# RETROSPECTIVE EXAMINATION OF RELATIVE PERMEABILITY DATA AND OPERATIONAL EFFICIENCY ASPECTS FOR STEADY-STATE 2-PHASE FLOW IN POROUS MEDIA

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## SUMMARY
Experimental evidence on the phenomenology of steady-state two-phase flow in porous media is recorded in the well-known relative permeability curves published in the literature. A retrospective examination of such curves identified an important process characteristic, the existence of optimum operating conditions, i.e. conditions whereby process efficiency - considered in terms of oil produced per kW dissipated by the process attains maximum values. A pertinent operational efficiency map is demarcating the overall process efficiency.

## OVERVIEW
Optimum operating conditions for steady-state two-phase flow in pore networks were first predicted by the *DeProF* theory [1]. The operational efficiency of the sought process is measured by the energy utilization index,

$$f_{EU}=r/W(Ca,r) \qquad (1)$$

where, r is the oil/water flowrate ratio and $W \equiv \tilde{W}\tilde{k}\tilde{\mu}_w(\tilde{\gamma}_{ow}Ca)^{-2}$ is the reduced mechanical power dissipation (including the effect of bulk viscosities and interfacial hysteresis on strain rates). Ca, the capillary number, and r, the oil-water flowrate ratio, are the process operational parameters; $\tilde{W}$ is the specific rate of mechanical energy dissipation of the two phase flow, and $(\tilde{\gamma}_{ow}Ca)^2/(\tilde{k}\tilde{\mu}_w)$ the rate for equivalent one-phase flow of water. Extensive simulations using the *DeProF* mechanistic model revealed the existence of optimum operating conditions in the form of a smooth and continuous locus, $[r^*(Ca)]$ in the domain of the process operational parameters (Fig. 6 [1]).
The transformation originally introduced in [1],

$$r=\frac{\tilde{q}_o}{\tilde{q}_w}=\frac{\tilde{U}_o}{\tilde{U}_w}=\frac{k_{ro}/\tilde{\mu}_o}{k_{rw}/\tilde{\mu}_w}=\frac{1}{\kappa}\frac{k_{ro}}{k_{rw}}$$
$$f_{EU}=\frac{k_{ro}}{\kappa(r+1)}=\frac{rk_{rw}}{r+1}=k_{ro}\left(\frac{k_{ro}}{k_{rw}}+\kappa\right)^{-1} \qquad (2)$$

where $\kappa=\tilde{\mu}_o/\tilde{\mu}_w$ is the oil/water viscosity ratio, valid for steady-state flow conditions, was implemented to reconstruct laboratory measured data sets of relative permeabilities, $k_{ri}(S_w)$, i=o,w into corresponding energy utilization values, $f_{EU}(r)$.
Such an indicative reconstruction is depicted in Fig. 1, whereby a set of relperm diagrams [2], is transformed into energy utilization diagrams.

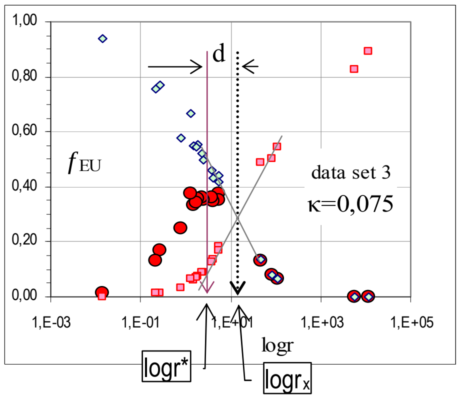


**Figure 1.** Steady-state relative permeabilities for oil (□) and water (◊) & energy utilization index, $f_{EU}$, (●) plotted against flowrate ratio, r, for two-phase flow in a fine sand pack. Seed data from [2].

Similar reconstructions were delivered for many (~35) published relperm diagrams pertaining to a variety of conditions in steady-state two-phase flow in sand packs, plug cores, glass micromodels etc. [3]. Observations show a universal trend that can be cast into an operational efficiency map

(Fig.2). This map consistently & rationally resolves the extent to which disconnected oil flow and associated capillarity effects regulate the flow and provides a guiding tool for designing more efficient processes.

Process operational efficiency aspects are demarcated as follows: in all diagrams, relperm interpolation curves intersect at a certain value of the oil/water flowrate ratio, $r_x$, irrespective of the porous medium structure, such that,

$$k_{ro}(r_x) = k_{rw}(r_x) \quad \Rightarrow \quad \kappa = 1/r_x \qquad (3)$$

Considering the physical characteristics of the process in the far end of the Ca spectrum, i.e. as Ca→+∞, yields the asymptotic value of the flowrate ratio, $r^*_\infty$, for which process efficiency reaches an upper limit value, $f^*_{EU\infty}$, i.e.

$$\left.\begin{matrix} Ca \to \infty \\ r^*_\infty \to 1/\kappa \end{matrix}\right| \Rightarrow f^*_{EU\infty} \to \frac{1}{1+\kappa} \qquad (4)$$

## CONCLUSIONS

Plotting the $k_{ri}$, and the respective, $f_{EU}(\log r)_i$, data sets into an operational efficiency map, certain interesting observations are made:

Relative permeabilities attain the form of an S-curve when expressed in terms of logr (useful to interpolate sparse relperm data).

The flowrate ratio values for which the flow attains its locally maximum efficiency, r*, are always shifted, into higher or lower values by a distance d with respect to $r_x$ values where relative permeabilities of oil & water are equal (Figs 1 & 2). The shift d can be used as a norm for evaluating the capillarity characteristics of the flow [4].

The map provides ample qualitative and quantitative information on process operational efficiency aspects and flow characterization.

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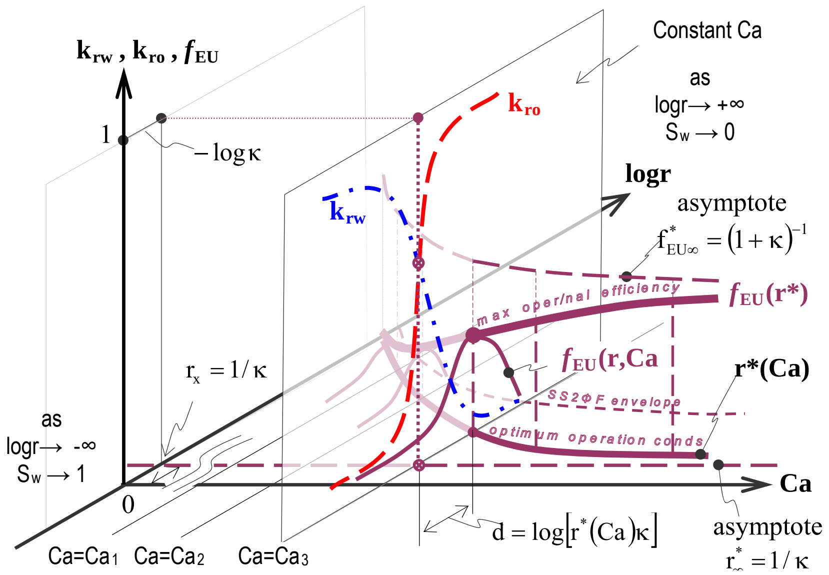


**Figure 2.** Operational efficiency map of steady-state 2-ph flow in porous media. Solid/phantom curves delineate the energy utilization coefficient, $f_{EU}$=r/W against operational parameters, Ca & r. The thick curve, $f_{EU}(r^*)$, delineates the ridge of the energy utilization surface $f_{EU}(Ca,r)$ and corresponds to optimum operation conditions, r*(Ca), whereby maximum process efficiency is attained. The asymptotes of r*(Ca) and $f_{EU}(r^*)$ as Ca→+∞, depicted with dashed lines, are given respectively by $r^*_\infty = 1/\kappa$ and $f_{EU}(r^*) = (1+\kappa)^{-1}$.