CAPILLARY vs VISCOUS FLOW: INTRODUCTION OF A NORMATIVE METHODOLOGY FOR CHARACTERIZATION OF 2-PH FLOW IN P.M.

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SCOPE &OVERVIEW

A new methodology is proposed for the *normative characterization* of two-phase flows in porous media as *capillary* or *viscous*. The proposed methodology is based on the provisions of the DeProF theory for steady-state two-phase flow in p.m. [1], as well as a retrospective examination [2] of the phenomenology of the process as recorded in the relative permeability curves and the resulting form of the energy utilization coefficient, f_{EU}=r/W, as a function of the process' operational parameters, i.e. the capillary number, Ca, and the oil/water flowrate ratio, r [3].

In general, the exact shape of f_{EU} is governed by the values of the system parameters e.g. the oil/water viscosity ratio, κ, contact angles and the p.m. geometric & topologic characteristics (microporosity, microroughness, tortuosity, fractality etc.). In addition, the energy utilization coefficient has a universal feature, the locus of *optimum operating conditions* (OOC), r*(Ca), i.e. conditions whereby process efficiency -in terms of oil flowrate per kW of total mechanical power dissipated by the process- attains locally maximum values. This OOC locus shows a distinct mutation: as Ca is increased -from "small" to "large" values- its effect turns from strong -whereby the flow is capillary dominated and process operational efficiency is drastically increased, to moderate -whereby the flow retains both its capillary and viscous character and improvement of process efficiency becomes less significant, to negligible -whereby the flow is dominated by viscosity and any further increase in process operational efficiency is insignificant [1,3]. Capillarity is observed to predominate the flow in the lower end of the flow variables regime, i.e. for "relatively small" values of the capillary number, Ca. In contrary, at the higher end of the flow regime, for "relatively large" values of Ca, the flow is dominated mainly by the bulk viscosities of the two phases. This mutation is regulated by the values of the system parameters.

Methodology

Flow characterization is based on the form of the OOC locus, r*(Ca), of any particular system. Examination of the operational efficiency flow map reveals a zone of width, $\log\kappa$ (Fig 1). This is outlined on the domain [Ca×r] by the Ca axis (i.e. r=1 or logr=0), and a straight line, $r = r_x = 1/\kappa$ on which the relative permeabilities are equal; it is also the OOC asymptote, $r = r^*_\infty = 1/\kappa$ [3]. For any particular system (e.g. oil/water/p.m.), the locus r*(Ca) may be approximated by a function of the form

$$r^*(Ca) = \frac{1}{\kappa} + \frac{a}{Ca^b}, \quad a, b > 0 \tag{1}$$

where a & b are positive real numbers that can be determined by least square interpolation of a set of laboratory determined optima r^*_i, Ca_i. Considering the values the oil/water viscosity ratio, κ, may take, three cases apply:

(i) When $0<\kappa<1$ (i.e. favorable viscosity ratio), a nominal capillary number value, Ca_{cv},

$$Ca_{cv} \approx \left[a\kappa^2/(1-\kappa)\right]^{\frac{1}{\beta}}, \quad 0<\kappa<1 \tag{2}$$

may be identified /conventionally set as a segregation point between the capillary vs viscous character of the flow [Fig. 1(a)].

(ii) When $1<\kappa$ (i.e. unfavorable viscosity ratio), a nominal capillary number value, Ca_{cv}, partitioning the capillary from the viscous flow domains [Fig. 1(c)] may be set as

$$Ca_{cv} \approx \left[a\kappa/(\kappa-1)\right]^{\frac{1}{\beta}}, \quad 1<\kappa \tag{3}$$

In both cases, the prevalence of capillarity or viscosity may be evaluated by the "distance" $d = \log r^*(Ca) + \log \kappa$, that may take positive [if $r^*(Ca) > \kappa^{-1}$] or negative [if $r^*(Ca) < \kappa^{-1}$] values. Note here, that flow characterization is based on the (laboratory) detection of the OOC locus.

(iii) When $\kappa = 1$, and considering that there is a continuous dependence of the locus r*(Ca) on κ, then, as κ crosses 1, r_x=r^*=1, i.e. OOC are met for r=1. The physical interpretation is that the bulk viscous properties of each phase are identical and the power dissipated within the process is indifferent to oil/water saturation (or any differences in phase velocities or flowrates) and it is only regulated by interfacial friction losses (mainly due to contact angles hysteresis effects), therefore, for r=1, i.e. when the flowrates are equal, the interfacial friction dissipation becomes minimum and the energy utilization coefficient, f_{EU}, becomes locally maximum and, consequently, by definition, r*=1. The local maximum value that f_{EU} attains, depends on the total mechanical power dissipation, that, in turn, depends on the structure of the porous medium (not only on absolute permeability, but also on tortuosity, pore size distribution and throat/chamber size correlations, other microstructure & fractal characteristics etc.). Therefore, for $\kappa = 1$, any nominal capillary number value segregating capillarity/viscosity may not be set alone from the OOC locus [Fig. 1(b)] and the f_{EU} form should be considered.

In all cases (of κ values), f_{EU} is S-shaped [2,3] usually spanning almost 3 to 4 orders of magnitude over Ca, similar to the S-curves observed in the residual oil ratio in terms of Ca [4] and of κ & network size as well [5].

CONCLUSIONS

A normative methodology for evaluating the viscous/capillary character of two-phase flows in p.m. can be implemented. It is based on the measurement of a set of relative permeabilities (macroscopic quantities) across various capillary number values and, to this end, the development of an appropriate protocol for laboratory measurements is essential.

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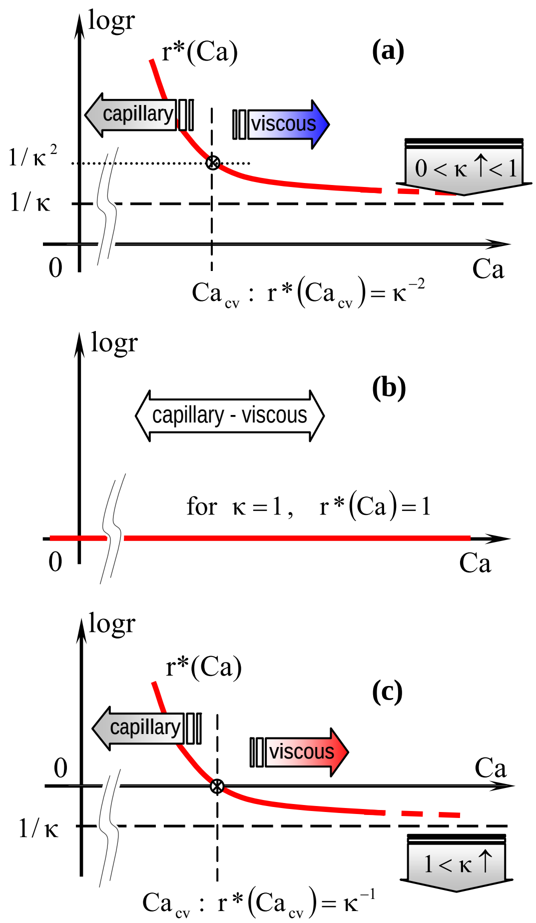

Figure 1. Delineation of the locus of optimum operating conditions r*(Ca) and flow partitioning into capillary and viscous regimes by Ca_{cv}, for various viscosity ratios (a) $\kappa < 1$ (favourable), (b) $\kappa = 1$ and (c) $1 < \kappa$ (unfavourable).

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