PREDICTING EFFECTS OF WETTABILITY VARIATIONS ON DISPLACEMENT BEHAVIOR AND THEIR INCORPORATION INTO INFLOW PERFORMANCE

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To my beloved family who always care about me

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ABSTRACT

Wettability plays a crucial role in reservoir fluid dynamics. Wettability controls the initial fluid distribution, fluid movement, further displacement of one fluid by another and hence effecting recovery from a reservoir. Wettability also has strong influence on capillary pressure and relative permeability. During different stages of reservoir development and depletion, this phenomenon becomes further complex, when wettability changes with the passage of time as a result of undergoing several processes. To-date, correlations are available for re-generating the laboratory data for capillary pressure curves, but there is still an immense need of set of correlations which can predict the capillary pressure curve behavior at any prevailing wettability conditions, when its behavior at any wettability is known. Keeping it in view, effective saturation correlation is modified and a set of correlations have been developed which can generate capillary pressure data at any prevailing wettability condition. Furthermore, the methodology for generating the corresponding relative permeability data at any wettability condition has been formulated. In order to use it in a time efficient manner, state-of-the-art system, comprising of suite of softwares have been designed, which is capable of generating capillary pressure and relative permeability curves, efficiently. In addition, the developed system is also capable of performing tubing flow calculations, providing real time monitoring and analyzing of subsurface production systems. The developed set of correlations and the suite of softwares, in conjunction with reservoir simulator, Eclipse 100, collectively named as state-of-the-art Subsurface Flow System Optimizer and Designer have been used for simulation studies of conventional and naturally fractured reservoir. The obtained results show improved history match and hence resulting into improved forecast and decision making, as a result of better understanding of wettability variations effect on displacement behavior and their incorporation into Subsurface Flow System Optimizer and Designer.

ABSTRAK

Keterbasahan memainkan peranan penting dalam dinamika bendalir resebor. Keterbasahan mengawal pengagihan awal bendalir, pergerakan bendalir, dan sesaran tambahan bendalir disebabkan oleh bendalir yang lain dan seterusnya memberi kesan kepada perolehan semula dari resebor. Keterbasahan juga sangat mempengaruhi tekanan kapilari dan ketelapan relatif. Fenomena ini bertambah menjadi lebih rumit pada tahap kepekatan yang berbeza, apabila keterbasahan berubah dengan masa disebabkan proses pengeluaran resebor dan selanjutnya. Sehingga kini, terdapat banyak korelasi untuk menghasilkan semula data makmal untuk lengkungan tekanan kapilari, tetapi set korelasi yang boleh meramal sifat-sifat lengkungan tekanan kapilari pada sesuatu keterbasahan masih amat diperlukan. Berdasarkan pandangan ini, korelasi keberkesanan ketepuan telah diubahsuai dan satu set korelasi telah diperolehi berdasarkan data-data yang diperolehi melalui eksperimentasi. Metodologi untuk menghasilkan data ketelapan relatif berpadanan pada mana-mana keadaan keterbasahan juga telah dibentuk. Untuk menggunakan kaedah ini dengan penggunaan masa yang lebih efisien, sebuah set perisian unggul telah direka, ia mempunyai kebolehan untuk menghasilkan lengkungan tekanan kapilari dan ketelapan relatif dengan sangat efisien. Selain itu, sistem yang dicipta ini turut berupaya untuk membuat pengiraan aliran tertiub, dan memberi cara-cara untuk membuat pengawasan semasa dan menganalisa sistem pengeluaran subpermukaan. Set korelasi dan set perisian berkenaan yang telah dihasilkan, diguna bersama perisian simulasi resebor bernama Eclipse 100, untuk mengkaji simulasi reserbor yang lazim dan retakan. Ini menghasilkan Sistem Pengurusan Aset Bersepadu yang terkini untuk memperbaharui pengurusan sesebuah resebor. Daripada keputusan yang diperolehi, ia membuktikan bahawa pemahaman yang mendalam tentang impak keterbasahan sifat pergerakan dan penggunaan Sistem Pengurusan Aset Bersepadu telah menghasilkan jangkaan dan keputusan yang lebih tepat dengan menyesuaikan data yang diperolehi dengan data-data sebelumnya.

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LIST OF ABBREVIATIONS

CHP	-	Casing head pressure
ESP	-	Electrical submersible pump
GLR	-	Gas-liquid ratio
H.S.S	-	Higher displaced fluid saturation stage
SFSOD	-	Subsurface Flow System Optimizer and Designer
IFT	-	Interfacial tension
L.S.S	-	Lower displaced fluid saturation stage
RDI	-	Relative displacement index
TFAD	-	Tubing Flow Analyzer and Designer
THP	-	Tubing head pressure
WHP	-	Wellhead pressure
WOR	-	Water-oil ratio

LIST OF SYMBOLS

A	-	Area
A_n	-	Anion
$a_{c\xi}$	-	Parameter related to fraction oil-wet bonds
B_g	-	Gas formation volume factor
B_o	-	Oil formation volume factor
B_w	-	Water formation volume factor
D, d	-	Diameter of tubing
D_L	-	Linear self-similar surface fractal dimension
dZ	-	Incremental length of tubing
f_f	-	Friction factor
F_s	-	Saturation ratio
f_{tp}	-	Two phase friction factor
g	-	Gravitational acceleration
G	-	Mass flux rate
I_o	-	Wettability index for oil
I_w	-	Wettability index for water
k	-	Absolute permeability, reservoir permeability
K_g	-	Effective permeability of gas
K_o	-	Effective permeability of oil
K_{rn}	-	Relative permeability of non-wetting phase
K_{ro}	-	Oil relative permeability
K_{rg}	-	Gas relative permeability
K_{rw}	-	Relative permeability of wetting phase or water
K_{sp}	-	Saturation solubility product
K_w	-	Effective permeability of water
L	-	Length
m	-	Mass flow rate

M_{air}	-	Molecular weight of air
M_e	-	Cation
N_c	-	Capillary number
N_{RE}	-	Reynolds number
N_w, W	-	USBM wettability number
P	-	Pressure
$\overline{P}$	-	Average pressure
P_b	-	Bubble point pressure
P_c	-	Capillary pressure
P_d	-	Displacement pressure
$P_{db.c}$	-	Base case displacement pressure
P_{NW}	-	Pressure of non-wetting phase
P_o	-	Pressure of oil phase
P_{pc}	-	Pseudo-critical pressure
P_{pr}	-	Pseudo-reduced pressure
P_{sc}	-	Standard pressure
PV	-	Pore Volume
P_w	-	Pressure of water phase
P_{WET}	-	Pressure of wetting phase
P_{wf}	-	Wellbore flowing pressure
P_{wh}	-	Wellhead pressure
q	-	Flow rate
R_s	-	Solution gas-oil ratio
r_t	-	Radius of tube
S^*, S_e	-	Effective or normalized saturation
S_D	-	Displacing phase saturation
S_{dM}	-	Maximum saturation of displaced fluid
S_{em}	-	Effective or normalized mobile phase saturation
S_o^*	-	Effective oil saturation
S_g^*	-	Effective gas saturation
S_{gc}	-	Critical gas saturation
$S_{mphase1}$	-	Mobile saturation of phase 1
$S_{mphase2}$	-	Mobile saturation of phase 2

$S_{mphase1.new}$	-	Mobile phase saturation of phase 1 under different wettability condition but at same capillary pressure
S_{nr}	-	Non-wetting phase residual saturation
S_o	-	Oil saturation
S_{om}	-	Minimum oil saturation
S_{or}	-	Residual oil saturation
$S_{rmphase1}$	-	Residual saturation of phase 1
$S_{rmphase2}$	-	Residual saturation of phase 2
S_w	-	Water saturation
S_w^*	-	Effective or normalized wetting phase saturation
S_{wc}	-	Connate water saturation
S_{wi}	-	Initial water saturation
S_{wir}	-	Irreducible water saturation
$S_{w1,\xi}$	-	Water saturation of the primary pore network
$S_{wc1,\xi}$	-	Critical water saturation of the primary pore network
S_{wr}	-	Wetting phase residual saturation
T	-	Temperature
$\bar{T}$	-	Average temperature
T_{pc}	-	Critical temperature
T_{pr}	-	Pseudo-reduced temperature
T_{sc}	-	Standard temperature
u, v	-	Velocity
u_L	-	Average liquid velocity
u_m	-	Mixture velocity
u_{sg}	-	Superficial gas velocity
u_{sL}	-	Superficial liquid velocity
v_1, v_2	-	Stoichiometric coefficients
V_b	-	Bulk Volume
W.I.	-	Wettability index
x_A	-	Mole fraction of dissolved organic in oil
$(x_A)_s$	-	Organic solubility at saturation conditions
y_L	-	Liquid holdup
$\bar{z}$	-	Average gas deviation factor

ΔP	-	Total pressure losses
ΔP_f	-	Frictional losses
ΔP_{KE}	-	Kinetic energy losses
ΔP_{PE}	-	Potential energy losses
ΔS_{os}	-	Change in oil saturation as a result of spontaneous displacement
ΔS_{ws}	-	Change in water saturation as a result of spontaneous displacement
ΔS_{wt}	-	Total change in saturation as a result of spontaneous and forced displacement
ΔW_{ext}	-	External work done
β	-	Pore shape factor
β_p	-	Universal critical exponent of accessibility function
σ	-	Surface tension or interfacial tension
σ_L	-	Liquid mixture surface tension
μ	-	Viscosity
μ_g	-	Gas viscosity
μ_L	-	Liquid mixture viscosity
μ_m	-	Mixture viscosity
μ_o	-	Oil viscosity
μ_w	-	Water viscosity
ϕ	-	Porosity
θ	-	Contact angle
θ_{adv}	-	Advancing contact angle
θ_d	-	Dynamic contact angle
θ_{rec}	-	Receding contact angle
$\Delta\theta$	-	Absolute difference in contact angle
ρ	-	Density
ρ_g	-	Gas density
ρ_o	-	Oil density
ρ_w	-	Water density
$\bar{\rho}_L$	-	Average liquid density

$\bar{\rho}_m$	-	Average mixture density
<r>	-	Mean value of pore radius distribution
ε	-	Relative roughness
ξ	-	Fraction of oil-wet bonds
γ	-	Interfacial tension
γ_g	-	Gas gravity
γ_o	-	Oil gravity
γ_w	-	Water gravity
γ_{sn}	-	Tension between the solid and the non-wetting phase
γ_{sw}	-	Tension between the solid and the wetting phase
γ_{wn}	-	Tension between the wetting phase and the non-wetting phase
λ	-	Characteristic constant
λ_g	-	Gas input fraction
λ_L	-	Liquid input fraction
λ_{rw}	-	Tortuosity ratio

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CHAPTER 1

INTRODUCTION

1.1 Background of the Problem

Reservoirs of the world are depleting rapidly, whereas the strong believe is that, the new discoveries will not be enough to fulfill future energy requirements, because of the increased fuel demand. In addition, the production from the current discoveries is declining as a result of depletion, which will further elevate the situation.

To meet the world energy requirements, in which oil plays a vital role, an effort should be made to enhance the oil recovery by improved reservoir surveillance[1-3]. For improved reservoir management, better understanding of effects of wettability and wettability variations on reservoir fluid flow is very important as it strongly influences the flow behavior within the reservoir. In the past, it was strongly believed for a long time that all reservoirs are water-wet[4] until the work done by Cuiec[5] revealed that the reservoirs can be oil-wet.

Reservoir wettability at the time of discovery can also change with the passage of time as a result of drilling, depletion, corresponding changes in a reservoir, or changes occurring when the reservoir is subjected to different enhanced oil recovery methods[6-9]. In case of immiscible fluids present in the reservoir, one will be wetting phase while the other will be non-wetting.

The wettability of a fluid depends on its ability to coat the rock surface[10,11]. Wettability[12-21] can be measured by using tests like, Amott test, modified Amott test, and USBM method. It can be expressed in terms of wettability index (W.I.), ranging from "+1" to "-1" or in degrees (contact angle), which ranges from "0^o" to "180^o".

Wettability and wettability variations[22-34] have strong influence on capillary pressure and relative permeability curves. It is very difficult and also extremely time consuming to measure the wettability variations and their corresponding effects on capillary pressure and relative permeability, using the actual core samples in the laboratory[35,36]. These parameters mainly control the displacement behavior, entrapment of one fluid by another, resulting in effecting the total recovery from a reservoir[37,38]. Any lack of information in wettability conditions[33,39] within the reservoir, will lead to improper history matching, simulation studies, and recovery estimates. Because of the effect of wettability on fluid flow behavior, it also influences the amount of fluid entering into the wellbore, resulting into affecting the tubing size selection[40-43].

Thus, there is an immense need of set of correlations to estimate capillary pressure while accounting for wettability variations[44,45] which can be further used to generate relative permeability curves at the corresponding wettability conditions, using the available capillary pressure data.

Reservoir studies to analyze the flow behavior always require very complex and tremendous efforts. To ease this situation, entire subsurface production system[46] need to be analyzed as a whole to increase the accuracy and to aid in decision making. This requires further development and refinements in correlations, software designing, leading to state-of-the-art Subsurface Flow System Optimizer and Designer (SFSOD).

1.2 Statement of the Problem

To-date, correlations exist which can re-generate capillary pressure data obtained at known wettability. However, there is an immense need of correlations which can estimate the resulting changes in capillary pressure for the entire range of wettability variations, which will be an improvement in the entire subsurface production studies while leading to state-of-the-art Subsurface Flow System Optimizer and Designer, as an Integrated Asset Management tool.

This research focuses on developing the set of correlations, which can estimate the capillary pressure for any wettability variation by utilizing the available capillary pressure data at known wettability condition. Software will be designed for the respective task which can also correspondingly generate relative permeability curves, to be used in reservoir simulation studies.

A system would be developed, to monitor the entire subsurface production system by designing state-of-the-art suite of softwares. The developed softwares, in conjunction with reservoir simulator, Eclipse 100, named as Subsurface Flow System Optimizer and Designer would result into improved simulation studies, better estimation of recovery, tubing and artificial lift designing, hence leading to optimized reservoir surveillance.

1.3 Objectives of the Study

The major objectives of this research are:

(i) To develop a set of correlations for generating capillary pressure curves at different wettability conditions.

(ii) To incorporate wettability variations effect into relative permeability data generation.

(iii) To develop state-of-the-art software for capillary pressure estimation based on wettability index and contact angle.

(iv) To develop a software for further generating relative permeability data at the prevailing wettability conditions.

(v) To develop a software for the analysis of flow through tubing capable of incorporating artificial lift design. With the developed suite of softwares including (iii) and (iv) will result into state-of-the-art Subsurface Flow System Optimizer and Designer, in which reservoir simulator, Eclipse 100, will be used for simulation purposes, making it possible to analyze the subsurface production system as a whole.

(vi) To implement the developed Subsurface Flow System Optimizer and Designer as an Integrated Asset Management tool, on different reservoirs to show the significance of developed set of correlations, methodologies and designed state-of-the art SFSOD.

1.4 Scope of the Study

In order to achieve the objectives of this research, the following scope of work has been covered:

(1) Effective wetting phase saturation correlations will be modified to obtain a standardized correlation for effective or normalized mobile phase saturation.

(2) Capillary pressure curve will be analyzed and segmented into different flow stages based on the displaced fluid saturation changes, during displacement process.

(3) A set of correlations will be developed representing the flow stages, capable of generating capillary pressure curve at any wettability conditions and the results obtained will be compared with the available capillary pressure data and data generated from Brooks and Corey model.

(4) Developed set of capillary pressure correlations will be incorporated into capillary pressure and saturation based relative permeability models and will be solved to generate relative permeability data at any prevailing wettability conditions.

(5) State-of-the-art software will be designed using Visual Basic 2008, to generate capillary pressure and relative permeability data in a time efficient manner, which will be used during reservoir simulation studies by using Eclipse 100.

(6) Incorporating effect of changes in reservoir wettability on tubing design, by designing software capable of handling any orientation of the well.

1.5 Significance of the Study

This research enables capillary pressure data generation under different wettability conditions and accordingly generating relative permeability curves at the above prevailing conditions. Overall optimization of the subsurface production system and decision making would improve by employing designed state-of-the-art Subsurface Flow System Optimizer and Designer. Developed SFSOD will result into improved history matching during simulation studies and monitoring flow through tubing, resulting into better reservoir management, recovery estimates and hence increased profitability.

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