AIR-OIL FLOW SIMULATION IN A POROUS COLUMN

Ryabikina A.S.
Scientific advisor: Ogorodnikov A.S., Candidate of Physical and Mathematical Sciences, Associate Professor
Linguistic advisor: Marugina N.I., Candidate of Philological Sciences, Associate Professor
National Research Tomsk Polytechnic University, Russian Federation, 634050, Tomsk, Lenin Avenue, 30
E-mail: ryabikina11@mail.ru

In general, porous medium stands for a solid object that contains pores or voids. Studies of flows in porous media form the basis in soil mechanics, industrial filtration, groundwater hydrology, water treatment and others. In oil extraction, flow modeling is used to model processes when water or gases are entered to the oil-saturated medium in order to displace and collect oil [1].

Phase is one of the substance states which could be liquid, solid or gaseous. Multiphase flow is a simultaneous flow of a few liquid-and-gas mixture phases [2].

The whole experiment is divided into 2 parts: the first one employs water and air while the second one includes air and oil. As two substances take part in this experiment one of them is referred to as 'wetting fluid' (water or oil) while another one is referred to as 'nonwetting fluid' (air). To study processes that occur in multiphase flows peculiar experimental setups are constructed the way as it is shown in Fig.1.

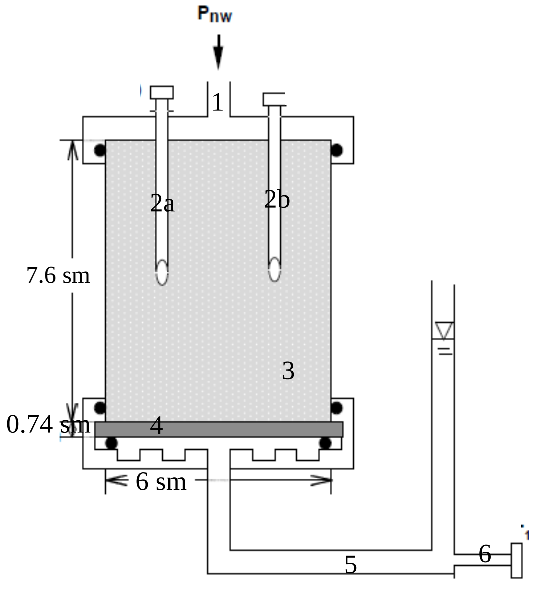

Fig.1. Experimental Setup

The experimental setup consists of: 1 – inlet; 2a, 2b – pressure sensors; 3 – soil column; 4 – ceramic disk; 5 – buret; 6 – wetting phase pressure sensor.

Initial time, the soil column posed on a ceramic disk 4 is saturated with the wetting fluid located in the receiving buret 5. Then, air is injected over the surface of the laboratory column 3 through the inlet 1 from 0.2 meters height under pressure of $p_{nw}(t)$. Air pressure is increased in time in order to observe the wetting fluid pressure behavior. The two-phase flow experiment covers 170 hours [3].

The following equations describe two-phase flows in porous media for the wetting fluid and the nonwetting fluid respectively [3]:

$$C_{p,w}\frac{\partial}{\partial t}(p_{nw}-p_w)+\nabla\cdot\left[-\frac{\kappa_{int}k_{r,w}}{\eta_w}(\nabla p_w+\rho_w g\nabla D)\right]=0,$$

$$-C_{p,w}\frac{\partial}{\partial t}(p_{nw}-p_w)+\nabla\cdot\left[-\frac{\kappa_{int}k_{r,nw}}{\eta_{nw}}(\nabla p_{nw}+\rho_{nw} g\nabla D)\right]=0,$$

where $C_{p,w}$ ($C_{p,nw}$) – wetting (nonwetting) fluid specific capacity (1/Pa); t – time (hrs); κ_{int} – intrinsic permeability of the porous medium (m^2); $k_{r,w}$ ($k_{r,nw}$) – relative permeability function for the wetting (nonwetting) fluid; η_w (η_{nw}) – dynamic viscosity for the wetting (nonwetting) fluid (kg/m*s); p_w (p_{nw}) – wetting (nonwetting) fluid pressure (Pa); ρ_w (ρ_{nw}) – wetting (nonwetting) fluid density (kg/m^3); g – acceleration of gravity (m/s^2); D – the coordinate (for example, x, y, or z) of vertical elevation (m).

The boundary conditions allow the water to exit only from the base of the soil column. For the wetting phase, the boundary conditions are [3]:

- for the inlet and sides

$$\mathbf{n}\cdot\left[-\frac{\kappa}{\eta}(\nabla p_w+\rho_w g\nabla D)\right]=0,$$

- for the base

$$p_w=0.1*\rho_w g,$$

where **n** is the unit vector normal to the boundary.

Because air enters at the column top but never exits, the boundary conditions for the nonwetting phase are [3]:

- for the inlet

$$p_{nw}=\rho_{nw} g h(t),$$

- for the base and sides

$$\mathbf{n}\cdot\left[-\frac{\kappa}{\eta}(\nabla p_{\mathrm{nw}} + \rho_{\mathrm{nw}}\, g\nabla D)\right] = 0,$$

where $h(t)$ - pressure head (m water).

Initial time, wetting fluid pressure is [3]:

$$p_w^{init} = -\rho_w g D.$$

Initial condition for air pressure is [3]:

$$p_{nw}^{init} = 0.2\rho_w g + (8.34 - D)\rho_{\mathrm{nw}} g,$$

where 0.2 – the first air pressure head (m water);
8.34 – soil column length (m).

When switching between air/water and air/oil experiments, the authors used clever scaling with interfacial tensions according to Leverett. The Leverett scaling adjusts the nonwetting phase pressure at the column top to produce the same volume of wetting fluid outflow at the column bottom regardless of the fluid pair [4]:

$$\sigma_{ao} p_{c,aw} = \sigma_{aw} p_{c,ao},$$

where σ_{ao} – interfacial tension between air and oil ;
$p_{c,aw}$ – capillary pressure for air/water system;
σ_{aw} – interfacial tension between air and water ;
$p_{c,ao}$ – capillary pressure for air/oil system.

Considering aforementioned assumptions, boundary conditions for the nonwetting phase in the air/oil system will take the form:

$$p_{\mathrm{nw}} = \frac{\sigma_{ao}}{\sigma_{aw}} \rho_{\mathrm{nw}} g h(t).$$

Meantime, air initial conditions for air/oil system will be:

$$p_{nw}^{init} = \frac{\sigma_{ao}}{\sigma_{aw}} 0.2\rho_w g + (8.34 - D)\rho_{\mathrm{nw}} g.$$

Such equations are difficult to solve because of its nonlinearity, however computers allow to find a solution via approximate numerical methods. Finite element method (FEM) built-in Comsol Multiphysics is one of them.

To prove model robustness via comparison with other authors experimental observations were made for air/water system. The experiment showed that results corresponded to the outputs obtained by other researchers thus the created model can be used for further observations and substances may be varied.

After that the model was modified so that the wetting fluid would be represented with oil instead of water. At the very beginning of the experiment, oil concentration was higher at the bottom of the laboratory column as it goes to the column from below.

The study output is oil pressure in the laboratory column at 170 hours (Fig.2).

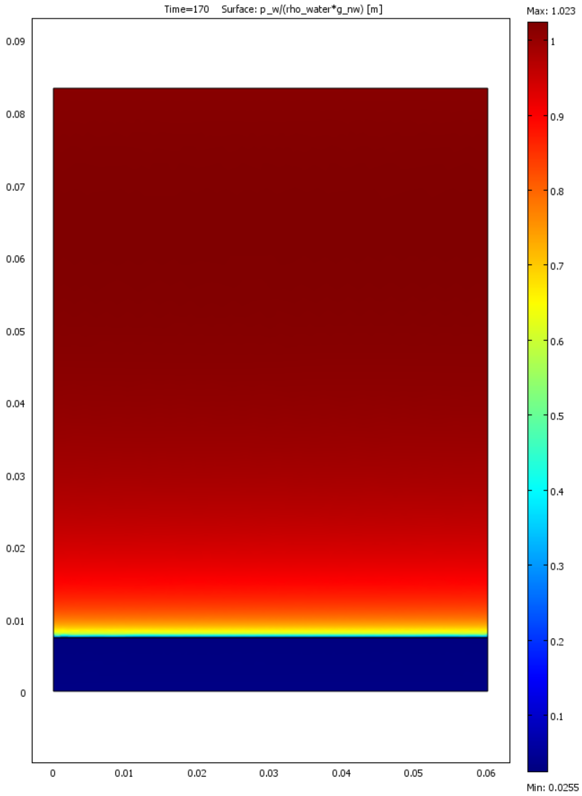

Fig.2. Oil pressure distribution ($t = 170$ hrs)

Conclusively, the experiment showed that despite air injection through the column's inlet, oil concentration is higher on top of the column thus the model can be used to study problems which require oil or any other substance extraction.

References

1. Scheidegger, A. The physics of flow through porous media.- Moscow: State Scientific and Technical Publisher of Petroleum and Technical Bibliography, 1960.
2. Kluev, N. & Solovieva, E. Mathematical models of two-phase flows.- Samara: Samara university, 2009.
3. Hopmans, J. Parameter estimation of two-fluid capillary pressure saturation and permeability functions.- Cincinnati: U.S. Environmental Protection Agency, National Risk Management Research Laboratory, 1998.
4. Leverett, M. Capillary behavior in porous solids. Transactions of the AIME. [Online]. p.152-169. Available from: https://www.archive.org. [Accessed: February 2014]