Oscillatory dynamics of two liquids interface in straight narrow gap

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Abstract. Oscillatory dynamics of the liquid-liquid interface in a straight slot channel is studied experimentally. We use fluids with a large difference in viscosity and similar densities. The experimental conditions are chosen in such a way that the oscillating motion of a low-viscosity liquid is inviscid, and the oscillating motion of viscous liquid obeys Darcy’s law. At the beginning of the experiment, the interface is oriented perpendicular to the channel axis. It is found that the interface takes a shape of a symmetric hill curved towards a viscous liquid under liquid oscillations. The equilibrium interface shape (the hill height) is determined by the amplitude of the interface oscillations.

1. Introduction

The dynamics of systems with an interface in constrained (slotted) channels or porous media is an actual problem in scientific and applied aspects. The monographs [1, 2] are devoted to the motion of a fluid in porous media, in particular, to the dynamics of the interface between two immiscible fluids. For example, the case of fluids with a large difference in viscosity is typical for oil production problems. The dynamics of such a pair of liquids has a number of interesting features. For instance, a classic technique in geophysics and oil recovery is based on the extraction of viscous fluid by low-viscosity fluid. Here, the low-viscosity fluid is unstable to the onset of finger instability, and “fingers” penetrate into the viscous fluid. This interface phenomenon is called the Saffman-Taylor instability [3]. The common experimental technique for modeling the dynamics of the interface between immiscible fluids in porous media is the use of a Hele-Shaw cell. The motion of a fluid in a cell is determined by viscous forces and, thus, is similar to the motion of a fluid in a porous medium. In both cases, the fluid motion obeys Darcy’s law [2]. The problem of steady displacement of one liquid by another one in a Hele-Shaw cell is studied experimentally and theoretically [4-6]. At the same time, the number of studies of the interface dynamics under harmonic pumping is very limited. We should mention that induced by vibrations averaged effects in hydrodynamic systems with the interface is a trend of vibrational fluid mechanics [7]. However, the theory of high-frequency oscillations of the interface between liquids is developed. The averaged effects at the oscillating interface between with a large difference in viscosity in a straight slot channel are experimentally studied.
2. Experimental setup and technique

The dynamics of an oscillating interface between two immiscible with a large difference in viscosity is experimentally investigated. The effect of a harmonic flow rate on the averaged shape of the interface in a narrow slot channel is considered. It is found that the motion of viscous fluid obeys Darcy law while the motion of a low-viscosity fluid is potential outside thin Stokes layers near the channel boundaries. Recently [9], the dynamics of the interface in a radial Hele-Shaw cell was considered.

The cavity is a flat straight slot channel formed by two glasses of 8 mm thick. Channel length $H$ is equal to 340 mm, width $L$ is 90 mm. The distance $d$ between glass plates (layer thickness) is 1.3 mm. The cell is filled with tinted water ($\rho_w = 1.0 \text{ g/cm}^3$, $\eta_w = 1.0 \text{ cP}$) and silicone oil PMS-1000 ($\rho_{oil} = 0.91 \text{ g/cm}^3$, $\eta_{oil} = 10^3 \text{ cP}$). The interface is located in the central part of the channel and, in the absence of oscillations, has the form of a slightly curved line elongated across the channel axis (Fig. 1). The coefficient of interfacial tension is $\sigma_{oilw} = 27 \text{ dyn/cm}$. In the experiments, the channel was located both horizontally and vertically.

![Figure 1. Scheme of the channel filled with two immiscible liquids](image)

The time evolution of the interface between liquids is recorded by a DSLR camera at a frequency of 60 fps. In the experiments, the amplitude and the frequency of oscillations are varied. The liquid oscillations are given by means of a setup described in [8]. The horizontal cell filled with fluid is connected to the hydraulic circuit by flanges with elastic membranes. These membranes separate fluids in the channel and in the circuit and also transmit the oscillating motion of the fluid in the circuit to the working fluid in the channel. The oscillation frequency $f = \frac{\Omega}{2\pi}$ changes in the range from 6 to 10 Hz. The averaged over the cross-section of channel fluid velocity changes according to the law $V = V_0 \cos(\Omega t)$, and the velocity amplitude $V_0$ varies from 1.32 to 11.31 cm/s.

3. Results

At the initial phase of the experiment, the interface between two stationary liquids is slightly curved (Fig. 2, a): silicone oil is in the upper part of the photo while tinted water is in the lower part. In the presence of low-amplitude oscillations, the interface oscillates along the channel axis with a given frequency. At small amplitudes of the fluid oscillations, the amplitude of interface oscillations is almost the same over the entire width of the channel. In this case, the oscillations have the meniscus character, when the contact line is almost stationary during the cycle of oscillations. Thus, under the action of oscillations, the shape of the interface becomes flat (Fig. 2, b). With an increase of the amplitude of the
fluid oscillations, the interface takes the form of a hill with the peak shifted towards the viscous fluid (Fig. 2, c). In this case, the amplitude of the interface oscillations becomes inhomogeneous over the channel width: it is significantly larger in the center of the channel than near the side walls. Note that Fig. 2 shows the interface in the phase of maximum displacement towards the viscous liquid. The solid line in Fig. 2, c indicates the position of the contact line and the dashed line indicates the maximum displacement of the interface during the cycle of oscillations. With further increase of the amplitude of oscillations, the height of the hill grows (Fig. 2, d). At critical value of the amplitude, the finger instability develops at the interface and grows within the amplitude (Fig. 2 e). The finger instability is out of the focus of the study.

With a decrease of the amplitude, the interface flattens and tends to become a straight line. Thus, the interface takes a dynamic equilibrium position depending on the amplitude of oscillations. The equilibrium shape of the interface is nearly the same in vertical and in horizontal positions, so that, it is determined only by oscillation parameters.

The equilibrium position of the contact line at a given frequency is determined by the amplitude of oscillations of the interface. In the course of the cycle of the fluid oscillations, the contact line oscillates with small amplitude about a mean position. Since the stroke of interface changes over the width of the channel, we choose the stroke (double amplitude) of the interface in the center of the channel $h_{\text{max}} - h_{\text{cl}}$ to be a characteristic length (Fig. 2 d). Here $h_{\text{max}}$ is the maximum displacement of the interface towards the viscous fluid, $h_{\text{cl}}$ is the contact line position (hill height). Both distances are measured from the contact point of the interface and the side wall (white cross in Fig. 2 d). With an increase of the amplitude, the height $h_{\text{cl}}$ grows (Fig. 3). The linear increase of the height $h_{\text{cl}}$ is observed at small amplitudes and then reaches the maximum value at critical value of $h_{\text{max}} - h_{\text{cl}}$. This is due to the appearance of "finger-like" instability at the interface (Fig. 2 e).

![Figure 2](image)

**Figure 2.** Evolution of the interface at various amplitudes of oscillations: the amplitude grows from (a) to (e); $f = 8$ Hz
Let us dwell on the interface oscillations. During the cycle of oscillations, the low-viscosity liquid moves towards the viscous liquid in the form of a tongue (Fig. 4, a). Here, the contact line of the interface is almost stationary (the dark blue border in Fig. 4, a). In the opposite phase of the oscillations, the tongue disappears, and the interface coincides with the contact line (Fig. 4, b). Thus, a column of low-viscosity liquid oscillates. At the same time, a thin layer of the viscous fluid between the oscillating column of the low-viscosity liquid and the channel walls remains stationary. This can be traced by the change of the color of tinted water (Fig. 4, a). This effect can be explained by the significant difference of the viscosities and by the fact that the viscous liquid wets the glass boundaries of the channel.

The equilibrium position of the interface in the form of a hill is characterized by the change of the amplitude of the interface oscillations along the contact line. In the center of the channel, the low-viscosity fluid oscillates with amplitude that exceeds the amplitude of oscillations near the side walls of the channel. This is clearly seen in Fig. 4, a, where the light blue domain demonstrates the displacement of the interface at the phase of the maximum displacement towards the viscous fluid. Fig. 5 shows the dependence of amplitude of the interface oscillations $b$ in the center of the channel (crosses) and near the side wall (diamonds) on the stroke of the interface in the center of the channel. One can find that the amplitude of oscillations near the side walls grows slowly, while in the center of the channel, the amplitude increases rapidly (dashed line) until the onset of the finger instability (solid line). At low amplitudes of the interface oscillations (in the absence of the hill), the amplitude of longitudinal oscillations is nearly the same over the entire width of the channel (Fig. 2, b).

![Figure 3. Height of the contact line $h_{cl}$ in the center of the channel versus the stroke of the interface in the channel center](image)

![Figure 4. Extreme positions of the interface during the cycle of oscillations, $f = 10$ Hz](image)
The question is: What determines the formation of the dynamic quasi-equilibrium shape of the oscillating interface (or contact line) in the form of a symmetrical hill? The interface shape is determined by the constant averaged over the period curvature of the boundary. It is possible to conclude that the averaged over the cycle interface curvature in the plane perpendicular to the gap, near the hilltop differ from the one near the hill base. Thus, the averaged over the period dynamic contact angle could be responsible for the found phenomenon.

![Figure 5. Amplitude of the interface oscillations near the side walls (diamonds) and in the center of the channel (crosses) versus the stroke of the interface in the center of the channel, f = 10 Hz](image)

4. Conclusion
The interface between two oscillating liquids in a narrow slot channel is experimentally studied. It is found that the transversal oscillations of the interface between two fluids with a large difference in viscosity in a narrow slot gap lead to the change of quasi-equilibrium shape of the oscillating interface. The shape of dynamically stationary interface is determined by the amplitude of the interface oscillations. The found phenomenon is new and needs further experimental and theoretical study.

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