ImproDeProF Project: Recent Advances and New Challenges in the development of the DeProF tentative theory for steady-state two-phase flow in porous media

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Abstract

The majority of industrial applications of two-phase flow in macroscopically heterogeneous porous media are based on inherently transient processes. Nevertheless, to understand the physics of such processes in a deeper context, we need first to understand the stationary case, steady-state flow in macroscopically homogeneous media. To this play, the *DeProF* theory implements hierarchical mechanistic modeling, i.e. scaling-up from pore- to core- to fracture scales, to predict relative permeabilities in terms of the values of the operational parameters (capillary number and flowrate ratio), given the values of the system parameters. This synopsis focuses on latest research advances within the development of the *DeProF* tentative theory, with scope in disseminating a portfolio of emerging research challenges and potential applications.

Introduction

To date, the characterization and modeling of multiphase flows in porous media has delivered promising theoretical and experimental results over a hierarchy of scales (pore-to-production). Nevertheless, integration across those scales remains an outstanding problem. Likewise, technological progress has enabled laboratory studies to expose latent flow mechanisms; pore-scale phenomena and critical interstitial physical quantities can now be identified and assessed digitally, computationally or experimentally. At the same time, pragmatic sustainability issues on energy production/management shifted "recovery increase" trends into "process efficiency optimization" scopes and targets. As a consequence, new challenges emerge within a wide spectrum of technological problems, extending from laboratory scales, e.g. design systematic protocols for regular/special core analysis (R/SCAL) for data collection/interpretation, to industrial scales, e.g. unconventional/ enhanced oil recovery (EOR) /carbon capture & sequestration (CCS), soil & aquifer pollution & remediation or operation of trickle-bed reactors (Valavanides *et al.*, 2015a)

To address these issues we need to think "out of the box" and decide to explore the untapped potential of theoretical tools and methodologies translated from other scientific fields. Some of the current approaches in modeling multi-phase flow propose a number of disruptive directions, such as:

- Disconnected flow - a substantial and many times prevailing flow pattern (Georgiadis *et al.*, 2013, Youssef *et al.*, 2014, Tsakiroglou *et al.*, 2007).
- Inherent degrees of freedom - nested within the physics of multi-phase flows, they are expressed on the process stationary character even under steady-state flow conditions (Van de Merwe and Nicol, 2009, Valavanides, 2012).
- Independent variables - reappraise the set without surrendering a specific-enough representation of the process phenomenology by oversimplification (Valavanides, 2012).

Without neglecting the fact that the majority of industrial applications of two-phase flow in macroscopically heterogeneous porous media are based on inherently transient processes, to understand the physics of such processes in a deeper context, we need first to understand the stationary case, steady-state flow in macroscopically homogeneous media.
To this play, the *DeProF* theory (Valavanides, 2012) implements hierarchical mechanistic modeling, i.e. scaling-up from pore- to core- to fracture scales, to predict relative permeabilities in terms of the values of the operational parameters (capillary number and flowrate ratio), given the values of the system parameters.
This research synopsis will focus on latest advances, indicative applications and future challenges in the development of a tentative theory for two-phase flow in porous media, namely the *DeProF* theory.

Results

The research was carried during the past 5 years, mainly under the ImproDeProF project (2015). It is the result of collaboration of a research group spanning 5 research organizations (see Acknowledgment). The results of the ImproDeProF project are as follows:

Theoretical developments

The delivery and proof-of-concept on the existence of a universal map that describes process performance and delineates its operational efficiency was furnished by Valavanides (2014b), including the delivery of a normative methodology for characterizing a process as to the predominance of capillarity or viscosity as well as its untapped efficiency margin.
Synergy with statistical thermodynamics will eventually correlate the multiplicity of physically admissible, internal flow arrangements with the existence of optimum operating conditions (Valavanides, 2010). In this context, Daras and Valavanides (2015) identified the ensemble of physically admissible microstates for the sought process and furnished an analytical methodology –based on combinatorics- to estimate their number. This is a prerequisite step taken towards developing a robust theoretical justification of the *DeProF* model predictions.

Laboratory work – experimental developments

Tsakiroglou *et al.*, 2015, have performed laboratory experiments of steady-state two-phase flows in packed sand columns with equal viscosity fluids to quantify the dependence of oil and water relative permeability on capillary numbers, and correlate the estimated parameters of power functions with the viscosity ratio. They provided new explicit relationships of relative permeabilities and water saturation with oil and water capillary numbers to set the bases for a new conceptualization of the two-phase flow at reservoir-scale where the mobility of the fluids is decoupled from saturation and become non-linear functions of the local flow rates.
Valavanides *et al.*, 2015b have provided a major re-examination of available experimental data on the phenomenology of steady-state two-phase flow in porous media processes, recorded in the conventional relative permeability diagrams. The objective was to test the *DeProF* model predictions (hypothesis) on the existence of steady-state flow conditions, for which the energy efficiency of two-phase flow in porous media processes attains a maximum value. The acquired data were transformed into energy efficiency data sets for the corresponding system and flow settings. This re-examination of relative permeability data sets from a total of 179 relative permeability diagrams in 35 published laboratory studies, pertaining to a variety of steady-state two-phase flow conditions and types of porous media, provided extensive experimental evidence on the existence of optimum operating conditions as well as on distinct trends of the energy efficiency over the pertinent flow regimes and system configurations.

Application developments

Within the ImproDeProF project, potential applications of the *DeProF* theory in process design and optimization have been furnished. The applications are focused on the exploitation of the true-to-mechanism description of the sought process in terms of the actual independent variables, i.e. the capillary number, Ca, and the flowrate ratio, r, as well as the incorporation of multi-physics modeling, in improving process efficiency (Valavanides and Skouras, 2014), and in providing more reliable simulations of industrial processes of two-phase flows in porous media (Valavanides *et al.*, 2015c, Skouras *et al.*, 2015a,b).

Other (translational) developments

The problem of saturated flow within a homogeneous and isotropic pore formation, confined between two horizontal impermeable planes, under 7-spot injection-extraction well pattern, has been considered by Kamvyssas and Valavanides, 2015. To deal with this unconventional geometry, a new method, for boundary value problems for the Laplace, the Helmholtz and the modified Helmholtz equations in the interior of an equilateral triangle, was implemented.
In an effort to examine the transfer of project results into other scientific areas, implementation of the maximum entropy production principle has been shown to provide a potential for optimizing project portfolio management (Valavanides, 2014a).

Concluding Remarks

The *DeProF* model has been developed on the purpose of providing a mechanistic modeling tool that could explain (on physical principles) the complicated phenomenology observed in two-phase flows in porous media (Valavanides, 2012). It turned out that the *DeProF* model was self-contained and rigorous enough to be further exploited as a simulating tool, with the capability to reveal latent process characteristics. Further downstream the evolution path, the *DeProF* model, harnessed with a rational theoretical framework (namely, the maximum entropy principle), eventually evolves into a new theory. The *DeProF* theory for steady state two-phase flow in porous media is consistent with the pre-existing theory (Darcy's fractional flow formulation) (nevertheless, it shows conventional wisdom to be not complete), shows remarkable specificity, is tentative and dynamic in allowing for changes as new facts are discovered, has the potential to serve as the current (for-the-time-being) theory for steady-state two-phase flow in porous media.
The proof of progress and the results accomplished to date, show that there are many potential applications of this new theory in numerous theoretical and application oriented developments.

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