Physica E 94 (2017) 15–21

Contents lists available at ScienceDirect

Physica E

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

Experiment and Lattice Boltzmann numerical study on nanofluids flow in a micromodel as porous medium

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ARTICLE INFO

Keywords:
Nanofluid
Micromodel
Porous medium
Lattice Boltzmann

ABSTRACT

Al_2O_3 nanofluids flow has been studied in etched glass micromodel which is idealization of porous media by using a pseudo 2D Lattice Boltzmann Method (LBM). The predictions were compared with experimental results. Pressure drop / flow rate relations have been measured for pure water and Al_2O_3 nanofluids. Because the size of Al_2O_3 nanoparticles is tiny enough to permit through the pore throats of the micromodel, blockage does not occur and the permeability is independent of the nanofluid volume fraction. Therefore, the nanofluid behaves as a single phase fluid, and a single phase LBM is able to simulate the results of this experiment. Although the flow in micromodels is 3D, we showed that 2D LBM can be used provided an effective viscous drag force, representing the effect of the third dimension, is considered. Good qualitative and quantitative agreement is seen between the numerical and experimental results.

1. Introduction

As a new type of particulate fluids, nanofluid has great potential advantages and applications in key fields such as heat exchangers, thermal management and control, medical, transportation, micro and nano electromechanical systems (MEMS & NEMS), etc [1–11].

Due to small sizes of nanoparticles, nanofluids can flow through the micro and nano scale throats [12,13]. Therefore one of the interesting applications of nanofluids is using them as working fluid in the porous media. Fluid flow through porous media has considered scientific and technological interest [14–17].

To describe flow at the pore measure, it is appropriate to use easy representations of porous media such as physical network models which can be made in the form of 2D networks. These models are a network of pores and throats which are prepared using the standard photolithography technique on a silicon, polymer or glass substrate. Glass network models are one of the most important tools for research and study about the flow in complicated geometries such as filters and oil reservoirs.

Nanoparticles have been considered as good operator for resolving reservoir engineering concerns in the place of projects. Nanofluids have been employed in oilfields for enhancing the injection procedures by altering porous media wettability, incrementing the viscosity of injecting fluid and diminishing the interfacial tension between reservoir and injection fluid [18].

One of the challenges for this novel approaches includes propagating these suspensions through a porous media. Compared to the emulsions stabilized by colloidal particles, nanofluids have better specifics. Nanoparticles are very smaller, and emulsions stabilized by them can pass a longer space through the pore throats. The solid nanomaterials can be irreversibly joined to the oil-water boundary and form an inflexible nanomaterial monolayer on the droplet surfaces, which make very stable emulsions [19]. Furthermore, emulsions stabilized with nanomaterials can stand out the conditions of high-temperature reservoir for long times. This can significantly expand the range of reservoirs to which Enhanced Oil Recovery (EOR) can be applied. Lastly, nanomaterials can transmit extra functionalities such as super paramagnetism and reaction catalysis. The former could allow transport to be organized by employing of magnetic field. The latter could enable in situ reduction of oil viscosity [20].

Using the nanofluids in porous media has two opposite effects on relative permeability and absolute permeability. Binshan et al. [21] mentioned that Nanofluids based on polysilicon materials could change the porous surfaces wettability. The mechanism of augmenting water injection is through improving relative permeability of the waterphase by altering wettability made by sorption of polysilicon on the porous surface of sandstone. On the other hand, the sorption on the porous surface and plugging at the small pore throats of the polysilicon may lead to reduce the absolute permeability (k) and porosity of porous media. Nonetheless, Yu et al. [22] showed that SiO_2 nanoparticles

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http://dx.doi.org/10.1016/j.physe.2017.07.008
Received 13 March 2017; Received in revised form 27 June 2017; Accepted 18 July 2017
Available online 19 July 2017
1386-9477/

Nomenclature

c	Lattice velocity
c_s	lattice speed of sound
Da	Darcy number
D_p	Obstacles length
f	Non-dimensional pressure drop
f_i	probability distribution function
f_d	effective viscous drag force
h	depth
I	Node number in x direction
J	Node number in y direction
k	permeability
L	inlet to outlet distance of the porous medium
p	pressure
$Q(f, f')$	Collision function
R	Gas constant
t	time
T	temperature
u	flow velocity in x direction
$\bar{u}$	Average velocity
U	the volumetric flow rate per unit cross-sectional area of porous medium
v	Flow velocity in y direction
V	Total volume
V_s	volume of the solid blocks
Δx	Lattice spacing
Δt	Time spacing
ρ	density
ν	Kinematic viscosity
$\vec{\xi}$	Particles velocity
μ	Dynamic viscosity
φ	Volume fraction
ε	porosity
τ	Non-dimensional relaxation time
λ	relaxation time

Subscripts and superscripts

B	lattice units
bf	Base fluid
eq	equilibrium
n	nano particle
nf	nanofluid

could effortlessly pass through the sandstone core without varying the core's permeability. Therefore, deposition and sorption of nanoparticles at surface pores causes the blockage in pore throat of porous media and reduces the permeability. Hence, the success degree in well treatment is specified by the nanoparticles size and pore throat of porous media.

Some particular nanoparticles types that probably are used include Alumina, Zinc oxide, Magnesium oxid, Iron oxide, Zirconium oxide, Nickel oxide, Tin oxide and Silica. It is consequently vital to discover the effect of these oxides of nanoparticles on oil recovery since this is the main purpose of the oil industry [23].

Recently, the Lattice Boltzmann Method (LBM) has been positively used in the investigation of flow in porous media at the pore scale such as micro-models. The flow field in micro-models is three-dimensional (3D) while the effective destabilization of the flow can be described in the two-dimensional (2D) plane. Flekkoy et al. [24] suggested that the third dimension can be taken into account using the following effective viscous drag force:

$$f_d = -\frac{8\nu}{h^2}u \tag{1}$$

where u is the flow velocity, ν is the fluid viscosity and h is the distance between the walls of the third dimension. This expression originates from approaching the velocity at the centerline of the Hele-Shaw cell with the maximum velocity of Poiseuille profile. The drag force takes the expression used by Grosfiles et al. [25] if the average velocity of the Poiseulle profile is used,

$$f_d = -\frac{12\nu}{h^2}\bar{u} \tag{2}$$

Using the above drag force, Venturoli and Boek [26] compared 2D and 3D LBM of fluid flow in a pseudo-2D micro-model and showed that 2D Lattice Boltzmann simulations can be employed to calculate the field of average velocity in 3D systems.

The aim of this paper is to evaluate the ability of the pseudo 2D LBM for simulation of nanofluid flow in a micro model as porous medium. To do this, the LB method is used for numerical simulation of the flow of nanofluid and obtained numerical results are compared with the achieved experimental data.

2. The Lattice Boltzmann Method

The base of LBM is the discretization of the Boltzmann equation. The Boltzmann equation is written as follows [27,28]:

$$\partial_t f + (\vec{\xi}\,.\,\nabla)f = Q(f, f') \tag{3}$$

in which $f(t, \vec{x}, \vec{\xi})$ denotes the probability of finding a molecule at position $\vec{x}$ with velocity of $\vec{\xi}$ at time t, and $Q(f, f')$ represents an integral of nonlinear collision term with f' and f being the post and pre collision probability distribution functions, respectively. because of the complicated nature of the collision integral, direct solution of the Boltzmann equation is very difficult [29]. In order to solve the Boltzmann equation, Bhatnagar et al. [30] suggested a easy model for the collision term well-known as the BGK model:

$$Q(f, f') = \frac{1}{\lambda}(f - f^{eq}) \tag{4}$$

where λ is the relaxation time, f^{eq} is the equilibrium distribution function estimated as Maxwellian form given by Eq. (5):

$$f^{eq} = \frac{\rho}{(2\pi RT)^{\frac{3}{2}}}\exp\left(\frac{-(\vec{\xi} - \vec{u})^2}{2RT}\right) \tag{5}$$

in which R denotes the gas constant. Moreover, $\vec{u}$, ρ and T are respectively velocity, density and temperature. The density and velocity are calculated by the moments of the distribution function as follow:

$$\rho = \int f d\vec{\xi}$$
$$\rho\vec{u} = \int f\vec{\xi}\, d\vec{\xi} \tag{6}$$

In the Lattice Boltzmann Method, the BGK-Boltzmann equation is discretized in momentum and physical spaces as well as in time. The evolution of the discrete particle distribution function $f_i(\vec{x}, t)$ is determined using the following equation:

$$f_i(\vec{x} + \vec{c_i}\Delta t, t + \Delta t) - f_i(\vec{x}, t) = \frac{1}{2}(Q_i(\vec{x} + \vec{c_i}\Delta t, t + \Delta t) + Q_i(\vec{x}, t)) \tag{7}$$

In the present study, D2Q9 model is employed to discretize momentum space for the computations [31]. In this model, the discrete