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Two-phase non-Darcy flow in heterogeneous porous media: A numerical investigation

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Significant inertial effects are observed for many applications such as flow in the near-wellbore region, in very permeable reservoirs or in packed-bed reactors. In these cases, the classical description of two-phase flow in porous media by the generalized Darcy's law is no longer valid. Due to the lack of a formalized theoretical model confirmed experimentally, this study is based on a generalized Darcy-Forchheimer approach for modelling two-phase incompressible non-stationary inertial flow in porous media. In this model, the momentum conservation equation for each phase, α, has a quadratic correction to generalized Darcy’s law and is expressed as: (α =”w” for water or “o” for oil):

$$-(\vec{\nabla}P_\alpha(\vec{x},t) - \rho_\alpha \vec{g}) = \mu_\alpha \overline{\overline{K_\alpha}}^{-1} \cdot \vec{V}_\alpha(\vec{x},t) + \rho_\alpha \left\|\vec{V}_\alpha(\vec{x},t)\right\| \overline{\overline{\beta}}_\alpha \cdot \vec{V}_\alpha(\vec{x},t) \quad (1)$$

This equation is completed with the mass conservation equation for each phase given by

$$\frac{\partial}{\partial t}(\phi S_\alpha) + div\vec{V}_\alpha = 0 \quad (2)$$

and the capillary pressure and saturation relationships

$$P_c(S_w) = P_o - P_w \quad (3)$$

$$S_w + S_o = 1 \quad (4)$$

Using a finite volume formulation, an IMPES (IMplicit for Pressures, Explicit for Saturations) scheme and a Fixed Point method for the treatment of non-linearities caused by inertia, a 3D numerical tool has been developed. For clarity, results are presented in 1D and 2D configurations only.

For 1D flow in a homogeneous porous medium, a validation is performed by comparing numerical results of the saturation front kinetics with a semi-analytical solution inspired from the “Buckley-Leverett” model extended to take into account inertia. The influence of inertial effects on the saturation profiles and therefore on the breakthrough curves for homogeneous media is analysed for different Reynolds numbers, thus emphasizing the necessity of taking into account this additional energy loss when necessary. For 1D heterogeneous configurations, a thorough analysis of the saturation fronts as well as the saturation jumps at the interface between two media of contrasted properties highlights the influence of inertial effects for different Reynolds and capillary numbers.

In 2D heterogeneous configurations, saturation distributions are strongly affected by inertial effects. In particular, capillary trapping of the displaced fluid observed for the Darcy regime in certain regions can completely disappears when inertial effects become dominant.

Keywords: Inertial two-phase flow - Heterogeneous porous media - Numerical simulations - Generalized Darcy-Forchheimer model.