements, or the development in the application of micro channels in thermal management of many cooling systems [1–6]. Therefore, understanding the fluid flow characteristics through micro capillary systems is very important for an optimum selection and design.

Up to now, many theoretical and experimental studies have been generally conducted on continuous flow. The first attempts to analytically describe the flow patterns refers to the work of Hagen [7] and Poiseuille [8], who studied the steady state flow of homogeneous Newtonian incompressible fluids through simple long tubes. Regarding the flow in microchannels, in the past Bailey et al. [9] provided a review on single-phase forced convective flows. Their results show a significant deviation of the laminar flow in microchannels from the conventional theories. Such deviations in the flow behavior through channels on a micro and macro scale are also reported elsewhere. For example, a 2D numerical simulation of a compressible gas flowing through a microchannel was presented by Ji et al. [10]. Their results show the impact of the wall roughness stronger than expected for conventional macro scale tubes. Less work was dedicated to the study of an oscillatory flow at high frequencies. One of the first attempts refers to the work of Richardson and Tyler [11]. Their studies for the oscillatory flows show that the maximum flow velocity occurs somewhere outside the center of the pipe. According to their studies, the maximum velocity is found close to the wall boundaries, especially at high frequencies. Later, Womersley [12] investigated the flow patterns for blood analysis applications. In literature, there are several works available dealing with the mechanisms of transport phenomena during oscillatory flows. A recent review on available experimental correlations describing heat transfer and hydrodynamic characteristics of oscillatory flows was published by Kuosa et al. [13].

Studying oscillatory flows, especially at high frequencies is now a challenge for many investigators as mostly described solutions are useful for regular assumptions of steady state and stationary developed flows. At conditions in which flow path is not long enough to become independent of upstream effects, the hydrodynamic characteristics along the tube are rather different from what is described for the conditions of a developed flow. The system is more complicated for dynamic conditions in which the effective region is changing with time and the flow patterns are dynamic and influenced by the governing hydrodynamic conditions. The effective region is the flow region where a transition from a defined upstream flow field to the fully developed one takes place. For such systems, the determination of the relaxation between the pressure gradient and the velocity distribution at different effective dynamic lengths is essential in order to understand the nature of the flow.

For oscillatory flows at high frequencies up to 80 Hz, the variation in velocity profile along with the effects of relaxation time on the amplitude of pressure gradient have been studied computationally by Javadi et al. [14]. The results were also experimentally supported using pressure amplitude measurements up to 25 Hz. Based on these results, the characteristics of the velocity profile and consequently the pressure loss amplitude for an oscillatory flow in micro channels at a sufficiently low frequency is close to the behavior of an unsteady variable continuous flow. However, for higher frequencies, the phase shift between the imposed oscillatory flow and the consequent pressure amplitudes becomes significant where the velocity profiles show a dominant deviation from a parabolic profile. There are several papers in literature in which this phase shift caused by a complex flow pattern is studied and discussed. For example, Wang [15] analytically studied the unsteady flow in a duct made by an unsteady pressure gradient using series sums of Bessel integrals. In another work presented by Erdoğan et al. [16] wall side effects on unsteady flows are studied. However, the functionality of such analytical solutions is limited to low frequencies. In addition, accurate experimental measurements are required to validate the results of such analytical solutions.

In this work, the high frequency oscillatory flow (in the range of 5 to 100 Hz) of water running through a micro tube of 450 μm diameter is studied experimentally using a capillary pressure technique developed recently for studies of dynamic interfacial phenomena [17]. In addition, CFD simulations are also performed and validated for frequencies up to 100 Hz. In literature only very few studies at high frequencies with a quantitative comparison of experimental and computational results of pressure amplitude and phase shift, are available.

In addition to the mentioned application and importance of such studies, these results are important for interfacial rheology of liquid interfaces by using the capillary pressure technique for oscillating drops. The hydrodynamic pressure loss and phase shift information are a pre-condition to be able to extract the capillary pressure values from the measured total pressure which are needed for the accurate determination of the surface viscoelasticity [17]. For studying the effects of non-stationary viscous flow in the capillary on surface viscoelastic measurements one may refer to the work of Kovalchuk et al. [18]. The main aim of this study is to characterize the values of the phase shift and its dependency on different flow parameters and the capillary diameter experimentally and by using CFD simulations.

2. Experimental setup

The details of the used Oscillating Drop and Bubble Analyzer instrument (ODBA) (Sinterface Technology, Berlin) are reported in Ref. [17]. In brief, the setup includes an accurate dosing system (accuracy of 0.0001 mm^3 in the frequency range of 0.1 to 300 Hz) connected to a microcapillary via a pressure chamber. To drive an accurate oscillatory flow, a piezo actuator is applied and controlled via an electronic processor. The setup is also equipped with a pressure sensor to measure the difference between the pressure in the chamber and the outside atmosphere with an accuracy measurement about 1 Pa. For experiments at high frequency oscillatory flows, to investigate the hydrodynamic effects of running flows through the capillary tube, the capillary tip is submerged in an external cell filled with water. This provides accurate measurements of the dynamic pressure loss along the capillary tube during experiments at a given frequency. Fig. 1 shows a schematic picture of the setup.

3. Computational domain, governing equations, boundary conditions and methodology

In this work, the Navier–Stokes equations are applied to a 2D axisymmetric incompressible unsteady flow domain. The conservation of mass and momentum for describing the velocity vector field in terms of intrinsic fluid properties and the pressure can be presented as follows:

$$\frac{D\rho}{Dt} + \rho\nabla \times \vec{u} = 0 \qquad (1)$$

$$\rho\frac{D\vec{u}}{Dt} = -\nabla P + \mu\nabla^2\vec{u} + \rho\vec{g} \qquad (2)$$

For the performed simulations, a quadratic mapped mesh is applied on a 2D capillary domain. The capillary geometry consists of a conical part with 10 mm length, 0.45 mm inner diameter at the tip and 0.61 mm inner diameter of the entrance. The capillary is connected from the top to the pressure chamber via a connecting part