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Energy efficiency characteristics in steady-state relative permeability diagrams of two-phase flow in porous media

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ABSTRACT

Experimental evidence on the phenomenology of steady-state two-phase flow in porous media processes is recorded in the conventional relative permeability diagrams. In the present work, the 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, has been tested against available laboratory data. The energy efficiency of the process is considered with respect to the oil transport over the mechanical power supplied to it or, “oil produced per kW of mechanical power dissipated in pumps”, appropriately reduced to a dimensionless variable, namely the energy utilization factor. Relative permeability data sets were acquired 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. The acquired data were then transformed into energy efficiency data sets for the corresponding system and flow settings. The transformation stems from the Darcy fractional flow relations, combined with the equality between the flowrate and mobility ratio observed when steady-state conditions are maintained. The objective of the present work is to reveal and provide 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. Areas of critical relevance that have not been investigated or require further investigation are also highlighted.

1. Introduction and scope of work

Two-phase flow in porous media is a physical process whereby two phases simultaneously flow within a porous medium. When the flow is immiscible (i. e. the two phases do not mix), one of the phases is wetting the interstitial surface of the porous medium against the other, non-wetting phase. The wetting phase is conventionally referred to as “water” and the non-wetting phase as “oil”. The combined effect of wetting and interfacial tension is the disconnection of the non-wetting phase into fluidic elements of smaller or larger size – compared to the average pore size. Two-phase flow in porous media occupies a central position in physically important processes with practical applications of industrial and environmental interest, such as: enhanced oil recovery (Lake, 1989; Alvarado and Manrique, 2010), carbon dioxide sequestration (Burnside and Naylor, 2014), groundwater and soil contamination and subsurface remediation (Khan et al., 2004), the operation of multiphase trickle-bed reactors (Van de Merwe and Nicol, 2009), the operation of proton exchange membrane fuel cells (Bazylak, 2009), etc. The majority of those applications are based on inherently transient processes whereby one phase displaces the other. Drainage is said to occur when a non-wetting phase (oil) enters the pore network to displace a wetting phase (water), whereas imbibition occurs if the latter displaces the former. Drainage and imbibition are predominantly *transient* processes: the pattern structure of the two fluids, as to their distribution within the network and to the disconnectedness of the non-wetting phase (oil), change during the process. In addition, averages of physical quantities -taken over any volume larger than the representative elementary volume (REV)- change with position and time. For example, the average saturation of the wetting phase over any region of the pore network increases with time as a wetting fluid (water) is replacing a non-wetting fluid (oil) during the imbibition process.

To understand the physics of such processes in a deeper context, we need first to understand the *steady-state flow*, whereby the two immiscible fluids, oil (the non-wetting) and water (the wetting), are forced to flow at pre-selected, constant flowrates. In this second class of processes, physical quantities also change with time, but in a different way: averages remain practically constant or their variability is extremely small, i. e. the variation of the local

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Nomenclature

Symbols, indices

$\sim$	A tilde indicates a dimensional variable (no tilde denotes a dimensionless variable)
$\Delta *$	small difference of variable *
$\{^*\}$	set of * values
o	“oil” or non-wetting phase (index)
w	“water” or wetting phase (index)

Physical variables – Latin letters

Ca	Capillary number
$\tilde{e}$	energy efficiency of the process
f	fractional flow
f_{EU}	energy utilization factor
$\tilde{k}$	absolute permeability of the porous medium
$\tilde{p}$	macroscopic pressure
r	oil/water flowrate ratio
S_w	wetting phase saturation
$\tilde{q}$	flowrate
$\tilde{U}$	superficial velocity
W	reduced rate of mechanical energy dissipation
x	reduced macroscopic pressure gradient
$x_{\text{p.m.}}$	vector containing the geometrical and topological parameters of the pore network
$\tilde{z}$	position length along the macroscopic flow direction

Physical variables - Greek letters

$\tilde{\gamma}_{ow}$	oil-water interfacial tension
κ	oil/water viscosity ratio
$\tilde{\lambda}$	mobility
$\tilde{\mu}$	dynamic viscosity

value (in time and space) is very small compared to the average value. The flow structure -comprising a mixture of connected and disconnected fluidic elements moving at different velocities- incessantly rearranges itself within a phase space of physically admissible flow configurations (Avraam and Payatakes, 1995; Erpelding et al., 2013). According to ergodicity principles, the time average of the flow is the same as its phase space average over all physically admissible configurations (Valavanides, 2012).

Two-phase flow in porous media is ubiquitous in industrial applications. Particular attention is given on tuning the design parameters and process interventions so as to increase the “sweeping efficiency”, i. e. the extraction of one phase (residing in-situ) and its replacement by another phase - wetting or non-wetting depends on the particular application. In this context, the decrease of saturation has become the main objective in process optimization (whether recovery, substitution, removal etc.). Nevertheless, at present, pragmatic sustainability issues on energy production/management (hydrocarbons, fuel cells, catalytic or trickle-bed reactors) shifts “recovery optimization” trends into “energy /cost efficiency optimization” scopes and targets (Charpentier, 2007; Clayton, 2014). As a consequence, new challenges emerge within a wide spectrum of technological problems, extending from laboratory to industrial scale, e. g. unconventional/enhanced oil recovery /carbon capture and sequestration processes, soil and aquifer pollution and remediation, operation of trickle-bed reactors [Valavanides et al., 2015a, 2015b]. To address these issues we need first to examine if any *energy efficiency* characteristics are inherent in the sought process, starting from its simpler form, immiscible steady-state.

The scope of the present work is to collect data from published laboratory studies of steady-state two-phase flow in porous media, in order to examine if there exists any operational characteristics related to the energy efficiency of the process, if such characteristics show a universal trend and if that trend can be exploited in a systematic way. The objective and driving force for this work, was to provide extensive experimental evidence on the predictions of the mechanistic model *DeProF*, that first revealed the existence of optimum operating conditions as well as other latent operational characteristics of two-phase flow in porous media.

The *DeProF* model has been developed by Valavanides & Payatakes (ca 1998). The purpose was to develop a mechanistic model that could explain (on physical principles) the various interstitial flow arrangements observed in the laboratory study of Avraam and Payatakes (1995). It turned out that the model was self-contained and rigorous enough to be further exploited as a simulating tool having the capability of revealing latent process characteristics. Such a characteristic is the existence of the locus of maximum operational efficiency of the process (Valavanides and Payatakes, 2003). To verify the validity of the *DeProF* model predictions, a preliminary laboratory proof was presented in a review of the progress in the development of the *DeProF* tentative theory (Valavanides, 2012). The paper presented past efforts and new results, highlighted critical issues and suggested future steps to be taken. With respect to laboratory verification of the *DeProF* model predictions, it referenced the examination of 23 relative permeability diagrams in total, from 7 published laboratory studies. That examination was preliminary and only indicative of the latent information one could extract from such diagrams.

It is well understood that two-phase flow in porous media is a complicated multi-parametric process extending across different scales and comprising a hierarchical system (Cushman, 1997; Payatakes et al., 1998; Perez-Mercader, 2004). Therefore, any attempt to describe it by developing a rigorous analytical model (overtaking any phenomenological description) requires, *a-priori*, the collection of an adequate number of laboratory data. Then, areas over the parameter domain being void of laboratory data should be filled and missing data should be recovered by designing more efficient laboratory studies. Such tasking should deploy in parallel to the development of “better” models.

As already stated, the scope of the present work is to provide extensive experimental evidence and reveal critical process characteristics with respect to energy efficiency.

On this purpose, the present work examines 35 laboratory studies and 179 diagrams, stretching across a broad range of types of porous media, fluids and flow conditions. The existence of optimum operating conditions taken apart, there are additional characteristics that need to be revealed, explained on physical considerations and then rationally justified on the provision of rigorous theoretical background. Said particular characteristics have been only recently identified and will be presented in the following sections. The extent, diversity and volume of collected laboratory data is the seed material for creating a tentative database that will provide the necessary laboratory strings of evidence (or, the vital clues) for revealing latent universal characteristics of the sought process.

In the following, we will present the concept of operational efficiency of steady-state two-phase flow in porous media and the corresponding predictions provided by the *DeProF* model