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Unstable two-phase flow rate in micro-channels and cracks under imposed pressure difference

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ABSTRACT

This paper numerically investigates two-phase flow rate instabilities in micro-channels comprising localized geometrical restrictions (i.e., a convergent–divergent duct). A numerical Lattice Boltzmann method is used to model and simulate multiphase flow with an accurate treatment of the contact angle at the triple line. A pressure difference is imposed between the inlet and outlet sections of the channel. This induces flow and allows its time evolution to be followed. Indeed, the resulting flow exhibits strong time fluctuations as it is strongly influenced by the induced viscous forces acting at solid–fluid interfaces and by pressure discontinuities sustained across the curved fluid–fluid interfaces (i.e., across the curvatures of the menisci). Flow fluctuations are investigated parametrically for wetting and non-wetting fluids and for different micro-channel geometrical irregularities. For this purpose, an equivalent dimensionless formulation is adopted. Flow fluctuations are analyzed and related to the controlling dimensionless parameters (Reynolds number, Laplace number, Bejan number, contact angle and channel constriction ratio). This allows quantification of the coupled influence of physical fluid properties (surface tension and contact angle), channel geometry, and loading conditions (imposed pressure difference) on flow evolution. Numerical results show that, under particular conditions, capillary pressure jumps sustained across the fluid bridge (owing to flow rate, contact angle, and local orientation of channel walls) entirely compensate for the imposed pressure difference. This situation results in a no-flow state, i.e., the flow becomes impossible even under an imposed pressure difference.

Introduction

Understanding of the main physical mechanisms controlling multiphase flow in micro-channels and cracks, in the presence of local variations in their cross-sections, plays a crucial role in many industrial and engineering applications.

In the microelectronics, energy, and biomedical industries, micro-pumps, heat-pipes, micro-capillaries, and micro-needles require proper control and mastery of multiphase flow at the micro-scales. This problem has attracted researchers' attention because of the increasing use of small-scale devices such as miniature power systems, compact heat exchangers, chemical reactors, and micro-electro-mechanical systems (MEMS). In particular, great efforts have been made to reveal multiphase flow instabilities (Wu and Cheng, 2004; Wu et al., 2006; Huh et al., 2007; Wang et al., 2007; Lee and Mudawar, 2008; Wang and Cheng, 2008; Han and Kedzierski, 2008; Liu et al., 2005; Xu et al., 2005) as they could lead to inaccurate predictions of mixing and, possibly, to unexpected damage.

In nuclear engineering applications, proper modeling of complex two-phase air steam flows (Simon et al., 2007; Vyskocil et al., 2014) through cracked concrete structures represent a real challenge. Under severe thermo-hydraulic loading conditions (e.g., a loss-of-coolant accident (Shekarchi et al., 2002; Dal Pont et al., 2007; Ahn et al., 2009; Medjigbodo et al., 2015)) phase changes can occur within cracks, leading to the formation of liquid water bridges. This significantly modifies leakage kinetics, thus inducing a loss in pertinence of the commonly adopted macroscopic modeling strategies (Simon et al., 2007; Rastiello et al., 2014, 2015a, 2015b).

In all the cited cases, global responses (e.g., flow rate evolution) are strongly influenced by local phenomena occurring near the triple line. A proper characterization of local fluid–fluid and fluid–solid interactions occurring during flow is therefore a key aspect for enhancing the physical validity of the adopted modeling strategies.

In the present work, multiphase flow fluctuations and instabilities induced by localized variations in channel cross-section (e.g., geometrical defects) are investigated through parametric numerical analysis. High-performance cluster simulation strategies are adopted to obtain real-time flow visualizations. This allows proper study of flow evolution, completing macroscopic variables with local

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information concerning the complex interactions between the phases considered.

Computations are performed according to a two-dimensional (2D) multiphase lattice Boltzmann (LB) numerical formulation. The chosen model follows the numerical formulation presented by Reis and Phillips (2007), along with the improvements by Leclaire et al. (2011, 2012, 2013, 2014, 2015) for the recoloring operator, the isotropic color gradient, the enhanced equilibrium distribution functions, the multiple-relaxation-time (MRT) collision operator, and the modeling of static contact angle. The first part of this paper presents the basic aspects of the numerical model.

The second part of the article presents the considered geometrical micro-channel configuration. A simplified geometry is analyzed for sake of simplicity: a horizontal rectangular micro-channel with high length-to-height aspect ratio, comprising a single convergent-divergent duct. Dimensionless parameters allowing proper definition of fluid properties and geometrical channel characteristics are then introduced and discussed.

In the third part of the article, the presented LB model is used to simulate two-phase flow through the channel. A single wetting/non-wetting fluid bridge is initialized at the entrance of the channel. A pressure difference is then imposed between the inlet and outlet sections of the channel in order to analyze flow rate evolution. Its main phases are identified and discussed, and representative macroscopic flow variables allowing for a proper description of average flow and its time fluctuations are defined. Parametric analyses allow identification of the role of physical fluid properties (surface tension and contact angle), channel geometry, and loading conditions (imposed pressure difference between the inlet and outlet) on flow evolution. Finally, conditions for the appearance of a so-called “fluid cork” such that the flow becomes impossible (i.e., flow rate decreases down to zero) even under a significant imposed pressure difference, are discussed in terms of dimensionless variables.

Some conclusive remarks close the paper.

Lattice Boltzmann formulation

The numerical model is briefly described here for convenience. For more details about the adopted LB formulation the reader can refer to Reis and Phillips (2007), Leclaire et al. (2011, 2012, 2013, 2014, 2015).

Problem setting

The 2D two-phase LB model considers two sets of distribution functions, one for each fluid, moving on a D2Q9 lattice with the velocity vectors $\mathbf{c_i}$. With $\theta_i = \frac{\pi}{4}(4-i)$, these velocity vectors are defined as follows:

$$\mathbf{c_i} = \left[c_i^x, c_i^y\right] = \begin{cases} [0, 0], & i = 1 \\ [\sin(\theta_i), \cos(\theta_i)]c, & i = 2, 4, 6, 8 \\ [\sin(\theta_i), \cos(\theta_i)]\sqrt{2}c, & i = 3, 5, 7, 9 \end{cases} \quad (1)$$

where $c = \Delta x/\Delta t$, $\Delta y = \Delta x$, Δx is the lattice spacing, and Δt is the time step.

The distribution functions for a fluid of color k (with $k = r, b$) are denoted $N_i^k(\mathbf{x}, t)$, while $N_i(\mathbf{x}, t) = N_i^r(\mathbf{x}, t) + N_i^b(\mathbf{x}, t)$ is the color blind distribution function. The evolution algorithm follows the operators below:

1. Collision operator:
   $|N^k(\mathbf{x}, t_*)\rangle = (\Omega^k)^{(3)}((\Omega^k)^{(2)}((\Omega^k)^{(1)}(|N^k(\mathbf{x}, t)\rangle)))$
2. Streaming operator:
   $N_i^k(\mathbf{x} + \mathbf{c_i}\Delta t, t + \Delta t) = N_i^k(\mathbf{x}, t_*)$

where the symbols $|\cdot\rangle$ denotes the Dirac ket notation with an expansion with respect to the velocity space. The collision operator results in three main operations: the single-phase collision operator $(\Omega^k)^{(1)}$; the multiphase perturbation operator $(\Omega_i^k)^{(2)}$; and the multiphase recoloring operator $(\Omega_i^k)^{(3)}$.

Single-phase collision operator

The first operator, $(\Omega^k)^{(1)}$, is the MRT operator of the single-phase LB model first introduced by D’Humières (1992). The moments are relaxed toward a local equilibrium, in which $\mathbf{K}$ denotes a diagonal matrix of relaxation coefficients and $\mathbf{M}$ is the matrix that shifts the domain from a distribution space to a moment space:

$$(\Omega^k)^{(1)}(|N^k\rangle) = |N^k\rangle - \mathbf{M}^{-1}\mathbf{KM}(|N^k\rangle - |N^{k(e)}\rangle) \quad (2)$$

Some details (not all) about the chosen operator are given below. The density of the fluid k is given by the first moment of the distribution functions:

$$\rho_k = \sum_i N_i^k = \sum_i N_i^{k(e)} \quad (3)$$

where the superscript (e) denotes equilibrium. The total fluid density is given by $\rho = \sum_k \rho_k$, while the total momentum is defined as the second moment of the distribution functions:

$$\rho\mathbf{u} = \sum_i \sum_k N_i^k \mathbf{c_i} = \sum_i \sum_k N_i^{k(e)} \mathbf{c_i} \quad (4)$$

where $\mathbf{u}$ is the velocity of the color-blind distribution functions. The equilibrium functions are defined by Leclaire et al. (2013):

$$N_i^{k(e)}(\rho_k, \mathbf{u}, \alpha_k) = \rho_k\left(\phi_i^k + \frac{3}{c^2}W_i\left[(\mathbf{c_i}\cdot\mathbf{u}) + \frac{3}{2c^2}(\mathbf{c_i}\cdot\mathbf{u})^2 - \frac{1}{2}(\mathbf{u}\cdot\mathbf{u})\right]\right) + \Phi_i^k \quad (5)$$

The weights W_i are those of a standard D2Q9 lattice:

$$W_i = \begin{cases} 4/9, & i = 1 \\ 1/9, & i = 2, 4, 6, 8 \\ 1/36, & i = 3, 5, 7, 9 \end{cases} \quad (6)$$

Moreover,

$$\phi_i^k = \begin{cases} \alpha_k, & i = 1 \\ (1-\alpha_k)/5, & i = 2, 4, 6, 8 \\ (1-\alpha_k)/20, & i = 3, 5, 7, 9 \end{cases} \quad (7)$$

As established by Grunau et al. (1993), the density ratio between the fluids γ must be taken into account as follows to obtain a stable interface:

$$\gamma = \frac{\rho_r^0}{\rho_b^0} = \frac{1-\alpha_b}{1-\alpha_r} \quad (8)$$

where the superscript “0” over ρ_r^0 or ρ_b^0 indicates the initial value of the density at the beginning of the simulation.

In each homogeneous-phase region, the pressure of the fluid k is:

$$p_k = \rho_k \frac{3(1-\alpha_k)}{5} c^2 = \rho_k \left(c_s^k\right)^2 \quad (9)$$

In the above expressions, only one α_k is a free parameter because of (8). In general, we let the blue fluid be the least dense, and we set the value of $0 < \alpha_b < 1$ so that the relation $0 < \alpha_b \le \alpha_r < 1$ is guaranteed to hold. This relation needs to be respected to avoid non-physical negative pressure. Also, these parameters set the isothermal sound speed c_s^k in each fluid k.