Comments on

"Analysis of Fundamentals of Two-Phase Flow in Porous Media Using Dynamic Pore-Network Models: A Review" by V. Joekar-Niasar and S. M. Hassanizadeh (2012) *Crit. Rev. Env. Sci. Tech.* 42:18 pp. 1895–1976

by

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Abstract

The aim of the present comment is to clarify misinterpretations regarding the structural features and performance of two mechanistic models for steady-state two-phase flow in pore networks, specifically the model for ganglion dynamics and the model implementing the concept of decomposition in prototype flows (DeProF model) developed by M.S. Valavanides and A.C. Payatakes and to argue on certain viewpoints regarding the applicability of the Payatakes group research works on network models.

Keywords pore-network models, two-phase flow, connected oil flow, disconnected oil flow, oil ganglia, oil droplets, relative permeability, capillary number

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Introduction

In their paper, Joekar-Niasar and Hassanizadeh (2012) review pore-network models and, in particular, their use as analytical tools in understanding the fundamentals of dynamics of two-phase flow in porous media in pore- and REV- scales. They address the following issues: classification of dynamic pore-network models according to structure, computational algorithm and local rules and applications; configurational properties of networks and computational algorithms employed; effects of flow and system parameters; topology of the invasion front (macroscopic interface dynamics); disconnected oil flow (ganglia flow dynamics); state-of-the-art in dynamic pore-network modelling; computational aspects of dynamic pore-network models and complex invasion mechanisms at pore scale. They conclude with a discussion of new challenges on network geometry and topology, computational costs, experimental benchmarking and validation of simulations and complexities of physics of two-phase flow dynamics.

Within the scope of the present comment, I will try to clarify some misinterpretations regarding the characteristics, performance and potential use of two models, the ganglia population balance ("GPB") kinematics model and the decomposition-into-prototype-flows mechanistic model ("DeProF"), both developed to describe steady-state two-phase flow in porous media for different degrees of disconnections of the non-wetting phase. In addition, I will argue upon certain viewpoints regarding the applicability of the Payatakes group research works, in particular on network models.

The comments will be focused on quoted passages exactly as they appear in the original document (in italics). The core subject of each commentary is underlined in the quoted text.

Note that the recurrent misprint [Valvanides, M.S.] should read [Valavanides, M.S.]

Comment C.1

In the 3rd paragraph of page 1904 it is stated:

> *"There are some other pore-network models, which do not explicitly consider pore bodies and pore throats. In these models, it is assumed that pore elements have varying cross sections; the narrowest part is located in the middle and it diverges toward both ends, which may be considered to play the role of a pore body (e.g.,*

Aker et al., 1998a, 1998b; Al-Gharbi and Blunt, 2005; Knudsen et al., 2002; Knudsen and Hansen, 2002; Valvanides et al., 1998). But, no specific geometry or configuration has been assumed at the connection point of these pore elements. In this article, these pore elements are referred to as composite pores."

The subject of the work of Valavanides *et al.* (1998) is the introduction /presentation of a mechanistic model for the description of steady-state two-phase flow when the non-wetting phase (oil) is totally disconnected into larger or smaller ganglia. Conceptually, the model is based on ganglion population balances (GPB) and the numerical solution of the integro-differential ganglia population balance equations (PBEs), originally furnished by Payatakes and coworkers (1980, 1982). The fundamental information on the cooperative flow behaviour of the two fluids at the scale of a few hundred pores is expressed through appropriate system factors, utilized by the PBEs to predict the macroscopic behaviour of the process. The values of these system factors are provided as functions of the macroscopic flow conditions (e.g. Figure 30 in the commented review paper) and comprise the necessary input to the ganglia PBEs. These functions are delivered from statistical elaboration of the numerical simulations of steady-state two-phase flow using the pore network simulator developed by Constantinides & Payatakes, 1996 (e.g. Figure 31 in the commented paper). The ganglion population balance (GPB) model is a *kinematics* model. It can only predict/deliver values for kinematic variables (mobilized and stranded ganglion size distributions, saturations etc.); it cannot predict the pressure field or any other kinetic variable. Its operation depends on input provided by appropriate dynamic pore network simulators such as the simulator of Constantinides & Payatakes, 1996, and, in that sense, it is not a self-contained model for two-phase flow in porous media with totally disconnected non-wetting phase.

Therefore, it would have been more consistent to reference the work of Constantinides & Payatakes, 1996, instead of Valavanides *et al.*, 1998. In the latter work, there is essentially no direct use/application of pore network modeling. The same comment, i.e. referencing the former work instead of the latter, applies for the 9th-row entry in Table 4, page 1967, in the commented paper.

Comment C.2

When discussing the influence of pore-network structure on the computational complexity and, specifically, the assignment of volume and/or resistance on pore elements (chambers

and throats), in lines 12-14 of paragraph "3.5 Geometry and Conductivity Assumptions", page 1913, the authors state that

"the only case, where volume and resistance were assigned to both pore bodies and pore throats, is the work of Mogensen and Stenby (1998)."

My comment is that there are also other works where volume / resistance are assigned to pore-bodies (chambers), e.g. Al-Gharbi & Blunt, 2005, Constantinides & Payatakes, 1989, 1996 & 2000 and Valavanides & Payatakes, 2001.

Focusing in the latter work, distinct analytic expressions for the conductivities of pore throats and pore chambers were included in the virtual pore network model implemented in the DeProF simulations. These expressions are indexed in the referenced paper as eqn(13) for the reduced unit cell conductances for one-phase flow and as eqn(35) for the reduced unit cell conductances when disconnected oil flow takes place. The expression in eqn(35) comprise two terms, A_{jik}^{b} and B_{n}^{b}. Term, A_{jik}^{b}, represents the reduced bulk phase resistance of a jik-class cell for different flow configurations, indexed with b, or equivalently, the effect of bulk viscosity in the overall conductivity. Term B_{n}^{b}, represents the reduced interfacial resistance of any n-ganglion conducting cell for different flow configurations, b. The term "interfacial resistance" stands for the resistance attributed to the interfacial hysteresis effects – expressed by the difference between the receding and advancing contact angles. In both terms, the geometry of each of the two chambers (indexed as j, k) and the throat (indexed as i) is explicitly accounted for [see equations (13) and (A.4)-(A.6) in Valavanides & Payatakes, 2001].

Comment C.3

In the second paragraph of page 1953 it is stated:

> *"The resulted populations dynamics equations for moving and stranded ganglia were integro-differential type of equations that were solved numerically.*
> *For sake of space the equations and their explanations have not been mentioned in this review. Complete explanation can be found in Payatakes et al. (1980) and Valvanides et al. (1998). Using the population dynamics equation, Valvanides et al. (1998) investigated fate of stranded as well as moving ganglia with space and time for two different types of regime: steady-state fully developed (SSFD) and steady-state non-fully developed (SSnFD). Under SSFD conditions, number*

concentrations of moving and stranded ganglia are independent of time and space. However, under SSnFD conditions, number concentrations of moving and stranded ganglia are only independent of time."

The purpose of this comment (better, note) is to address a characteristic that will prove useful in discussing comment C.5. The set of ganglion population balance equations describes the *kinematics* of the disconnected oil flow (see Comment C.1). In the referenced work (Valavanides *et al.*, 1998), the evolution of ganglion size distributions was examined as different "seed" patterns (triangular, uniform & unimodal) were continuously injected within the water flood under fixed, but non-fully developed, flow conditions (SSnFD conditions). The main results were: (a) fully developed conditions set up at relatively short lengths of only a few hundreds of pores downstream the ganglia injection line source and, (b) the SSFD ganglion size distributions depend only on the imposed macroscopic flow conditions, irrespective of the injected ("parent" or "seed") ganglion size distribution patterns. Based on those results and on a closer observation of the interim ganglion size distributions (see Fig. 14 in Valavanides & Payatakes,1998), one may infer that, if ganglion size distributions are not significantly perturbed from their fully developed configuration, then, any such perturbation would vanish in very short lengths, say some tenths of pores downstream. This is in compliance with the concluding suggestion of the authors (in 9.2 Outlook & Challenges – Computational costs) that *"In some works [ref. Gielen et al., 2005, Joekar-Niasar et al., 2010b] the REV size for the pore network can be a cube with 30-35 pore bodies in each direction*". This inference is still more important when the consistency of continuum-scale models (such as DeProF) is considered. A few tenths, or even a few hundreds, of pores correspond to length scales many orders of magnitude smaller than the macroscopic scale implemented by continuum-scale models. Therefore, it can be safely assumed that, interstitial configurational flow variables, such as the ganglion size distribution, will "immediately", or at infinitesimal lengths on a continuum scale, adapt to changes imposed on the flow conditions at the macro-scale. This characteristic will prove useful in discussing the next comment (C.5 – 3rd bullet point).

Comment C.4

In the second paragraph of page 1957 it is stated:

"Afterwards, Valvanides and Payatakes (2001) developed a continuum two-phase flow model, which included the nonlinear dependence of permeability

coefficients. Their model was based on the decomposition of a two-phase system into two sub-domains: connected-oil path domain and ganglion dynamics domain. The main goal in their model was to save computation time to have a mesoscale predictive model that for practical applications (...?). The model results were compared with experimental results done in a two dimensional micro-model by Avraam and Payatakes (1995a). They founded fairly good to good agreement with experimental results for low capillary numbers ($Ca=10^{-6}$) at different viscosity ratios (Fig. 37b,e). It seems that for high capillary numbers, where ganglia dynamics can be important, the model was not fully successful and there was a need for further improvement before it could be used for predictive purposes (Fig. 37c)."

The referenced model (Valavanides & Payatakes, 2001), based on the concept of decomposition of the macroscopic flow into prototype flows, hence the acronym *DeProF*, does not include any *a priori* dependence of the relative permeability coefficients on system parameters. In essence, values of the relative permeability coefficients are determined from the conventional fractional flow Darcy relation given the macroscopic pressure gradient for oil and water. The latter is computed by implementing the DeProF algorithm for each set of imposed flowrates of oil and water. The computational effectiveness of the DeProF algorithm (up to ~5 mins per complete simulation on a typical desktop computer, depending on the values of system and operational parameters) is based on an inherent hierarchical theoretical modeling approach (Payatakes *et al.*, 1998): at a pore scale level, the different configurations of two-phase flow within classes of unit cells [imbibition and drainage invoking larger oil blobs (ganglia and large droplets) within pores, and core annular flow of tiny oil droplets within pore throats] are modeled by implementing relatively simple computational schemes, i.e. lubrication approximation of Stokes flow and Young-Laplace law for the interfacial tension, to derive the corresponding unit cell conductances (nevertheless, modern CFD techniques can also be applied); then, the fractional distribution of conductances are scaled-up, using effective medium theory and mass & flowrate balances, into a macroscopic description of the flow to reveal/detect all the physically admissible flow configurations, consistent with the externally imposed flow conditions; finally, the canonical ensemble of physically admissible flow configurations is integrated into a corresponding average (or effective) configuration of the macroscopic flow (ergodicity).

Addressing the subject of experimental validation of the DeProF model, the reference to Figure 37(b, e) in page 1958 of the commented paper is erroneous and may confuse the reader. In it there is no comparison between DeProF predictions and experimental data, but the presentation of the data of the experimental study conducted by Avraam & Payatakes (1995), addressing the correlation between the conventional & generalized relative permeability coefficients and the operational & system parameters. The appropriate reference, whereby the validation of the DeProF model predictions against experimental measurements is shown, is Figure 8, page 402, in Valavanides & Payatakes, 2001. For convenience, the particular figure is reproduced here[1] as Figure 1(a). With reference now to Figure 1(a), indeed the DeProF predictions are fairly good to good, this is rightfully correct for the higher part of the range of Ca values examined and/or favorable o/w viscosity ratio ($\kappa = M^{-1} = \mu_o/\mu_w < 1$). The predictions in Valavanides & Payatakes, 2001, were delivered by using the first version of the DeProF model that incorporated only two prototype flows, connected pathway flow (CPF) and ganglion dynamics (GD). In addition, in an effort to represent the unit-cell of the actual glass micro-model used by Avraam & Payatakes (1995) with a simple geometry, the virtual pore network implemented in the DeProF simulations was of the "blister-and-flat-stick" type whereby all unit-cells comprised quarters of two very short normal cylinders (as chambers) interconnected with a throat of fixed elliptic cross section. Although there were concerns on whether all the actual flow mechanisms were adequately incorporated in the virtual model (see also Comment C.5), still this was considered to be an acceptable modeling approximation, at least for evaluating the potential of that first version of DeProF. Discrepancies observed between model predictions and actual (measured) values, bottom-left corner diagram in Fig. 1(a), indicated the need for further improvement. The DeProF model was improved in a follow-up work[2], Valavanides & Payatakes, 2000, by including the contribution of the motion of oil droplets within the disconnected oil flow. In this later version, the total flow is decomposed in three prototype flows, i.e. connected

[1] *Note to the editor*: should the reviewers of the present manuscript, see no need for reproducing these figures, these can be omitted. The originals for Figures 1(a) & (b) can be found in the literature: Fig. 8, Valavanides & Payatakes, 2001 and Fig. 3, Valavanides & Payatakes, 2000; the latter is also readily available as Fig. 5, in Valavanides, 2012.

[2] The publication (reference) dates are not representative of the actual DeProF model development history. The original manuscript of the 1st version of DeProF model incorporating CPF+GD prototype flows (Valavanides & Payatakes, 2001), was sent on August 1999 and its revision on March, 2000. This paper was published later than the 2nd version of DeProF incorporating CPF+GD+DTF prototype flows (Valavanides & Payatakes, 2000).

pathway flow (CPF), ganglion dynamics (GD) and drop traffic flow (DTF). Predictions are much better, see Fig. 1(b), reproduced from the original, Fig. 3 in Valavanides & Payatakes, 2000.

The predictive accuracy of simulations with the CPF-GD-DTF DeProF model, implementing network geometry and system of fluids identical to those used in Valavanides & Payatakes, 2001, is excellent when benchmarked against the laboratory measurements of Avraam & Payatakes (1995), see Figure 1(b). [Note that, in the diagrams in Figure 1(b), no fitting or interpolation was implemented whatsoever.] The conference paper presenting this improved version of DeProF (implementing CPF, GD & DTF), is not easily accessible and the particular diagrams [Figure 1(b)] were reproduced in a recent publication [Valavanides (2012, Figure 5)]. Following 2001, all works using the DeProF model are implementing the decomposition of the flow into all three of the prototype flows (CPF, GD & DTF).

In addition, one may claim that the predictions of the DeProF model are globally robust and consistent. These claims are advocated by simulations over an extended domain of the operational variables Ca and r, for various viscosity ratios, $\kappa = \mu_o/\mu_w$, for different unit cell geometries (2D pore networks implementing "blister-and-flat-stick" type u.c. and 3D networks implementing "ball-and-stick" type u.c.) and different wetting conditions. The results of the aforementioned simulations have been published in Valavanides & Payatakes, 2002(a), 2002(b) & 2004. The consistency and robustness of the predictions is such that -one may figuratively say- they "challenge" the effectiveness of laboratory studies –at least for cases when the latter do not comprise an extensive parametric study. In essence, the DeProF model predictions may be implicitly validated by comparison with many preexisting laboratory studies of steady-state two-phase flow in pore networks and porous media, at least for externally measured physical quantities (power dissipation, pressure drop, etc.), see Fig. 7 in recent publication by Valavanides (2012).

Comment C.5

When discussing the modeling complexities of two-phase flow, when invasion mechanisms at pore scale level are to be tackled, and reviewing the models developed by Payatakes and co-workers, (pp. 1962-1963, 2nd paragraph and associated bullet points in "9.1.3. COMPLEX INVASION MECHANISMS AT PORE LEVEL"), the following is stated:

"Other complexities in dynamics of two-phase flow, which are absent in quasistatic models, are related to the mobilization of a disconnected phase. This issue was studied extensively by Payatakes and his coworkers from 1980 to 2002. Generally, they focused on the mobilization of a disconnected phase (ganglia) and its contribution to dynamic effects in relative permeability curves. Despite the substantial works they performed, there are some major shortcomings in their approach such as the following:

- *Their micromodels and pore-network models had idealized and regular geometries. Thus, effects of topological and geometrical properties of porous media were not investigated. Since pore-scale phenomena (snap-off, invasion, corner flow) are highly dependent on pore geometry, shape factor, and aspect ratio, the results of their micromodels and network models are not directly applicable to most natural porous media.*
- *Their pore-network model was based on the single-pressure algorithm for circular cross sections. Thus, effects of corner flow, snap-off, capillary diffusion, and interface relaxation behind the invading interface could not be studied.*
- *Valvanides et al. (1998) and Valvanides and Payatakes (2001) used dynamic pore-network models to obtain statistical relationships for coalescence, breakup, and mobilization of ganglia as a function of ganglia size and flow velocity. They obtained statistical kernel functions and employed them in macroscopic equations of population dynamics of ganglia for one dimensional systems. However, they did not clarify how this approach can be followed in a three-dimensional system. Moreover, due to complexities of their approach, as well as dependence of kernel functions on geometry and topology of porous media, it seems that their methodology cannot be used for practical purposes.*
- *From a practical point of view, according to Al-Gharbi and Blunt (2005), the range of capillary numbers considered in the works of Payatakes and his co-workers are much larger than the range encountered in reservoir engineering; under small capillary numbers, mobilization of disconnected phase is not significant."*

The reviewers are referencing a variety of research efforts of the Payatakes group

spanning 2 decades (80's to early 00's). The following comments address each bullet point.

Comment on the 1st & 2nd bullet points:

The complexity of natural porous media makes the exact description of their pore structure extremely difficult if not impossible. For this reason, and in order to study -experimentally or theoretically- any associated transport processes, idealizations of the porous space must be adopted by appropriate network models, should these be laboratory micro-models or their equivalent theoretical conceptualizations (virtual models). The idea of "collapsing" an intractably large parameter space –necessary to fully describe a natural porous structure- into one which can be addressed in a coherent study is a subject of on-going research, the ultimate challenge being the ability to handle/tackle problems associated with the heterogeneities lurking across scales in small or large formations of natural porous media. A porous medium model must incorporate those geometric characteristics of the prototype that affect the essential features of the transport process under consideration, while it remains as simple as possible (as is recommended at the end of paragraph 1.2 of the commented paper, referencing Celia *et al.*, 1995). The micro-models developed and used by Payatakes and co-workers were "idealized" and had "regular" geometries up to the point where: (a) any sought geometry /topology would be reconstructed in a controllable /reproducible manner for laboratory use, (b) the phenomena observed within the specific system (comprising the network micro-model and fluids) could be modelled with a simple yet consistent and trust-worthy true-to-mechanism model, (c) any necessary computational /numerical analysis of the observed phenomena would be feasible with the available computational resources and (d) the models could be reproduced according to laboratory standards with the available technology.

The various glass network micro-models of the chamber-and-throat type -used by the Payatakes group- had these characteristics. Experimental investigation of the referenced pore-scale phenomena (snap-off, invasion, corner flow), as observed and studied using the glass network micro-models, may be found in the literature (Vizika *et al.*, 1994, Avraam *et al.*, 1994, Avraam & Payatakes, 1995, Tsakiroglou *et al.*, 1997, Tsakiroglou & Payatakes, 1998). These glass network micro-models incorporated all the pertinent characteristics of natural porous-media: tailor-made pore-size correlation, aspect ratio and genus, wall micro-roughness and angular pore cross-section (eye-shaped, similar to the 4th type of cross-sections depicted in Figure 5 of the commented paper).

Apart from glass network micro-models, the Payatakes group have also developed and used virtual (theoretical) pore network models for the study of the principal mechanisms of oil flow in various forms, from the basic modes of mobilization and migration of solitary ganglia, to organized patterns of migration of ganglia population. Addressing the 2nd bullet point, these virtual networks were constructed with unit cells made up of chambers connected with constricted tubes, (Dias & Payatakes, 1986), had randomized one- or two-layered lattice (Constantinides & Payatakes, 1989 & 1996, Vizika *et al.*, 1994) with variable coordination number and with either two types of wall microroughness (Constantinides & Payatakes, 2000) or fractal pore wall roughness (Tsakiroglou & Payatakes, 2000). These studies progressed in parallel to advances in computational technology.

Recent advances in imaging technology (X-ray micro-CT) have made possible the acquisition of interstitial images of natural porous media with resolutions of a few micrometers, e.g. Bauer *et al*. 2011 & 2012, Youssef e*t al*., 2010), providing (or "provoking") more accurate (albeit complicated) description of the pore structure (e.g. dual porosity networks within the pore-to-core scale were revealed). The results of studies combining steady- & unsteady-state lattice-Boltzmann simulations within virtual pore networks produced from micro-CT images, (Ramstad *et al.*, 2012) advocate the inferences derived from micro-model observations and network modelling. Nevertheless, the problem of deriving a "reduced" description of the "exact" intrinsic structure of natural porous media in order to study any associated transport process and flow mechanisms that would be complete, consistent, exact and practicable (efficient) is still (?) open. (The question mark is deliberately inserted to think on the possibilities we may still have in improving this situation.)

Addressing the last statement of the 1st bullet point, i.e. on the extent of direct applicability of the Payatakes group research works on natural porous media, the idea/concept, for developing these (micro- and virtual-) model networks as well as the mechanistic models, was to derive a theoretical foundation to infer the effects of pertinent flow mechanisms (taking place across pore- to core- or even to field- scales) in the macroscopic state of two-phase flow in porous media. To this end it would be worth identifying exponents of pore network modeling, or even of other approaches, that have succeeded in furnishing a complete, accurate and practicable (efficient) description of two-phase flow processes in natural porous media and that could be readily implemented in practical applications.

Comments on the 3rd bullet point:

Addressing the issue of system dimensionality, there are two aspects, microscopic and macroscopic dimensionality.

The effect of network dimensionality (microscopic dimensionality) was examined in (Valavanides & Payatakes, 2002) by comparing DeProF simulations (model incorporating CPF+GD+DTF prototype flows) for a 2D network implementing blister-and-flat-stick unit-cells, with simulations for a 3D network, implementing unit-cells of the ball-and-stick type. The simulations revealed quantitative but not qualitative differences. These differences are attributed partly to the mobilization of disconnected oil (ganglia and droplets) because of different types of unit-cells, and partly to differences in tortuosity because of different network dimensionalities.

Addressing the issue of dimensionality on the macroscopic scale, the DeProF model may be applied for two- or three-dimensional geometries (macroscopic dimensionality). It predicts the reduced macroscopic pressure gradient, x, in terms of the values of the operational parameters Ca and r, given the values of the system parameters, in the form of the following transfer function

$$x = x\left(Ca, r; \kappa, \theta_A^0, \theta_R^0, \mathbf{x}_{pm}\right) \tag{1}$$

where, $x = \left(-\partial\tilde{p}/\partial\tilde{z}\right)\tilde{k}\left(\tilde{\gamma}_{ow}Ca\right)^{-1}$ is the reduced macroscopic pressure gradient, $\tilde{k}$ is the absolute permeability of the porous medium, Ca is the capillary number, defined as $Ca = \tilde{\mu}_w\tilde{U}_w/\tilde{\gamma}_{ow}$ ($\tilde{\mu}_w$ is the viscosity of water, $\tilde{U}_w$ is the superficial velocity of water, and $\tilde{\gamma}_{ow}$ is the interfacial tension), $r = \tilde{q}_o/\tilde{q}_w$ is the oil/water flowrate ratio, $\kappa = \tilde{\mu}_o/\tilde{\mu}_w$ is the oil/water flowrate ratio, θ_A^0 and θ_R^0 are the advancing and receding contact angles and $\mathbf{x_{pm}}$ is a parameter vector composed of all the dimensionless geometrical and topological parameters of the porous medium affecting the flow (e.g. porosity, genus, coordination number, normalized chamber and throat size distributions, chamber-to-throat size correlation factors, etc). Now, since the DeProF algorithm is computationally efficient, it is easy to deliver look-up tables in the form $x_{ij}(Ca_i,r_j)$ for a "fixed" set of system properties $\mathbf{v}_{system.} = \left\{\kappa, \theta_A^0, \theta_R^0, \mathbf{x}_{pm}\right\}$. This map may be incorporated in any continuous-scale simulator (implementing FEM or BEM) and solve accordingly the investigated technical problem. The $x_{ij}(Ca_i,r_j)$ look-up table is easy to deliver since it takes a maximum of 5 min of an ordinary PC time per (Ca_i,r_j) DeProF simulation. The slow part of the whole process is in

the delivery of the conductance maps (either semi-analytically or by implementing an appropriate numerical /CFD technique); these maps need to be provided as input to DeProF. If porous media heterogeneities or alteration of physicochemical characteristics of fluids are invoked, then an extended look-up table, x(Ca, r; $\mathbf{v}_{system}$), needs to be provided.

Comments to the 4th bullet point:

What is written in the 4th bullet point may mislead the reader since it is hardly tenable in the light of the following facts.

The Ca values examined by the Payatakes group were in the range of 10^{-8} to 10^{-4}, specifically: $5\times10^{-8}<Ca<10^{-4}$, see Figs. 4, 5, 12 & 14 in Vizika *et al.*, 1994, $10^{-7}<Ca<5\times10^{-6}$ in Avraam & Payatakes, 1995 & 1997, $10^{-8}<Ca<10^{-3}$, see Figs. 6, 7 & 8 in Constantinides & Payatakes, 2000 (also 1996) and $10^{-6}<Ca<10^{-5}$ in Valavanides & Payatakes, 2001, 2002, 2004. Note that the range of Ca values examined is that for which the well known S-curves of S_{or} vs Ca are predicted. Typical Ca values encountered in EOR applications are in the range from 10^{-6} to 10^{-4} (Cense & Berg, 2009, Terry, 2001, Virnovsky *et al.*, 1998, Lake, 1989). These facts provide conclusive evidence that, in their studies, Payatakes and co-workers implemented capillary numbers within the range encountered in reservoir engineering. One should also consider that in EOR the referenced Ca values inevitably increase when the recovery flood approaches the well bore(s).

In their paper, Al-Gharbi and Blunt, 2005, express their constructive criticism for those works of the Payatakes group in which the wetting layer flow is not taken into account and, consequently, an artificial restriction is implicitly imposed in the connectivity of the wetting phase. Nevertheless, there are works that tackle the issue. As long as experimental study is concerned, the micro-models used by Payatakes and co-workers, comprised a network of straight throats (all with an angular cross-section and wall micro-roughness) interconnecting lenticular chambers. These features induce flow of water along the acute edges of pores (both in chambers and throats) bypassing –to a certain extent- any disconnected oil. Laboratory studies (Vizika *et al.*, 1994) showed that the extent of mobilization of the disconnected oil and the residual oil saturation following a water flood (imbibition), depend not only on the capillary number but on the combination of the oil/water viscosity ratio and the capillary number, or, in other words, on the balance between the pressure-drop across an oil blob -that is induced by the viscous-flow stresses in both fluids, against the net capillary pressure difference induced by hysteresis effects on

o/w menisci. Turning to the semi-analytical/numerical arsenal of the Payatakes group, Constantinides & Payatakes (2000) incorporated in their pore network algorithm the effect of precursor films. Their simulations showed the combined effects of capillary number, viscosity ratio and wetting layer (due to pore wall micro-roughness) on the mobilization of disconnected oil, and indicated the extent to which the latter is significant in reducing the residual oil saturation. Valavanides & Payatakes (2004) used the DeProF model to investigate to which extent wetting films around droplets affect the macroscopic flow. To this end, two cases were examined with respect to the movement of oil-drop menisci. The base case, the *contact line* mode (CL), considers the advancing/receding o/w menisci in line contact with the pore walls. The alternative case, the *lubricated drops* mode (DL), considers the movement of oil droplets to be lubricated by an annular ring of water. A direct comparison over the values of key physical characteristics of two-phase flow, specifically, the interfacial area per unit volume, the mechanical power dissipation p.u.v., the degree of disconnectedness of the non-wetting phase, and the energy utilization factor, which were obtained with and without wetting films [see Fig. 2 (c) & (d) reproduced from Figs. 3-10 & 11, in Valavanides & Payatakes, 2004] reveals only quantitative differences. Still, a potential improvement in the DeProF predictions may be induced by incorporating the effect of wetting films (due to pore-wall micro-roughness) or the effect of corner flow if triangular or square sectioned pore cells are to be modelled [similar to what Al-Gharbi & Blunt (2005) have used in their pore network model].

Additional remarks & discussion

The GPB and DeProF models cannot be considered as pure pore network models (they have many characteristics that are inherent in continuum-scale models); nevertheless, since they rely –to a significant degree- on pore network modelling to recover information on the pore- and REV- scales, they are affined to pore network modelling.

I would also like to comment on the way we characterize any Ca value as "small" or "large". It is well understood that, given the structure of the porous medium, under "small" capillary numbers mobilization might or might not be significant, depending on the value of the oil/water viscosity ratio. If the oil/water viscosity ratio is significantly less than one (favorable viscosity ratio), then, mobilization of oil ganglia is significant even for "small" capillary numbers. It should be stressed here that there exists no reference measure or normative methodology for validating a Ca value as "small" or "large" even if the latter is "weighted" against the viscosity ratio. This is so because if we consider two

immiscible steady-state flows, with identical sets of capillary number and viscosity ratio values but within different porous media, then we would observe discernible differences in terms of the disconnectedness of the non-wetting phase, the mechanical power dissipation, the moving/stranded oil fractions, the saturation etc. Therefore, to characterize any two-phase flow in porous media, e.g. as viscous- or capillary- dominated, one should examine the values of at least 3 reduced numbers, i.e. the capillary number, the viscosity ratio and another dimensionless number (or set of numbers) representing the intrinsic properties of the porous medium (structure, pore size distribution etc.). This -still unresolved- issue is similar to the -resolved- issue of characterizing an incompressible flow as creeping, dynamic, transient, turbulent etc. In essence, to characterize a flow, one should consider the value of the Reynolds number in combination to the roughness factor (referring to the Moody diagram, just comparing the Reynolds number to some reference range of values is not adequate/exact). Such normative methodology has not yet been proposed and tested for two-phase flows in porous media, therefore the characterization "small" and "large" for the capillary number is contextual and not self-contained.

Concerning the direct applicability of the results of the micro-models and network models in natural porous media processes, the idea/concept, for developing these (micro- and virtual-) model networks as well as the mechanistic models, was to derive a theoretical foundation to infer the effects of pertinent flow mechanisms (taking place across pore- to core- or even to field- scales) in the macroscopic state of two-phase flow in porous media processes. I believe that it is questionable to what extent pore network modelling may be an efficient way to simulate a process taking place on a macroscopic /field scale. A terra-scale network is still insolvable and, even if it would be possible to solve it with the advances in computational technology, this still would result in an inefficient use of computational resources. To this end, I strongly agree with the authors of the commented paper that the main use and advantage of pore network modelling is to grasp a representative image and -as it is stated in their abstract- *"...give a better understanding of the physics of a process at pore scale as well as at the scale of representative elementary volume"*. The scale of the representative elementary volume forms the regime of pore network modelling and is demarcated by the currently available computational technology. So long as the *performance* of computational technology increases so the REV scale will increase; nevertheless the computational *efficiency* will always have to be validated. Merit should be given to the potential capacity of a pore network to provide

insight into the pertinent pore scale mechanisms and then integrate this *knowledge* (I am deliberately not using the word *information*) into the next scale and so on. To this end, focusing once more on the DeProF model, it integrates REV information extracted from simulators (implementing CFD or LB algorithms) to put into effect an overall (effective) description of the process and it has the potential to provide an exact description of the sought process. Nevertheless, there are still open problems to be tackled, such as those discussed in the previous comments, or the problem of extending it to study compressible steady-state two-phase flows (water-gas, miscible/immiscible) or unsteady flows.

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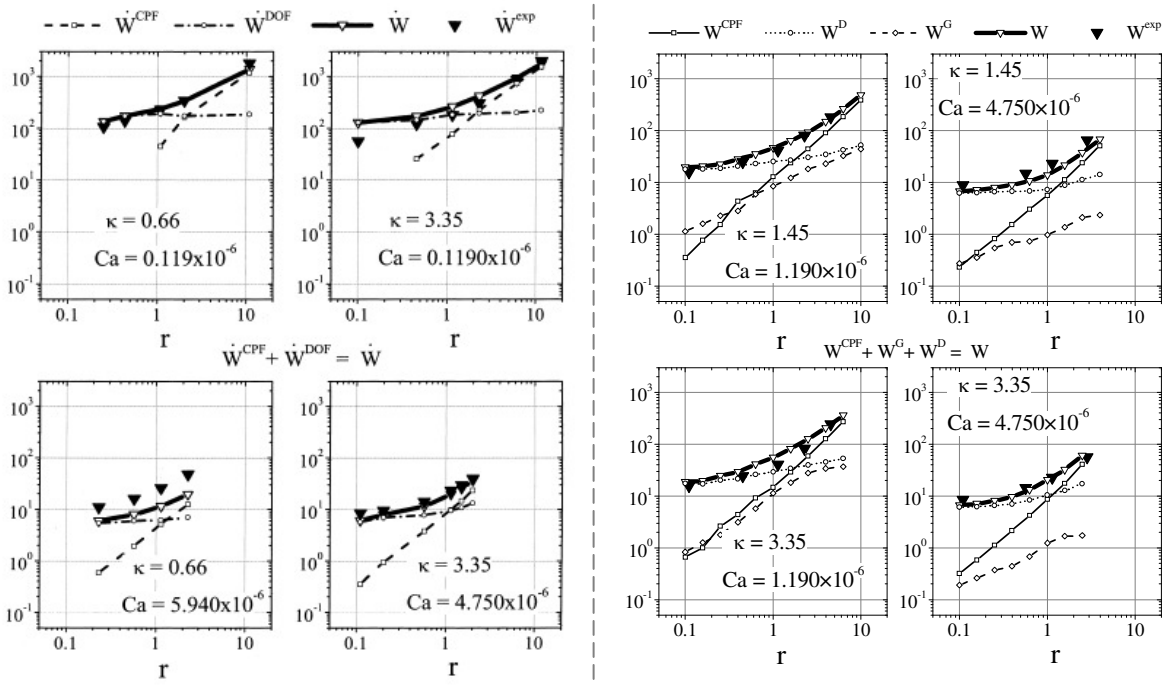
Figures with Figure Captions



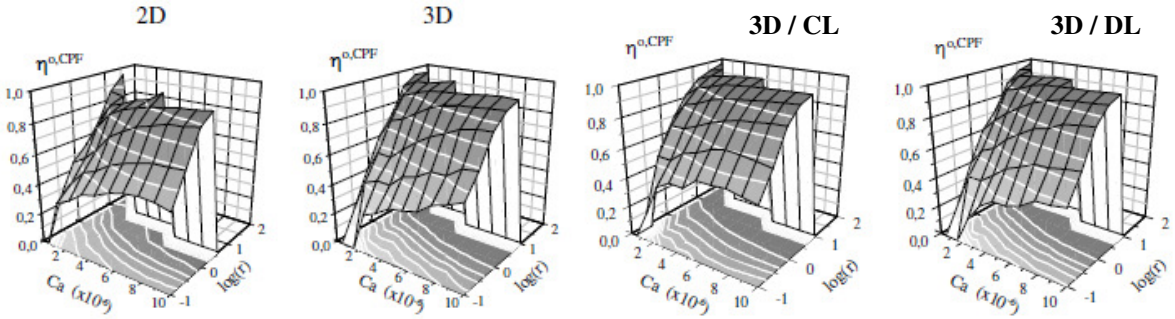
(a) DeProF ≡ CP + GD **(b)** Full DeProF ≡ CPF + GD + DTF

Figure 1

Reduced mechanical power dissipation, W, as predicted by the *DeProF* model (▬▽▬) vs actual mechanical power dissipation (▼) measured in the laboratory study of Avraam & Payatakes (1995) for different values of the capillary number, Ca, and viscosity ratio, κ. Large solid triangles represent measured values; smaller void symbols represent the corresponding DeProF theory predicted values for the total flow (void triangles over thick lines) and for the prototype flows (void symbols over thin lines).

(a) DeProF predictions when the total flow is decomposed in two prototype flows, connected pathway flow (CPF) and ganglion dynamics (GD) are benchmarked against measured values. Source: Valavanides & Payatakes, 2001

(b) DeProF predictions when the total flow is decomposed in three prototype flows, connected pathway flow (CPF), ganglion dynamics (GD) and drop-traffic flow (DTF) are benchmarked against measured values. Source: Valavanides and Payatakes, 2000.



(a) (b) (c) (d)

Figure 2

Effect of network dimensionality and/or mode of drop flow in throats on the reduced macroscopic connected oil flowrate, $\eta^{o,CPF}$, as a function of Ca and r. The diagrams from left to right correspond to: (a) two-dimensional networks of the blister-and-flat-stick type (throats with elliptic cross section) (b) three-dimensional networks of the ball-and-stick type (throats with circular cross section) (c) three-dimensional ball-and-stick networks and flow of oil drops in contact with the throat (CL), and (d) three-dimensional ball-and-stick networks and lubricated flow of drops (DL). [Source: Figs (a) & (b) and figs (c) & (d) taken from Valavanides and Payatakes, 2002 and 2004 respectively]