Experimental setup for a high-resolution visualization of two-phase flow in a micro-model.

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Universiteit Utrecht

N.K. Karadimitriou*, S.M. Hassanizadeh and P. J. Kleingeld.
Utrecht University, Earth Sciences Department, Faculty of Geosciences.
Budapestlaan 4, 3584 CD, Utrecht, The Netherlands.
* e-mail: nikos@geo.uu.nl, tel: 0031302535024

Introduction

Current theories of two-phase flow in porous media are based on Darcy's law, wherein saturation is included as an additional state variable. However, a number of theoretical, computational, and experimental studies have shown that capillary effects are not adequately described by saturation alone. It is found that fluid-fluid interfacial areas play a major role in the dynamics of two-phase flow and capillarity. In particular, theories have been developed which include specific interfacial area, as a state variable, in addition to phase saturations and pressures. In order to investigate the role of interfacial are, an experimental setup to study and visualize two-phase flow in a micro-model under dynamic conditions was constructed. A combination of lenses, three beam splitters and four cameras are being used to visualize flow in a two-dimensional micro-model. Through image analysis, both average saturation and average interfacial area can be determined as a function of time and space.

Theory

In current two phase-flow theories, the so-called extended Darcy's law, the only driving forces were assumed to be the pressure gradient and gravity.

$$\vec{q}_\alpha = -\frac{k_\alpha \vec{K}}{\mu_\alpha} \bullet (\vec{\nabla} P_\alpha - \rho_\alpha \vec{g}), \alpha = w, n$$

where w,n are for wetting and non-wetting phase respectively.

A rigorous derivation of governing equations for two-phase flow in porous media, based on principles of mass, momentum and energy conservation and the second law of thermo-dynamics, has resulted in the following true extension of Darcy's law for two-phase flow.[1]

$$\vec{q}_\alpha = -\frac{k_\alpha \vec{K}}{\mu_\alpha} \bullet (\vec{\nabla} P_\alpha - \rho_\alpha \vec{g} - \lambda_\alpha^1 \vec{\nabla} S_\alpha - \lambda_\alpha^2 \vec{\nabla} \alpha^{wn})$$

In current theories the pressures of the two fluid phases are different because of the capillary pressure induced by the interfaces. Capillary pressure is assumed to be a function of saturation. However, thermodynamic theories have led to the following generalized equation for capillary pressure[2].

$$P_n - P_w = P_c(S_w, \alpha^{wn})$$

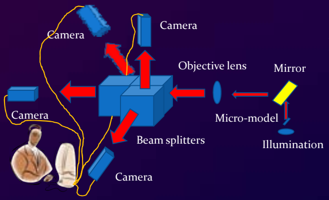
Experimental setup

Micro-model:

An elongated micro-model will be used with dimensions 1x10 mm^2. The micro model will be produced using photolithography techniques. First, a polymer layer will be applied on a glass slide. Then, regions of the polymer will be removed through photo-chemical reactions to create a 2D pore network. The geometry of the network will be determined by Delaunay triangulation. Three different configurations will be used with three different mean pore size of 2.5μm, 8.5 μm and 14.5 μm.

A drawing of the flow network and the inlet and outlet areas. This drawing will be used as a mask in order to produce the actual micro-model.

A drawing of the flow pattern which is based on Delaunay triangulation with 2000 pore bodies and 5956 pore throats.



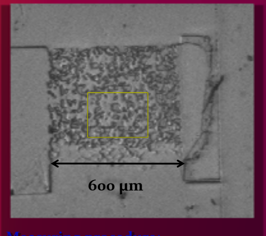
A schematic of the visualization setup.
The fourth camera will be mounted on top of the black box with the beam-splitters.
The mirror will be used in order to make the light beam horizontal.

Monitoring setup:

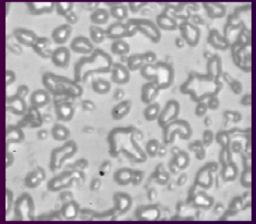
In order to be able to visualize the distribution of fluids inside the micro-model, four very high resolution CMOS cameras will be used. The cameras have a refresh rate of 15 frames per second, a very high resolution. The dimensions of the micro-model and the dimensions of the cameras make it impossible to put the cameras next to each other. For this reason, three beam-splitters will be used in order to split the initial image into four identical ones, magnified by a factor of five. Each camera will be able to monitor 1x1.68 mm^2 of the initial image with the needed resolution. By focusing each camera on a different part of the micro-model, a total area of 1x6.7 mm^2 will be monitored.

The cameras are put on translation stages in order to be able to focus and monitor a specific area of the flow-network. Windows are mounted so that their sensors will be kept free of dust.
In the black box, three beam-splitters are placed in a way that the cameras can receive the optical signal.
These beam-splitters are of good optical quality (loss of signal less than 5% per direction) and are covered with this black box in order to avoid any unwanted internal reflection that could distort the image.

With the use of a plano-convex lens with a diameter and focal length of 50 mm, a micro-model fabricated for testing purposes with dimensions of 600 x 600 μm^2 was visualized. Given the fact that the smallest dimension of the flow-network will be around 2 μm, a resolution of 0.7 μm / pixel is needed. Given the dimensions of the flow network in the testing micro-model and the size of the image on the sensor of the camera, this resolution was easily achieved. In the examples below, the lowest magnification factor is seven.



This picture from the micro-model was taken with one of the cameras. The magnification factor is close to seven.
By changing the distance between the lens and the camera, and between the lens and the micro-model we can get an even higher resolution without using digital means. In this way, the efficiency of the setup was tested with more than satisfying results.



A collimated light source. where light beams are parallel to each other, will be used. Collimation is necessary in order to avoid any optical aberration introduced by the light source. The wavelength (λ) of the source will be 570 nm. The choice of this wavelength is made based on two facts. The first is that if the wavelength of the light source is close to the violet/ultra-violet region, this will initiate a reaction in the photo-resist in the micro-model that produces nitrogen bubbles. Since the micro-model is sealed, these bubbles finally destroy the flow pattern in their effort to escape. The second reason is that if the wavelength of the light source is close to the red/infrared region, the discrimination efficiency of the setup is lower and this lowers the resolution. From the following equations it is obvious that as the wavelength becomes higher, the distance (R) between two points that is needed in order to be identified as individual points becomes bigger, which means that the resolution decreases.

Numerical aperture **(A)** is the ratio of the focal length of a lens over its diameter. It is a function of the optical medium, by means of its refractive index **(n)**, in which the lens is working and an angle **(Φ)**. **Φ** is the angle of the maximum cone of light that can enter or exit a lens with respect to a specific point P. For a given Numerical Aperture **(A)** in the same optical medium **(n)**, **R** becomes bigger for bigger wavelengths **(λ)**. A convenient compromise is to choose a wavelength of **570 nm**.

$$A = n \sin \frac{\Phi}{2}$$

$$R = 0.61 \cdot \frac{\lambda}{A}$$

Measuring procedure:

The micro-model will be filled with a wetting phase, and then a non-wetting phase will be injected. As the micro-model is transparent, it can be photographed and observed through the CMOS cameras. All the cameras will be connected to a central processing unit for the acquisition of data and to monitor continuously the synchronization between the cameras.
This experiment will be a dynamic one. With the use of the photographs and the proper software for image analysis, the evolution of saturation and interfacial area in time and space will be determined.

1.Hassanizadeh and Gray, Mechanics and thermodynamics of multiphase flow in porous media including interphase boundaries, Adv Water Resour.,13, 169-186, 1990.
2. Hassanizadeh and Gray, Towards and improved description of the physics of two-phase flow, Adv. Water Resour. 16:53-76,1993b