Correlations between X-over and critical flow conditions for steady state 2-ph flows in porous media: do they exist?

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Abstract

Preamble - During routine /special core analysis (R/SCAL) **plots of relative permeabilities against saturation always intersect at the so-called cross-over poin**t (**X-over**), indicating there is a certain flow set-up whereby relative **permeability** of the **NWP** becomes **equal** to that of the **WP** [1]. A virtual saturation value can then be identified.

In addition, so long as the mobility ratio equals the flow rate ratio (a direct result of flow analysis for steady-state conditions), the corresponding, **X-over flow rate ratio** value is reciprocal to the NWP/WP viscosity ratio, $\kappa=\mu_n/\mu_w$ [2]. Moreover, analysis of steady-state two-phase flow, from an **energy efficiency** point of view, has revealed a universal flow characteristic, the existence of a unique locus of the so-called ***critical flow conditions***, whereby the **energy efficiency of the process** (NWP flow rate per unit of total power spent) attains locally maximum values, Fig.1. Both of these universal theoretical results are verified against ample experimental evidence [1].

The existence of a unique locus of critical flow conditions per N/W/PM system has opened new perspectives in effectively describing the sought process in terms of the actual independent variables, i.e. the NWP and WP flow rate intensities or -equivalently- the capillary number, *Ca*, and the N/W flow rate ratio, *r*. Corresponding, values of **critical saturation** and of **X-over flow rate ratio** can also be identified for different N/W/PM systems and flow conditions.

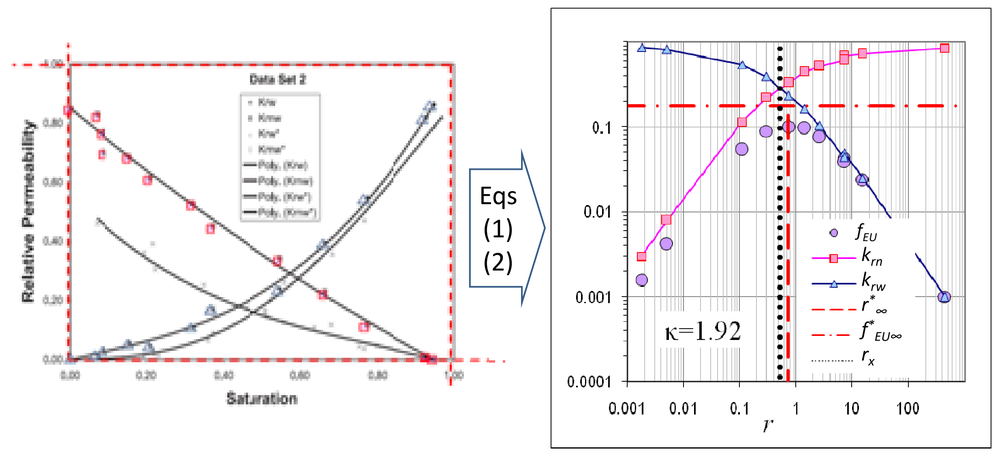

Figure 1 - A typical rel-perm diagram (Bentsen, 2005 [1] transformed Into a rel.-permeability and energy efficiency diagram (right) using Eqs (1) & (2)

Scope - In an effort to improve our understanding of the behavior of the sought process and its inherent, universal flow characteristics, we have plotted **X-over values** (**x**) against **critical values** (*****) of saturation and flow rate ratio, S_x, S^* and r_x, r^*, Fig. 2. The values have been retrieved from a review of 180 published relative permeability diagrams, pertaining to different N/W/PM systems and flow conditions [1].

Outcome - **Preliminary results** indicate a **latent, weak correlation** between the **X-over** and **critical values** of the **saturation**, Fig.3. The correlation tends to become linear when $\kappa\rightarrow1$, i.e. when the viscosity of the NWP approaches that of the WP. Similar, but weaker correlations can be observed for the X-over /critical values between saturation and flow rate ratio. Yet, because of the disparities between the N/W/PM systems and the flow conditions of the examined R/SCAL measurements, still no definite conjectures can be drawn. A systematic, specially designed experimental study would reveal more concrete trends – if any.

Definitions

X-over point (x) for saturation and flow rate ratio → S_x and r_x conditions where relative permeability curves intersect

Critical saturation and flow rate ratio (*) → S^* and r^* conditions where SS 2ph flow within the N/W/PM system attains maximum values of energy efficiency (flow rate of NWP "per kW spent in pumps" - see below).

In steady-state conditions, the N/W flow rate ratio equals the mobility ratio,

$$r=\frac{U_n}{U_w}=\frac{k_{rn}/\mu_n}{k_{rw}/\mu_w}=\frac{\lambda_n}{\lambda_w}=\frac{1}{\kappa}\frac{k_{rn}}{k_{rw}} \qquad (1)$$

The energy utilization factor, or energy efficiency index, f_{EU}, is defined as the NWP flow rate per total unit power spent).
It is calculated from the corresponding pair of relative permeability values as

$$f_{EU}\equiv\frac{r}{W}=\frac{k_{rn}}{\kappa(r+1)}=\frac{rk_{rw}}{(r+1)}=k_{rn}\left(\frac{k_{rn}}{k_{rw}}+\kappa\right)^{-1} \qquad (2)$$

Results

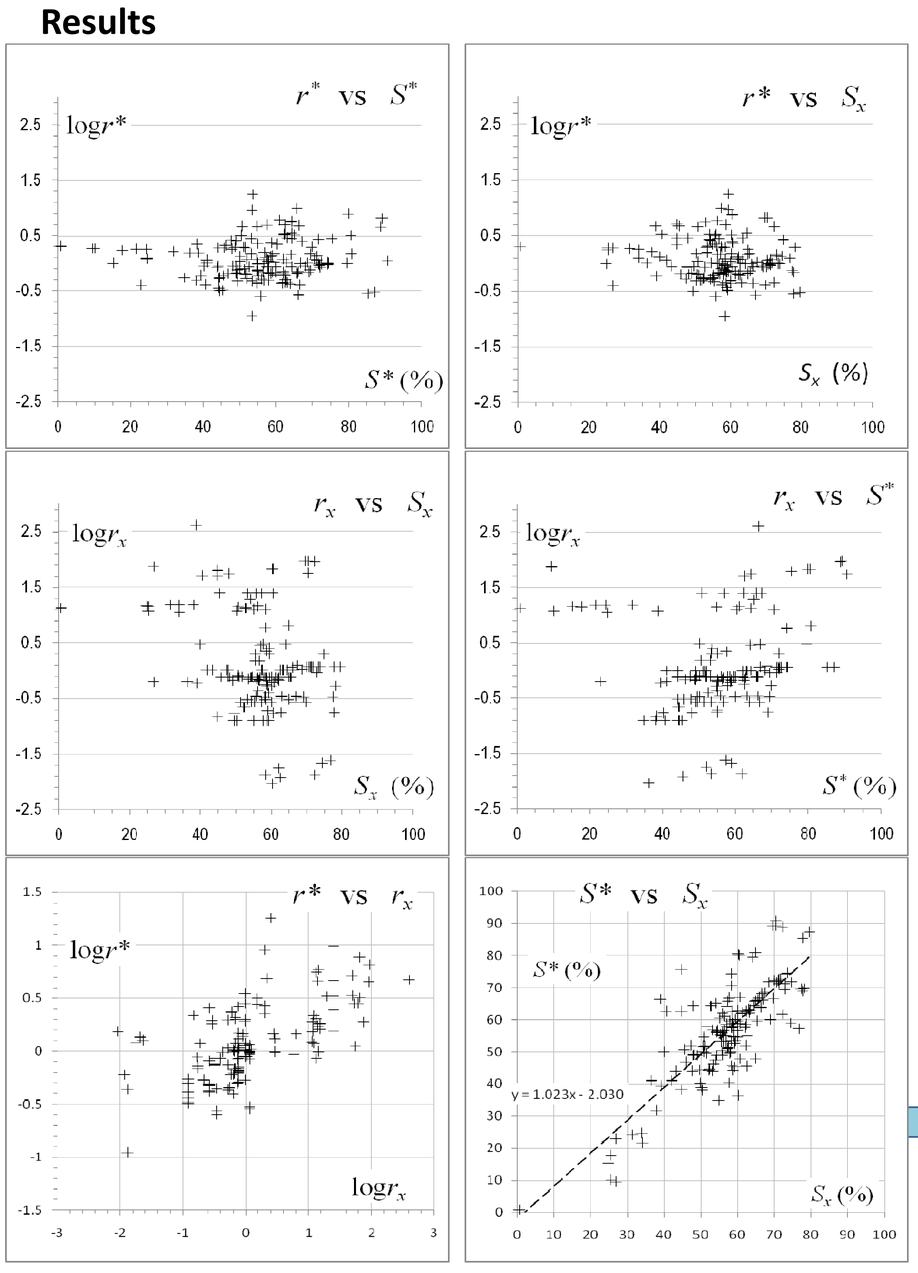

Figure 2 – Examined correlations between X-over (x) and critical (*) conditions

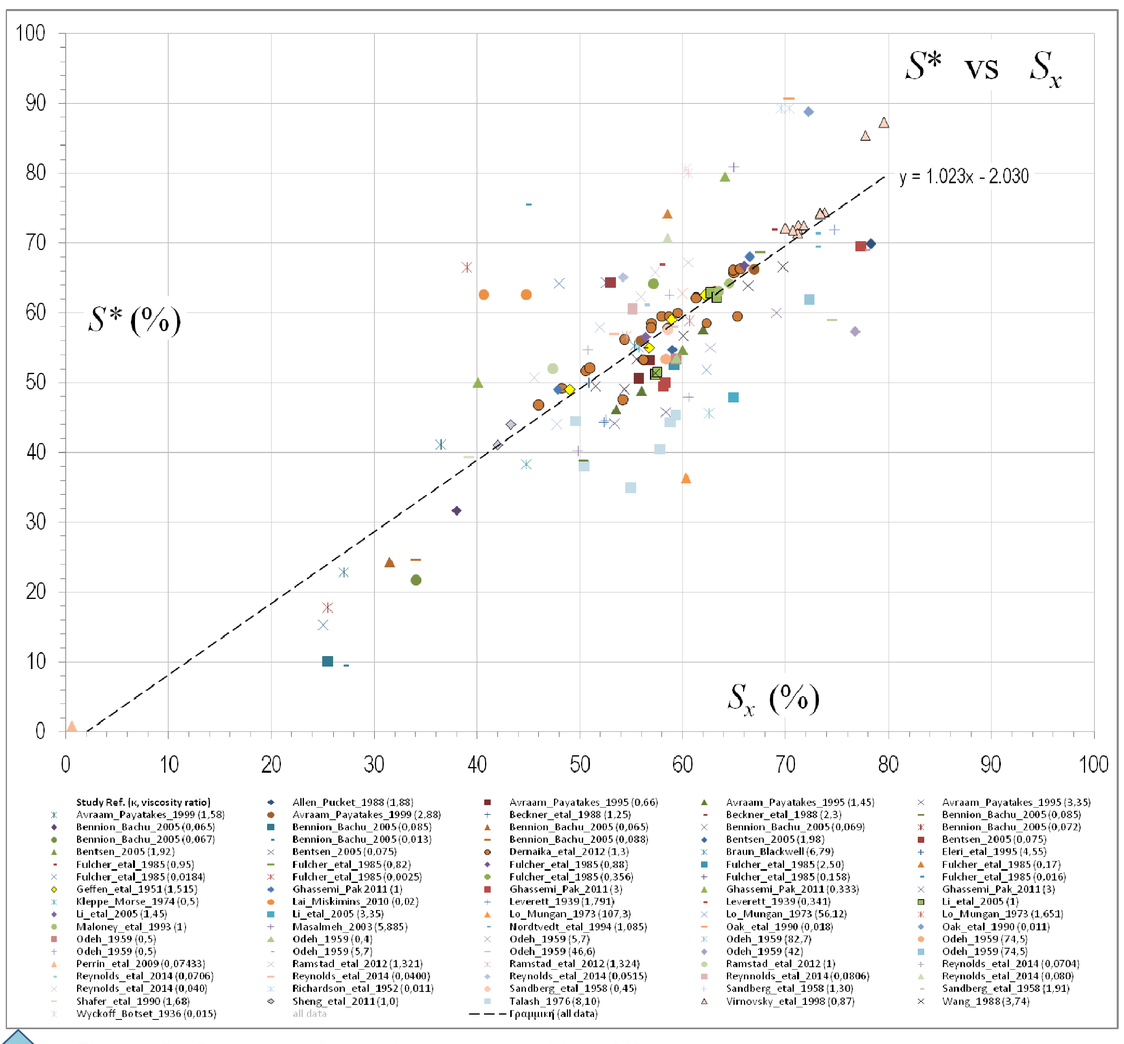

Figure 3 - Saturation for critical flow conditions VS saturation of cross over points. Each pair corresponds to a specific value of viscosity ratio, whereas ech marker type pertains to R/SCAL measurements performed using N/W systems with the same κ. Weak linear correlation is observed for systems with viscosity ratio approaching unity.

Conclusions

With the available data, we cannot reveal any concrete correlation between the X-over & critical values of saturation and/or flow rate ratio.
A weak indication of correlation between S_x and S^*, in particular, a linear correlation is more possible to exist for N/W systems with almost equal viscosities, Fig. 2, Fig.3. Although it should not be accounted as a trustworthy conjecture, the observed trend may be attributed to R/SCAL measurements performed at high flow rateσ (high capillary number values). At those flow conditions, the capillary resistances are negligible. As a result, critical flow conditions tend to be close to X-over flow conditions and the corresponding saturations become equal, i.e. $S_x \approx S^*$

References

1) M.S. Valavanides *et al. J. Petrol. Sci. Eng.* **147**, 181–201 (2016). https://doi.org/10.1016/j.petrol.2016.04.039
2) M.S. Valavanides. *Transp. In Porous Media* **123** (1), 42-99 (2018), https://doi.org/10.1007/S11242-018-1026-1