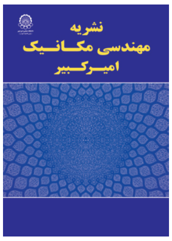

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Phenomenological Study of Droplet Behavior Passing through a Porous Medium at Pore-Scale, Using Lattice Boltzmann Method

A. Amiri Hezaveh[1], M. R. Salimi[2*], M. Taeibi Rahni[2]

[1] Department of Mechanical Engineering, Islamic Azad University Central Tehran Branch, Tehran, Iran
[2] Department of Aerospace Engineering, Sharif University of Technology, Tehran, Iran

ABSTRACT: Single-phase and multiphase flows in porous media, both in nature and in industries, are very important for the wide range of researchers. Specifically, they have many applications in processes such as plant leaf sprays, pesticides, printers, and penetration of rain or surface waters to the soil. The main objective of this research is the analysis of droplet interaction with a porous medium. The droplets are of have similar scale of the pores of the porous medium, which its application is penetration of droplet with specific size into the bed rocks and filtering the droplets. In this study, the porous medium consists of square obstacles with porosity value of 0.8, is exposed to a two-phase flow. The porous medium that is wetted by primary phase is intruded by a droplet. The regimes of the flow is non-Darcian. The effective dimensionless numbers of the physics are Reynolds, Capillary, and Ohnesorge number. The values of exerted dimensionless pressure in the study are 0.000108, 0.000144, and 0.000180 and the range of Ohnesorge is 0.19-0.76. The factors connected with the droplet and secondary phase (related to fluid's properties), such as surface tension and density ratio along with flow characteristics (such as exerted pressure) are effective and create variations in the behavior of droplet breakup, which in the frame of a comprehensive parametric study, are investigated. The types of droplet breakup, categorized and are presented by characteristic pictures of each case. Moreover, the zoning of each case in Re-Ohn Figure (as a droplet phenomenological breakup map on the basis of two dimensionless number and exerted pressure) is done. The results of the simulations, show the ability to predict droplet behavior in the porous medium using presented charts and moreover, make a comparison on relative effect of effective factors, are the redeeming features of this study. In this study, Lattice Boltzmann method is used as the numerical method that shows a high degree of capabilities and flexibility in relation with multi-phase flows and porous media.

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1- Introduction

This study is devoted to analyze behavior of a droplet in a porous medium. The droplet has the similar scale of the pore scale of the porous medium. In the literatures, there are several recent studies with respect to interaction of droplet on a porous medium [1-2] that all have considerable difference in the scale of droplet and the surrounding porous media.

Selecting a Representative Elementary Volume (REV) would lead to more simplified study on the porous medium by maintaining the desired level of precision. The description of the problem setup is presented in Table 1. Also a schematic representation of the sample geometry can be seen in Fig. 1. The flow regime of the study can be determined according to the Reynolds number of the flow in a porous medium.

As a parametric study, totally 60 simulations in form of two different density ratios, three dimensionless pressure gradients, and ten Ohnesorge numbers were conducted.

In the Reynolds number, U, D, ρ and μ are the fluid average speed in a cross section area, the diameter of the flow entrance pore of the porous medium, the density and the fluid dynamic viscosity, respectively. In the Capillary number, U, μ and σ are the fluid average speed in a cross section area, the dynamic viscosity of main phase and surface tension of two phases, respectively. Accurately, this dynamic multiphase flow number shows the efficacy of the main phase on the primary phase (droplet). In the Ohnesorge number, μ, σ, ρ and D in-order are the dynamic viscosity of droplet, the surface tension of two phases, the density and the initial diameter of droplet. Somehow, this number states the droplet resistance regardless of the flow effects (static nature).

Table 1. Problem Description

Porosity of the porous medium	0.8
Lattice size	201-201
Boundary condition	Periodic up-down and left-right
kinematic viscosity of phases	0.1666666, 0.1666666
Density ratio	1(drop):2, 1(drop):3
Reynolds number	2-16 (in non-Darcian range)
Assumptions:	Incompressible, Newtonian, and Isothermal flow, Constant surface tension, Wall adhesion effects are ignored, Exerted body force acts as a pressure gradient.

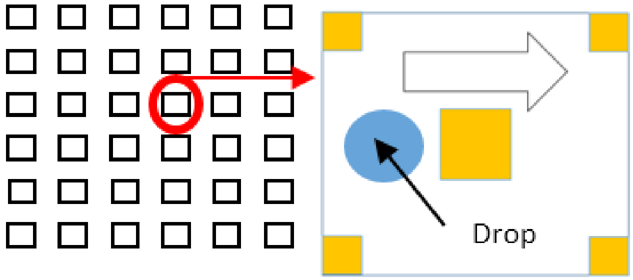

Fig. 1. Schematic of Geometry

Corresponding author, E-mail: mrsalimi@sharif.ir

2- Methodology

As a numerical method, Lattice Boltzmann Method (LBM), the multiphase model of the He et al. 1999 [3], D2Q9 and Bhatnagar–Gross–Krook (BGK) approximation are used. The LBM has been posed as an appropriate solution in fluids flow simulation and widely used during the recent years [4]. Against the common numerical methods on the basis of macroscopic continuum equations, the LBM is based on macroscopic models and mesoscopic kinetic. The basic idea in the LBM is to create simplified kinetic models which can satisfy the equations of macroscopic variables by using the fundamental principles of mesoscopic physics and the macroscopic properties obtained afterwards. The LBM shows the higher ability in multiphase flow and intricate geometries in proportion to other methods like macroscopic approaches. The basic idea of the LBM model proposed by He is to use an index function to track the interface between two different phases which is similar to the level set approach [5]. The model uses two distribution function (f is index distribution function and g is pressure distribution function) which are described as below [1]:

$$\frac{Df}{Dt}=-\frac{f-f^{eq}}{\lambda}-\frac{(\xi-u).\nabla\psi(\phi)}{RT}\Gamma(u)$$
$$\frac{Dg}{Dt}=-\frac{g-g^{eq}}{\lambda}-(\xi-u).[\Gamma(u)(F_s+G) \tag{1}$$
$$-(\Gamma(u)-\Gamma(0)\nabla\psi(\rho))]$$

The corresponding equilibrium distributions are defined as below:

$$f^{eq}=\phi\Gamma(u), g^{eq}=\rho RT\,\Gamma(u)+\psi(\rho)\Gamma(0)$$
$$\Gamma(u)=\frac{1}{(2\pi RT)^{D/2}}exp\left[-\frac{(\xi-u)^2}{2RT}\right] \tag{2}$$

The density of the index fluid, the pressure, and the velocity, are calculated using:

$$\phi=\int fd\xi, p=\int gd\xi, \rho RTu=\int \xi gd\xi \tag{3}$$

The real fluid kinematic viscosity can be calculated from the index function using:

$$\nu(\phi)=\nu_l+\frac{\phi-\phi_l}{\phi_h-\phi_l}(\nu_h-\nu_l) \tag{4}$$

3- Results and Discussion

As a validation, Laplace test is conducted and the results presented in the Fig. 2. To evaluate the mesh independency, density distribution in and around a droplet [6], was studied and lattice size of 201-201 was selected.

Several patterns of droplet break-up are observed that as representative samples, key frame of each pattern is presented in Fig. 3. The distinctive phenomenon between the two below break-up cases, is the occurrence of coalescence in the collapsed and detached droplets after the impact of primary droplet to the obstacle. In a trapped case the droplet trapped behind the obstacle, no penetration to the porous medium occurs and the intrusion of droplet to the porous medium

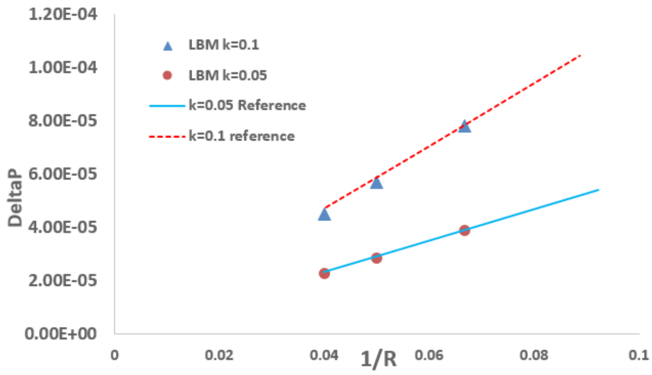

Fig. 2. The result of Laplace validation

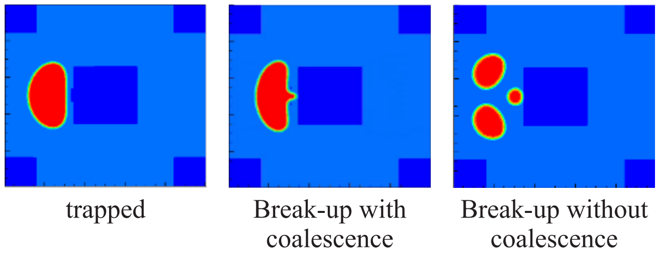

Fig. 3. Droplet break up patterns

failed.

According to Fig. 4, for each density ratio (1:2 and 1:3) and between different pressure gradient curves belongs to each density ratio, it can be seen that:

- By decreasing the Ohnesorge number down to specific value, Reynolds number levels out and the droplet also passes the obstacle (break-up without coalescence). Then, at a specific low limit value of Ohnesorge number (that can be considered as a critical Ohnesorge number), the droplet trapped behind the obstacle, result in a barrier against passing current and reduction of Reynolds number. In fact, the Reynolds number monotonously decrease to the minimum value (critical Ohnesorge value), the droplet also passes the obstacle (break-up with coalescence). With further decrease in Ohnesorge number, the droplet becomes more tangent to the frontal face of the obstacle and the Reynolds number of the flow slightly increases. Consequently, there are values of Ohnesorge numbers that indicate the transition of breakup patterns. Therefore, the Ohnesorge-Reynolds figures can be separated to several zones which denote specific and distinct break-up patterns (trapped, break-up with and without coalescence).
- By increasing the pressure gradient (via body force), Reynolds number range increases (curves moves to higher values of Reynolds number in vertical direction) and critical Ohnesorge numbers also moves to the left (lower values), in other words, trapping the droplet occurs sooner and in lower critical Ohnesorge number.

In the Fig. 5, the solid and dashed lines indicate 1:2 and 1:3 density, respectively. Increasing in the pressure gradient releatively leades to increase in Capilary number range and the portion of break-up phenomenon.

These figures can be produced and developed (by increasing the number of simulations that leads to more accurate border and marginal values in the figures) for every porous medium

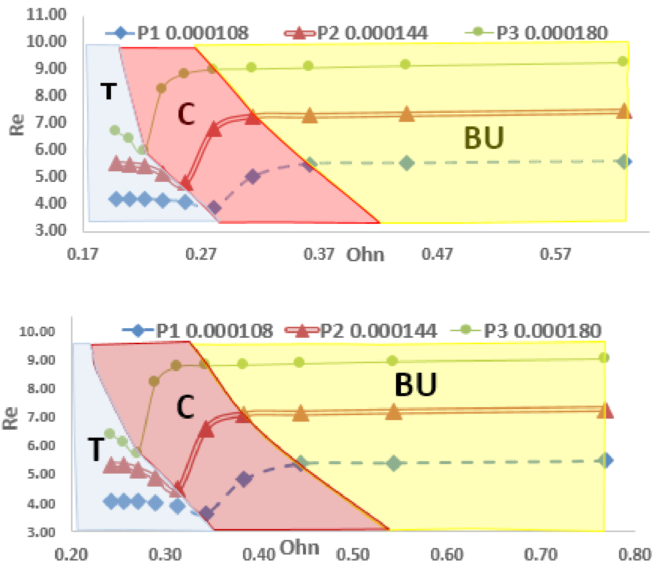

Fig. 4. Ohn-Re figure-Density ratio of 1:2 (above), 1:3 (Below)

(with different configuration and porosity), fluid, and flow properties. The adopted approach in the study and the figures obtained through, can predict droplet behavior using presented phenomenological breakup charts.

4- Conclusion

In the study, two-phase flow in a porous medium was analyzed. The porous medium wetted by the primary phase was intruded by a droplet. The regimes of the flow was non-Darcian. The model shows the ability to predict droplet behavior in the porous medium.

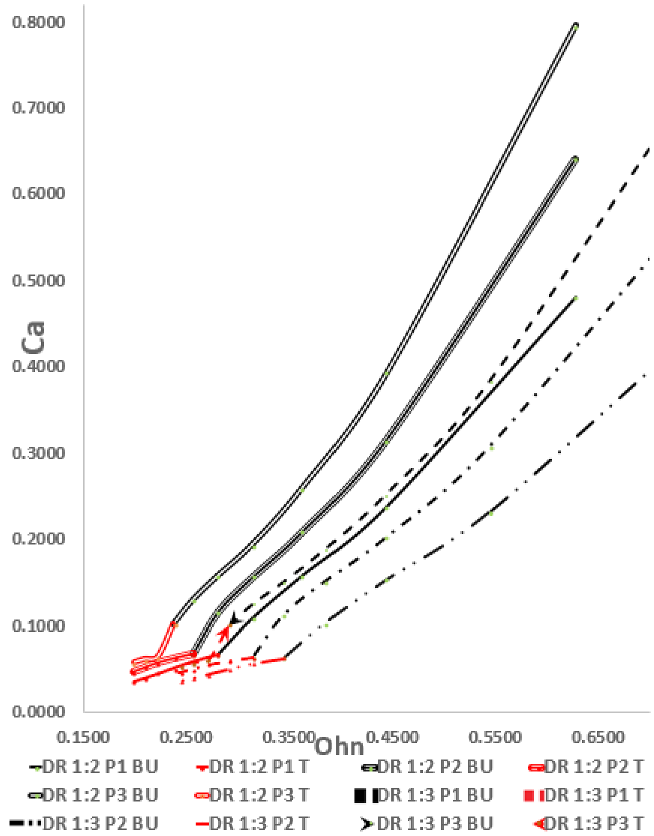

Fig. 5. Ca-Ohn figure-Density ratio of 1:2 and 1:3

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