OVERVIEW OF THE LET FAMILY OF VERSATILE CORRELATIONS FOR FLOW FUNCTIONS

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ABSTRACT

The LET family of correlations for flow functions is gradually gaining foothold among core analysts, reservoir engineers and scientists due to their flexibility, accuracy and ease of communication. This makes LET excellent for interpretation of flow experiments, for upscaling of flow functions and for history matching models of fields in production. The LET family of capillary pressure correlations avoids singularities when approaching residual saturations. The family includes several capillary pressure correlations available to suite various needs. The LET family of correlations, parameter trend functions, recommended workflow and some applications has been presented in [1][7][8][9][10] and denoted LET and LETx. An overview of the 2018 version of the LET family of correlations for flow functions is displayed together with comments / explanations. An overview of selected flow parameters like L_o, L_w, S_{orw} and $K_{rwr} = K_{rw}(S_{orw})$ is also displayed. New elements in the family are invertible correlation for primary drainage P_c (LETh) and imbibition P_c (LETs) correlation with independent spontaneous and forced P_c-branches.

INTRODUCTION

LET family [1][7][8][9][10][15] of correlations consists of bounded (i.e. finite) functions of normalized saturation(s). Whether the dependent variable is normalized or not varies. L, E and T are called shape parameters, and we will use the short compact form LET for both the correlation name and the sequence of parameters. L influences the lower part of the curve, T influences the top part, and E influences the elevation or the positions of the slope. LET are empirical parameters that can be adjusted to match available observations.

Core plugs are heterogeneous to some degree, comes from different parts of the reservoir and SCAL experiments are difficult in themselves, so it should not be a big surprise that the final measurements, interpretation of results and parameters often show a significant scatter. It is recommended to establish a database for the parameters in the LET correlations and other parametric correlations. Due to scatter in the data, Ebeltoft et alios [1] also recommend that the trend functions, related to the database, should be based on an underlying conceptual model. Our conceptual model says that for a given reservoir rock and its oil, brine and gas, the initial water saturation S_{wi} is a primary cause of wettability variations in the reservoir. This is supported by research findings of Morrow et alios [5][13] and Hamon [2]. Well above the capillary transition zone, S_{wi} approaches a value we interpret as a practical value for irreducible (or connate) water saturation S_{wir}. However, we say that the water has approximately the same effect on the parameters in flow functions whether it is caused by S_{wi} at one place in the reservoir or by S_{wir} in another place, as long as the two values are equal; $S_{wi}(1) = S_{wir}(2)$. Thus, the conceptual model says that we should link our flow functions to the reservoir model via $S_{wi.}$ This link we find in the trend functions of parameters for curve shape and endpoint. The conceptual model will also guide us in establishing behaviour of trend functions (parameter-correlations) for flow parameters and uncertainty modeling. Due to lack of space, this paper will only present oil/water (o/w) systems. Gas/oil and gas/water systems have similar correlations, and the most important are presented in [7][8][9][10].

IRREDUCIBLE WATER SATURATION

It is recommended to use oil permeability K_o with irreducible water saturation present, as absolute (single phase) permeability, and base for relative permeability, in the reservoir zone (the hydrocarbon column). Production wells respond according to oil permeability. Below free water level (FWL), it is recommended to use 100% water based permeability K_w as absolute permeability. Injection wells below FWL and aquifer respond according to water permeability. S_{wir} is related to pore-throats via grain cementing clay etc., or in short oil permeability K_o. We should therefore link our flow functions to the reservoir model via S_{wir} and/or K_o. This link we find in the formula for normalization of saturation.

RELATIVE PERMEABILITY

Oil permeability K_o normalize oil relative permeability (e.g. $K_{row} = 1$) at $S_w = S_{wir}$, but LET formulas keep a top point coefficient / parameter K_{rot} (note subscript t) in case you prefer another base permeability in the reservoir. WOGn is a bookkeeping system that is used to keep track of all correlations that occurs. It consists of the change indicators **I**ncreasing, **D**ecreasing, **C**onstant in the saturation triplet S_w, S_o, S_g for each general flooding cycle n. LET formulas for DIC1 K_r are old, but displayed here for the first time:

$$K_{row} = \frac{K_{rot}\left(1-S_{wp}\right)^{L_o}}{\left(1-S_{wp}\right)^{L_o}+E_o S_{wp}^{T_o}} \quad \wedge \quad K_{rw} = \frac{K_{rwt} S_{wp}^{L_w}}{S_{wp}^{L_w}+E_w\left(1-S_{wp}\right)^{T_w}} \quad \wedge \quad S_{wp} = \frac{S_w-S_{wir}}{1-S_{wir}} \qquad (1)$$

Thus, DIC1 is the well-known primary (first cycle) drainage for an oil/water system. LET formulas for IDC2 Kr (first shown in [7]) are:

$$K_{row} = \frac{K_{rot}(1-S_{wn})^{L_o}}{(1-S_{wn})^{L_o}+E_o S_{wn}^{T_o}} \quad \wedge \quad K_{rw} = \frac{K_{rwr} S_{wn}^{L_w}}{S_{wn}^{L_w}+E_w(1-S_{wn})^{T_w}} \quad \wedge \quad S_{wn} = \frac{S_w-S_{wir}}{1-S_{orw}-S_{wir}} \qquad (2)$$

Thus, IDC2 is the well-known (second general cycle) imbibition for an oil/water system. By utilizing the LET flexibility, the K_{rw} curve can be extended to 100% water with a top point $K_{rwt} = 1$ at $S_w = 1$, while keeping the imbibition end point K_{rwr} (which is the K_{rw}

value at residual oil S_{orw}) based on oil permeability K_o. This enables use of the same K_{rw} curve for IDC2 in the reservoir and for a tiny oil drainage involuntarily dipping into the water zone. We denote this extended K_{rw} formula for LETx.
LETx formula for IDC2 K_{rw} (first shown in [9]) is:

$$K_{rw} = \frac{K_{rwt} S_{wp}^{L_w}}{S_{wp}^{L_w} + E_w\left(1 - S_{wp}\right)^{T_w}} \quad and \quad S_{wp} = \frac{S_w - S_{wir}}{1 - S_{wir}} \tag{3}$$

The LETx formula for K_{rw} was the motivation for development of the K_{rwr} endpoint correlation, and K_{rr} endpoints in general, where S_{wir} usually is replaced by S_{wi}. Similar LET and LETx formulas for gas/oil and gas/water systems are displayed in [7][9]. The L, E, T parameters are of course different for the different WOGn signs.

Moghadasi et alios [12] evaluated Corey, Chierici and LET correlations for oil/water K_r, and found that LET was clearly the best one for both oil and water K_r. Sakhaei et alios [14] evaluated 10 common and widely used empirical K_r correlations for gas/oil and gas/condensate systems, and found that LET showed best agreement with experimental values for both gas and oil/condensate K_r.

PARAMETER TREND FUNCTIONS AND UNCERTAINTY

Then we turn to preparation of flow functions for use (usually table lookup) in the reservoir simulator [1]. The laboratory starts the imbibition flow at the practical S_{wir} value, but when we calculate the shape-parameters LET and e.g. S_{orw} and K_{rwr}, we interpret the applied water saturation in the parameter trend functions as initial water saturation S_{wi} of a grid cell in the reservoir model. The applied parameter S_{wir} that is used in normalization of the dynamic saturation is still the irreducible water saturation S_{wir} of the grid cell. The conceptual model guides us how a specific trend function must behave in order to give the desired effect on the K_r curve. Due to the large number of shape and endpoint parameters generated by the WOGn variations, it is recommended to standardize the empirical trend functions. We recommend the generic LET trend functions which originate from S_{orw} and K_{rwr} trend functions [1][9]. Generic LET trend functions for the simplest parameter trend functions AL (AR) with apex to the left (right) are for the first time displayed as formulas below. For K_r IDC2 AL = L_o, E_w, T_w, S_{orw}:

$$AL = C + \frac{\left[A - C + BS_{wi}^{M}\right](1 - S_{wi})^{L}}{(1 - S_{wi})^{L} + ES_{wi}^{T}} \tag{4}$$

For K_r IDC2 AR = E_o, T_o, L_w:

$$AR = C + \frac{\left[A - C + B(1 - S_{wi})^{M}\right]S_{wi}^{L}}{S_{wi}^{L} + E(1 - S_{wi})^{T}} \tag{5}$$

The above correlations have boundaries at S_{wi} equal 0 and 1. LET IDC2 Pc has boundaries at S_{orw} and S_{wir}, and the new LETs IDC2 Pc has also a new boundary S_{wzo} (formerly S_{wso}) in between S_{orw} and S_{wir} (replaced by S_{wi} in the trend functions). For IDC2 S_{wzo} (shown for the first time):

$$S_{wzo} = S_{wi} + C + \frac{\left[A-C+B(1-S_{orw})^{M}\right]S_{orw}^{L}}{S_{orw}^{L}+E(1-S_{orw})^{T}} \tag{6}$$

For IDC2 K_{rwr} (first shown in [9]):

$$K_{rwr} = C + \frac{\left[A-C+BS_{wi}^{M}\right](1-S_{orw}-S_{wi})^{L}}{(1-S_{orw}-S_{wi})^{L}+ES_{orw}^{T}(1-S_{wi})^{N}} \tag{7}$$

For CID3 K_{ror} (first shown in [9] with B = N = 0):

$$K_{ror} = C + \frac{\left[A-C+BS_{wi}^{M}\right]\left(1-S_{org}-S_{gro}-S_{wi}\right)^{L}}{\left(1-S_{org}-S_{gro}-S_{wi}\right)^{L}+ES_{gro}^{T}\left(1-S_{org}-S_{wi}\right)^{N}} \tag{8}$$

We don't necessarily optimize all 8 correlation parameters. We select e.g. B = 0 if we don't want a local max/min in the trend curve. The parameter N is usually zero to avoid instability at the singularity. B is usually zero, except for saturation correlations.

The discussion and formulas above show that our flow functions are linked to the reservoir model via parameter trends that are functions of S_{wi}. We use three trend functions (called low, base and high) for each parameter. For base / deterministic / most likely K_{row} model we use only base parameters. For pessimistic K_{row} we use high L_o, high E_o and low T_o i.e. more oil wet K_{row} curve than the base curve. For optimistic K_{row} we use low L_o, low E_o and high T_o i.e. more water wet K_{row} curve. For pessimistic K_{rw} we use low L_w, low E_w and high T_w i.e. more oil wet K_{rw} curve. For optimistic K_{rw} we use high L_w, high E_w and low T_w i.e. more water wet K_{rw} curve.

CAPILLARY PRESSURE AND INITIAL WATER SATURATION

The LET formula for DIC1 P_c (first shown in [8]), including an optional parameter for threshold / entry pressure P_{ct}, is displayed below.

$$Y = \frac{P_{cow}-P_{ct}}{P_{cir}-P_{ct}} \quad and \quad Y = F\left(S_{wp}\right) \quad where \quad S_{wir} \le S_w \le 1 \tag{9}$$

$$P_{cow}(S_w = S_{wir}) = P_{cir} \quad and \quad P_{cow}(S_w = 1) = P_{ct} \tag{10}$$

$$F = \frac{\left(1-S_{wp}\right)^{L}}{\left(1-S_{wp}\right)^{L}+ES_{wp}^{T}} \quad and \quad S_{wp} = \frac{S_w-S_{wir}}{1-S_{wir}} \tag{11}$$

A LET function with either L or T equal to one is called a semi-simple LET function, and a LET function with both L and T equal to one is called a simple LET function. The simple LET function is equal to the Pc-correlation of Honapour et alios [4] except for the arrangement of the empirical coefficients. Petrophysicists use the invers P_c-function (or J-function). The LET P_c function does not have a simple analytical invers function if L and T are different real numbers. An approximate invers Pc-function can usually be obtained if we represent it by a standard LET function and optimize the $L_{inv}E_{inv}T_{inv}$ parameters. In order to offer an exact analytical inverse function, we introduce a new Pc-correlation for DIC1 that is called LETh and is displayed below.

$$F = \left[\frac{(1-S_{wp})^T}{(1-S_{wp})^T + ES_{wp}^T}\right]^{1/L} \quad and \quad S_{wp} = \frac{S_w - S_{wir}}{1-S_{wir}} \tag{12}$$

Figure 1 illustrates the response of these correlations to a value of the power parameters. We select the parameter values $1/L = L_h = 2$ and $E = E_h = 10$ and $T = T_h = 0.5$. LET gives a lower capillary transition zone, and LETh gives a generally higher capillary transition zone. Note that by changing the parameter values, each correlation can match the other correlation to an acceptable / reasonably accuracy. Figure 2 illustrates the ability of mutual matching of LET and LETh. Manual optimization gave $L = 0.2$, $E = 2.8$, $T = 0.43$ and $L_h = 0.9$, $E_h = 8$, $T_h = 0.5$. Figure 3 shows LET P_c and LETh P_c match DIC1 data from a centrifuge experiment on a core plug from Norwegian Continental Shelf (NCS).

CAPILLARY PRESSURE AND WATER INJECTION

LET formulas for IDC2 P_c (first shown in [8]) are:

$$P_{cow} = (P_{cir} - P_{ct})G_n + (P_{cor} - P_{ct})F_n + P_{ct} \tag{13}$$

$$where \quad S_{wir} \leq S_w \leq 1 - S_{orw} \quad and \quad P_{cow}(S_w = S_{wzo}) = 0 \Rightarrow E_{sn} \tag{14}$$

$$G_n = \frac{(1-S_{wn})^{L_{sn}}}{(1-S_{wn})^{L_{sn}} + E_{sn}S_{wn}^{T_{sn}}} \wedge F_n = \frac{S_{wn}^{L_{fn}}}{S_{wn}^{L_{fn}} + E_{fn}(1-S_{wn})^{T_{fn}}} \wedge S_{wn} = \frac{S_w - S_{wir}}{1-S_{orw}-S_{wir}} \tag{15}$$

For an oil field with paleo o/w contact below todays initial o/w contact, it may be desirable to model the initial water saturation using a (pseudo-) IDC2 P_c curve because it may be desirable modify the spontaneous branch without disturbing the forced branch or vice versa. To achieve this flexibility we follow the method of Kralik et alios [6] for normalization of saturation, and split the spontaneous (subscript s) and forced (subscript f) branch by scaling them before and after the spontaneous water saturation S_{wzo}. We therefore introduce the new LETs P_c correlation with short (or split) saturation scaling, and display it below.

$$P_{cow} = \begin{cases} P_{cir}G_s & when \quad S_{wir} \leq S_w \leq S_{wzo} \\ P_{cor}F_f & when \quad S_{wzo} \leq S_w \leq 1 - S_{orw} \end{cases} \tag{16}$$

$$G_s = \frac{(1-S_{ws})^{L_s}}{(1-S_{ws})^{L_s} + E_s S_{ws}^{T_s}} \quad and \quad S_{ws} = \frac{S_w - S_{wir}}{S_{wzo} - S_{wir}} \tag{17}$$

$$F_f = \frac{S_{wf}^{L_f}}{S_{wf}^{L_f} + E_f(1-S_{wf})^{T_f}} \quad and \quad S_{wf} = \frac{S_w - S_{wzo}}{1 - S_{orw} - S_{wzo}} \tag{18}$$

Figure 4 shows LET and LETs correlations match IDC2 data from a centrifuge experiment on a core plug from NCS. Experimental data from the spontaneous branch is missing, as usual, but Figure 4 also shows that the LET model provides a high quality prediction of the spontaneous IDC2 branch. LET DIC3 Pc (first shown in [8]) is transferred to LETs DIC3 Pc following the same simple method as shown above.

THREE-PHASE WATER CAPILLARY PRESSURE OIL APEX

LET three-phase K_r and P_c correlations are natural generalisations of the two-phase correlations, and the reader is therefore referred to [10][15] for further information. The new LETs three-phase P_{cw} correlation is also a natural generalisation of the two-phase correlation, and the new LETs correlation for P_{cw} in an oil reservoir is shown below.

$$P_{cw} = \begin{cases} P_{cir} G_s & when \quad S_{wir} \le S_w \le S_{wz} \\ P_{cor} F_f & when \quad S_{wz} \le S_w \le 1 - S_{or} \end{cases} \tag{19}$$

$$G_s = \frac{S_{os}^{L_s}}{S_{os}^{L_s} + E_s S_{ws}^{T_s}} \quad and \quad F_f = \frac{S_{wf}^{L_f}}{S_{wf}^{L_f} + E_f S_{of}^{T_f}} \tag{20}$$

$$S_{ws} = \frac{S_w - S_{wir}}{S_{wz} - S_{wir}} \quad and \quad S_{os} = \frac{S_o - 1 + S_{wz}}{S_{wz} - S_{wir}} \quad and \quad S_{gs} = \frac{S_g}{S_{wz} - S_{wir}} \tag{21}$$

$$S_{wf} = \frac{S_w - S_{wz}}{1 - S_{wz} - S_{or}} \quad and \quad S_{of} = \frac{S_o - S_{or}}{1 - S_{wz} - S_{or}} \quad and \quad S_{gf} = \frac{S_g}{1 - S_{wz} - S_{or}} \tag{22}$$

To simplify the presentation, the P_{cw} model above is displayed without hysteresis. Generalisations of S_{orw} and S_{wzo} to three-phase saturation paths denoted S_{or} and S_{wz}, are displayed in [10], where S_{wz} is denoted S_{ws}.

CURVE FITTING, UPSCALING AND HISTORY MATCHING

Standard LET correlation can be rewritten as shown for IDC2 K_{rw} in equation (23). Using a quadratic objective function, the unknown shape parameters L, Log(E), T now occurs linearly in the optimization equations, which means that the optimization equations can be solved analytically, which means exact and without iteration i.e. fast. The LETs correlation for IDC2 P_{cow} has the same properties, and this is shown in equation (24).

$$Log\left(\frac{K_{rwr} - K_{rw}}{K_{rw}}\right) = Log(E_w) + T_w Log(1 - S_{wn}) - L_w Log(S_{wn}) \tag{23}$$

$$Log\left(\frac{P_{cor} - P_{cow}}{P_{cow}}\right) = Log(E_f) + T_f Log(1 - S_{wf}) - L_f Log(S_{wf}) \tag{24}$$

It is recommended to use residual oil S_{orw} and endpoint K_{rwr} from multispeed centrifuge experiment. We call this S_{orw} value for the ultimate residual saturation and this K_{rwr} value for the ultimate endpoint value. It is recommended to interpret K_{rw} and K_{row} curve shapes from a steady state experiment, but include an extension to the ultimate S_{orw} and K_{rwr}. The oil flow will now stop flowing due to the low K_{row} value at some point on the K_{row} curve. The ultimate S_{orw} can be treated similar / equivalent to S_{wir} and S_{wi}, and therefore be upscaled as them by using pore-volume weighted arithmetic mean. The ultimate endpoint K_{rwr} can be treated as single phase flow, and therefore upscaled (which is symbolized by < >) as:

$$\langle K_{rwr} \rangle = \langle K_{rwr} \cdot K_o(S_{wir}) \rangle / \langle K_o(S_{wir}) \rangle \tag{25}$$

This leaves us with the curve shape and its shape parameters both in core plug interpretation, upscaling and history matching.

Both K_{rw} and K_{row} often display a distinct non-Corey shape, often an S-shape, after upscaling or homogenization. This is shown by Hasanov [3][9] using upscaling, and shown by McKee [11] using homogenization. Hasanov used a traditional history matching method for a production-injection well pair. McKee divided the fine reservoir model into boxes of fine grid cells and matched inflow-outflow of each box. Each box has constant values of upscaled static properties such as permeability. This process is called homogenization. Both achieved an excellent match with the original fine grid model. Since upscaling and history matching have much in common, this indicates that the versatile LET correlation probably makes K_r adjustments within the streamline region of a production well, a very efficient last adjustment tool in history matching. Since K_r is sensitive to both saturation and pressure, adjustment of the versatile LET Kr correlation is probably also an efficient tool to combine with 4D seismic.

Use of diagonal tensor K_r (also called directional K_r) is often important for upscaling from 3D fine model to 3D coarse model, because several studies has shown that upscaled K_{rwx}, K_{rowx} and K_{rwz}, K_{rowz} can be quite different. In addition to geological / petrophysical heterogeneities, this anisotropy is probably also caused by the fact that the pressure gradient and gravity force are not parallel, and that the outflow areas of a coarse grid cell is very different in the x- and z-direction. Since this anisotropy effect occurs in upscaling, the effect of diagonal tensor K_r is probably also important in a workflow for high quality history matching.

CONCLUSION

A brief overview of the 2018 version of the LET family of correlations has been presented. These correlations have grown to cover large parts of the interpretation work, modeling work and reservoir engineering applications of flow functions. Independent researchers have compared the LET correlation to the most common and widely used empirical correlations and parametric models. Their conclusion is that LET relative permeability is the best model and estimator for all datasets that they have considered.

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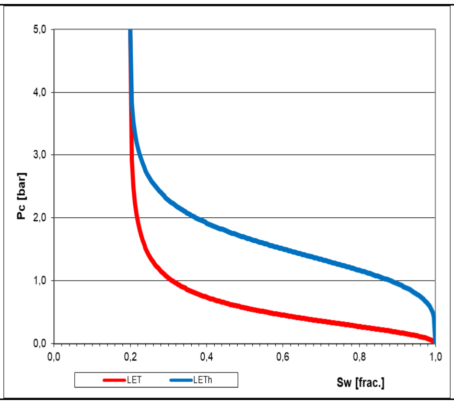

Figure 1: Illustration of response to values of power parameters in LET (red) and LETh (blue) correlations.

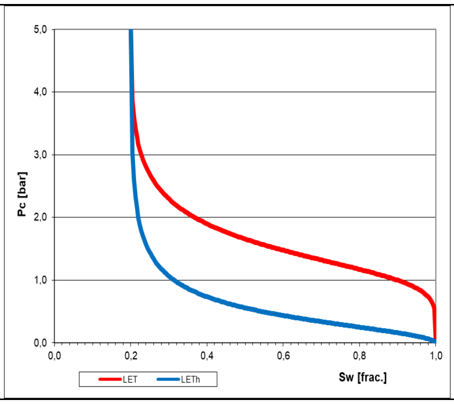

Figure 2: Illustration of the ability of mutual matching between LET (red) and LETh (blue) correlations.

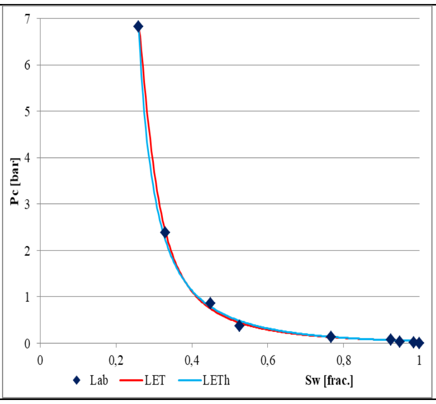

Figure 3: Primary drainage P_{cow} modeled by LET (red) and LETh (blue). Lab data from NCS in dark blue.

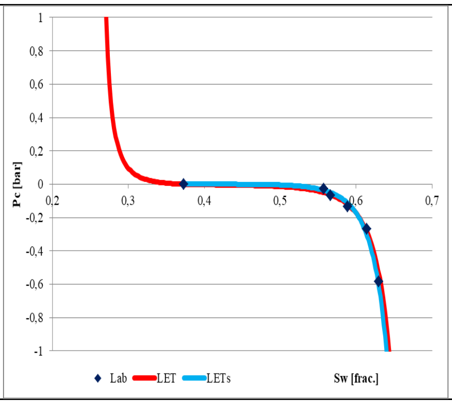

Figure 4: Imbibition P_{cow} modeled by LET (red) and the forced branch of LETs (blue). Lab data from NCS in dark blue. The figure shows a zoomed section of the original graph.