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Research paper

Theoretical Modelling of Gravity Segregation in WAG Improved Oil Recovery for Tilted Reservoirs

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A b s t r a c t

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Water injection, gas injection or WAG flooding can have drawbacks such as increases in residual oil, introducing areas where oil sweeping does not occur and fluid segregation. Gravity segregation needs some time and distance to occur, so that the vertical conformance is good in places near the well and will be deterred as far from injected well. The size of these regions is principally related to injection rate, vertical permeability and density difference between water and gas. Furthermore, fluid injection has adequate length in which the vertical conformance is maintained. In IOR flooding processes it is essential to design a reservoir flooding that water-gas mixed the region is larger relative to the reservoir volume to be flooded by each well. This study benefits from prior associated researches to investigate the dominant factors controlling segregation around the injection wells and proposes a new analytic model for tilted reservoirs. The model has better prediction to the length of segregation rather than former models.

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1. Introduction

The most renowned approaches in IOR are water flooding, gas flooding and water alternating gas (WAG) flooding. In gas flooding, gas overrides to top of the formation due to the gas' low. In this sense, contradictory results are obtained when flooding a reservoir with water [1-3]. To reach the maximum hydrocarbon recovery it is expedient to maintain vertical conformance throughout the flow path from injection wells to production wells. This maintenance causes injected fluid volumes to preserve a piston-wise state and lessens fingering in the formation. In 1982 Stone proposed a convenient model for gravity segregation which Jenkins in 1984 enhanced [4,5]. This model is employed for the steady sate, uniform co-injection of gas and water in a homogeneous porous medium with the assumption that in the steady state injection, the formation separates into three specific divisions of uniform saturation that have sharp boundaries linking them. These subordinate zones consist of an override gas flowing zone, an under ride water flowing zone and a mixed zone with both gas and water flowing in coexistence.

By supposing that the horizontal (or radial) coordinate of pressure gradient is independent of its vertical coordinate at any location, Stone and Jenkins derived equations for the specific length of complete segregation of water, gas or WAG injection in rectangular and cylindrical reservoirs, respectively as:

$$L_g = \frac{Q}{k_z(\rho_w - \rho_g)gW\lambda_{rt}^m} \tag{1}$$

$$R_g = \sqrt{\frac{Q}{\pi k_z(\rho_w - \rho_g)g\lambda_{rt}^m}} \tag{2}$$

Where Q is the total injection rate of gas in addition to water, k_z is the vertical permeability, g is the gravity acceleration, W is the formation thickness in the vertical direction, ρ_w and ρ_g are densities of water and gas respectively and λ_{rt}^m is the total relative mobility in a mixed zone.

Eqs 1 and 2 were developed into dimensionless equations by Shi and Rossen, a dimensionless equation based on Eq 1, for rectangular coordinates is [6]:

$$\frac{L_g}{L} = \frac{1}{N_g R_L} = \left(\frac{|\nabla p|_m}{(\rho_w - \rho_g)g}\right)\left(\frac{Hk_h}{Lk_Z}\right) \tag{3}$$

In Eq 3, L is the reservoir length, N_g and R_L are dimensionless gravity numbers and reservoir aspect ratio, respectively, $|\nabla p|_m$ is the lateral pressure gradient in the mixed zone at the injection face, H is reservoir height and k_h is horizontal permeability.

It should be noted that a similar equation for cylindrical coordinates is also presented by Shi and Rossen (1998). Equations above could be utilized to simulate results of gas, water and WAG injection to match experimental data [6-8].

In 2009 Jamshidnezhad argued that all Stone-based Equations, like Jenkins', 1984, Shi and Rossen's, 1998 and lastly Rossen and Van Duijin's, 2004 , equations which have been used for simulating flooding injections, are only applicable to horizontal reservoirs and they yield unreliable results if the reservoir is tilted. He proposed an empirical correlation based on simulation data which mitigated this shortcoming [9].

$$L_{G,New} = L_{G,Stone} \frac{(\cos\theta)^{-2.288}}{(\Delta\rho)^{-0.0279}} \tag{4}$$

The debatable matter in Jamshidnezhad's work is that he based his theories on practical data while stone's formulas were obtained analytically.

In this research we exploited an innovative analytical model valid for tilted reservoirs.

2. Theoretical Modeling

2.1. Derivation of Equations

Equations founded on Stone's equation take the following assumptions into consideration [10]:

(1) Reservoir homogeneity; although porous media may be anisotropic. ($k_h \neq k_v$)

(2) Reservoir is either rectangular or cylindrical; with an open outer boundary. The injection well is completed over the entire vertical interval. The reservoir is confined by sealed boundaries above and below.

(3) The system is at steady state, with steady injection of fluids at volumetric rate Q and injected fractional flow of water $f_w = f^j$. This implies that any remaining oil in the region of interest is at its residual saturation and immobile.

(4) Phases are considered incompressible. No mass transfer between phases.

(5) Assuming absence of dispersive processes, including fingering and negligible capillary pressure gradients.

(6) Newtonian mobilities of all phases.

(7) Immediate attainment of local steady-state mobilities, which depend only on local saturations.

(8) The reservoir comprises three regions of uniform saturation, with sharp boundaries between them, as illustrated in Figure 1.

(a) An override zone with only gas flowing

(b) An underride zone with only water flowing

(c) A mixed zone with both gas and water flowing

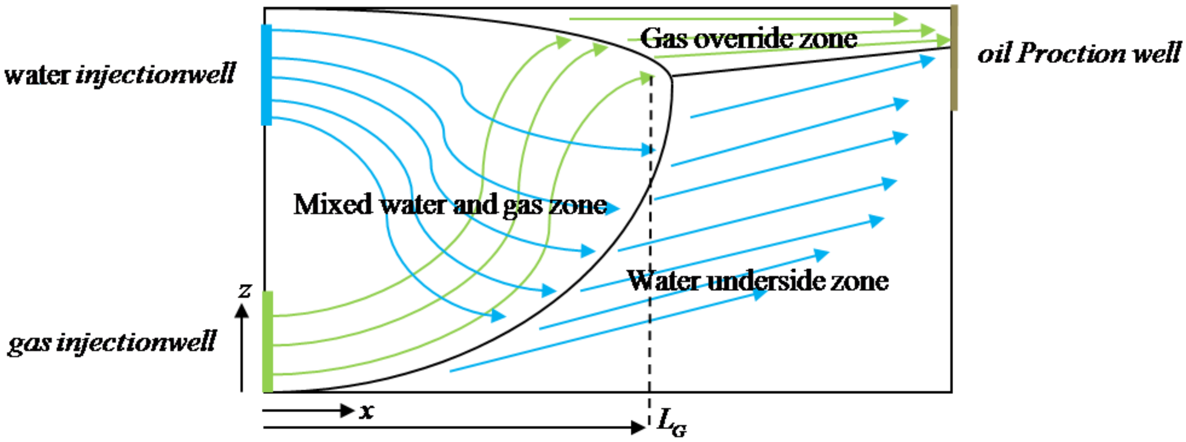

Fig. 1: Schematic of the three uniform zones in Stone and Jenkins' model.

(9) At each horizontal position x (or r), the pressure gradient in the x (or r) direction is the same in each three regions; i.e. $\partial / \partial z(\partial P / \partial x) = 0$. But $\partial P / \partial x$ can (and does) vary with x.

(10) The reservoir is horizontal.

We ignore the last assumption and solve the problem for a tilted case. If there is a gradient θ between reservoir and the horizontal surface, the gravity vector is split into two components. Perpendicular, countercurrent flow of water and gas within simultaneous flow zone is validated by applying the Buckly-Levertt theory to a differential element of space moving through the system with velocity equal to the injection velocity. Figure 2 demonstrates a schematic of our new case with its differential element.

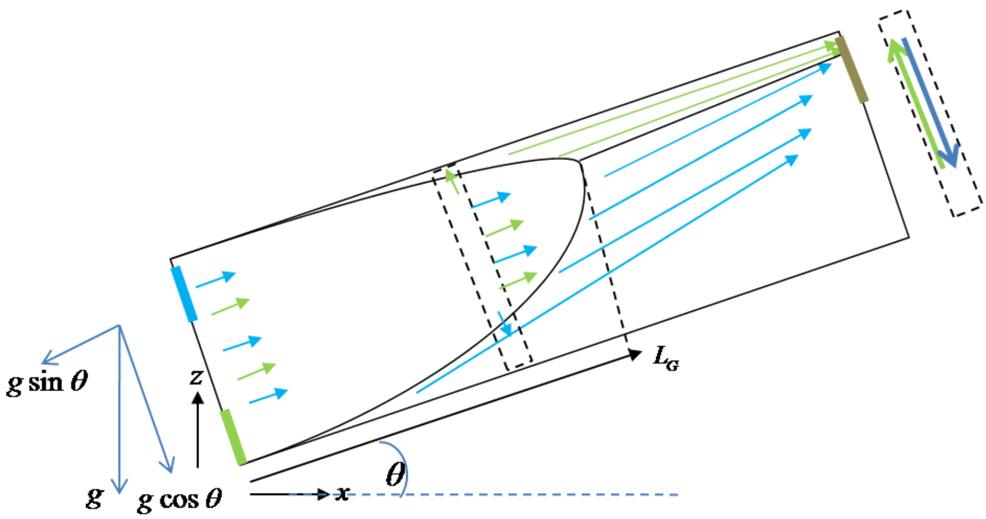

Fig. 2: Volumetric element for a tilted reservoir model. (Green lines show gas streams and blue lines show water streams).

Oil in the immediate vicinity of the wellbore will be displaced by the miscible gas and water injection mixture as observed in Figure 2. At steady state conditions, this region approaches the uniform water saturation ($S_{w,i}$) at which the water-gas ratio is equal to the water-gas mobility ratios and so the water-gas ratio can be evaluated from Darcy's equation:

$$\text{Water} - \text{gas ratio} = \frac{q_W}{q_G} = \frac{\frac{K_w}{\mu_w}\left(\frac{\partial P}{\partial l} + \rho_w g \sin\theta\right)}{\frac{K_g}{\mu_g}\left(\frac{\partial P}{\partial l} + \rho_g g \sin\theta\right)} = \frac{k_w \mu_g}{k_g \mu_w} + \frac{k_w A}{\mu_w} \times \frac{\Delta\rho g \sin\theta}{q_g} \tag{5}$$

In the reservoir's mixed zone, the gravity forces cause two phase segregation and consequently the lighter fluid, gas, rises upwards while water descends downwards. Since the net fluxes of both water and gas at the boundaries of the volume element is zero, the problem is simplifies to a gravity segregation along the differential element. The initial saturation of water along the element is invariable at a value of $S_{w,i}$. As the element moves across the reservoir the segregation accrues and the saturation changes in to steps from (1-S_{org}) to $S_{w,i}$, and from $S_{w,i}$ to (1-S_{orw}). The region of high gas saturation develops at the top of element and descends to the center of element at a constant velocity. Similar to this region a high water saturation region is formed at the bottom of element and rises. If compressibility effects are considered negligible, the countercurrent gas and water velocities are equal in magnitude. By applying Darcy's law to each phase separately and eliminating the vertical pressure gradient ($\frac{\partial P}{\partial z}$) which is equal in both cases, the velocity of segregation becomes:

$$V = \frac{k_w}{\mu_w}\left(\Delta\rho g \cos\theta\right) \Big/ \left(1 + \frac{k_w \mu_g}{k_g \mu_w}\right) \tag{6}$$

By introducing equation 5 into equation 6, the velocity of segregation in a slanted reservoir simplifies to:

$$V = \frac{q_g \Delta\rho g \cos\theta}{\left(\frac{\mu_w Q_T}{k_w} - A\Delta\rho g \sin\theta\right)} \tag{7}$$

Where k_w is the effective permeability of water at a saturation of $S_{w,i}$. If divide the mixed zone into two part from its summit, so that all the gas that segregates at the lower part is cross the perpendicular plate (with an inclination of θ degrees rather than horizontality) of reservoir by the velocity of V. By material balance:

$$V L_G W = Q_T f_w f_g \tag{8}$$

By incorporating equation 7 into equation 8, the length of segregation in the tilted rectangular reservoir ensues as:

$$L_G = \frac{f_w \left(Q_T \frac{\mu_w}{k_w} - A\Delta\rho g \sin\theta \right)}{W\Delta\rho g \cos\theta} \tag{9}$$

Where L_G is the length of segregation, f_w is water fraction of flow, Q_T is the total injected fluid (water as well as gas), $\Delta\rho$ is difference in density of water and gas, W is width of reservoir or horizontal distance between analogous injection wells, μ_w is water viscosity, A is the cross sectional area (thickness times W), g is gravity acceleration and θ is the degree of deviation of tilted reservoir as depicted in Figure 2.

Equation 9 which appears similar to Jenkins' (1984) equation for length of segregation in WAG flooding processes of horizontal cases has a broader spectrum and can be utilized for calculations in slanted reservoirs as well as horizontal reservoirs.

2.2. Simulating the new model

The assumptions made by Stone (1982), Jenkins (1984) and Rossen and van Duijn (2004), as mentioned earlier, are used in the simulations [3, 5, 10]. The only difference is that the reservoir is tilted reservoir rather than horizontal.

In Jamshidnezhad's work (2009), a Cartesian grid system of 200m*1m*40m dimensions is simulated. Fluid and rock properties of his model have been replicated from his paper and we remodel his work to analyze the results of our model. The CMG (Computer Modeling Group, Alberta, Canada, 2008) advanced processes' simulator is used in both researches for modeling the three-phase multi-component fluid flow. Time to reach steady state conditions is 20 years of injection, identical to Jamshidnezhad's assumption. The values used to simulate the model are available in Table 1. A schematic of the saturation curve of water and gas phases and slanted reservoir is also plotted in Figure 3.

Table 1: Fluid properties used in the simulations

Gas	Quantity	Unite
Density (ρ_g), at reservoir conditions	165	kg/m^3
Viscosity (μ_g) at reservoir conditions	1.886E-5	Pa s
Compressibility (c_g)	5E-12	1/bar
Water		
Density (ρ_w), at reservoir conditions	1000	kg/m^3
Viscosity (μ_w) what conditions	0.001	Pa s
Compressibility (c_w)	0	1/bar
Residual water (S_{wr})	0.20	
Injected water fractional flow (f_w)	0.21	
W , injection well distance (wide of model)	1	m
A , cross section area	40	m^2
Q_T , total fluid injection rate	221.1	sm^3/day

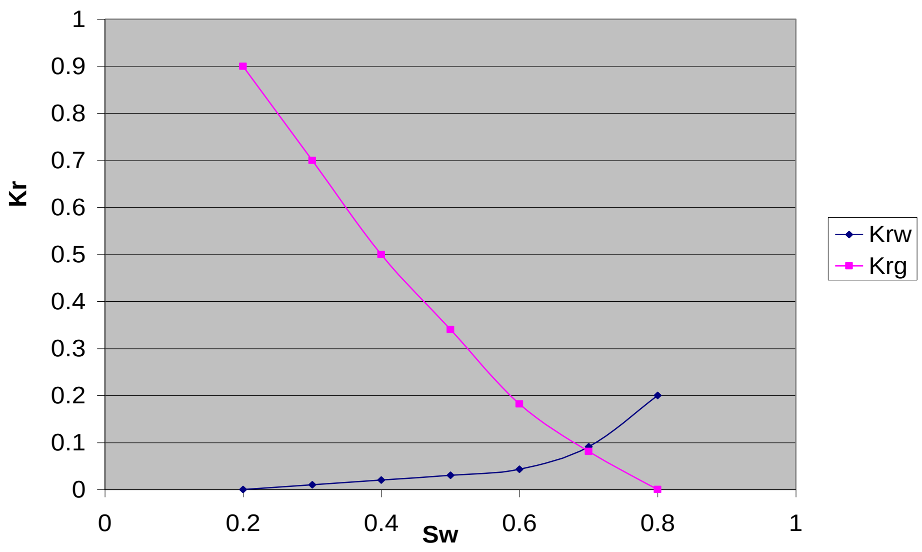

Fig. 3a: Relative permeability curves for water and gas.

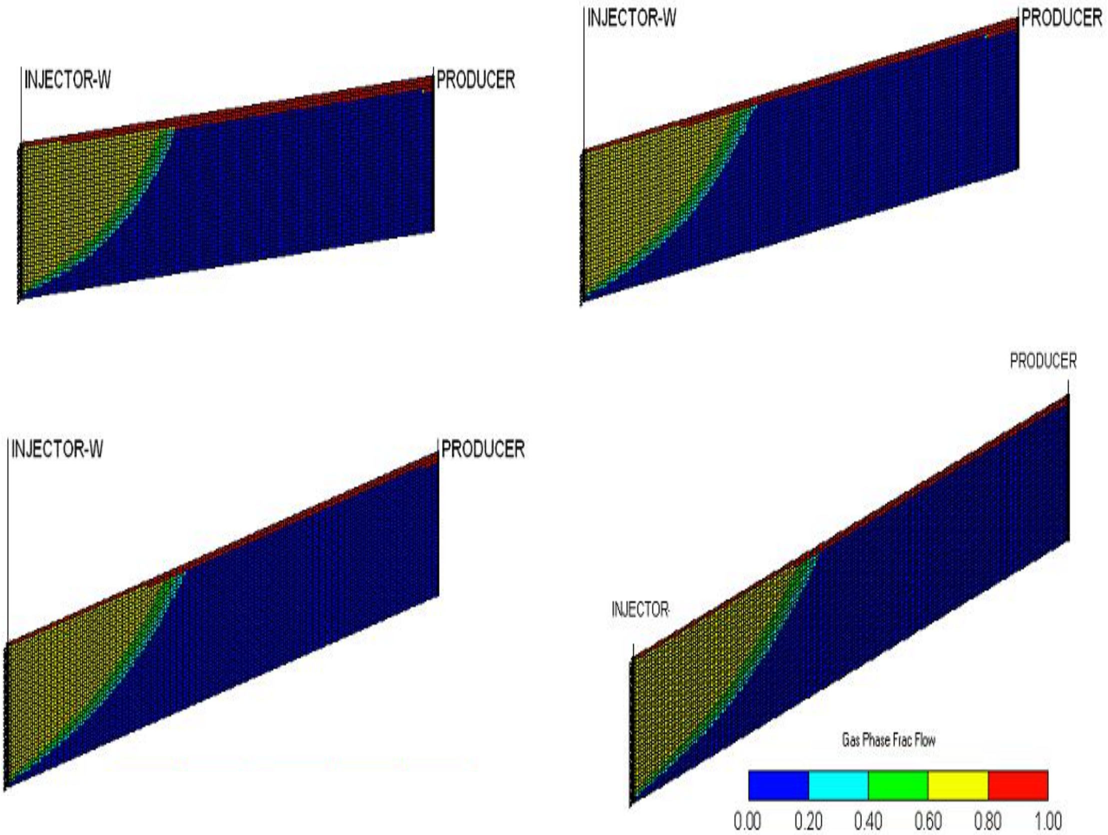

Fig. 3b: Simulated reservoir with tilting angles of 5^0, 10^0, 20^0, 30^0. Complete segregation at Grid 77, 80, 85, 95.

3. Results and discussion

To analyze the results of simulation and check recent model with stone (1982)-Jenkins (1984) model and Jamshidnezhad's correlation, Table 2 is accomplished.

Table 2: Results of simulation and prediction of different models

Angle of tilting	Stone's model (m)	Jamshidnezhad's correlation(m)	New model (m)	Simulator (m)
0	65	78.42	65	72
5	65	79.10	75.22	77.29
10	65	81.21	79.35	81.23
15	65	84.89	85.21	86.96
20	65	90.41	88.90	90.45
30	65	108.98	107.3	109.7
60	65	382	225	240
90	65	∞	∞	∞

The WAG injection is analyzed in 7 different inclination angles of 0^0, 5^0, 10^0, 15^0, 20^0, 30^0 and 90^0. Simulation results indicate that Stone, 1982, model is impervious to slope alteration and the segregation length remains constant for various slanted reservoirs. On the other hand, Jamshidnezhad's model is more responsive to inclination deviation and is therefore more precise. By increasing the slope, the segregation length is increased. An associated flaw with this model is that if the slope is a negative value or the deviation degree exceeds 0 to 30^0 limits, results become inconvenient. An addition defect arises from the fact that this model is a correlation of a special case and isn't general. As demonstrated in Figure 4 and Table 2 the new proposed model is more general, theoretical based and has the least error.

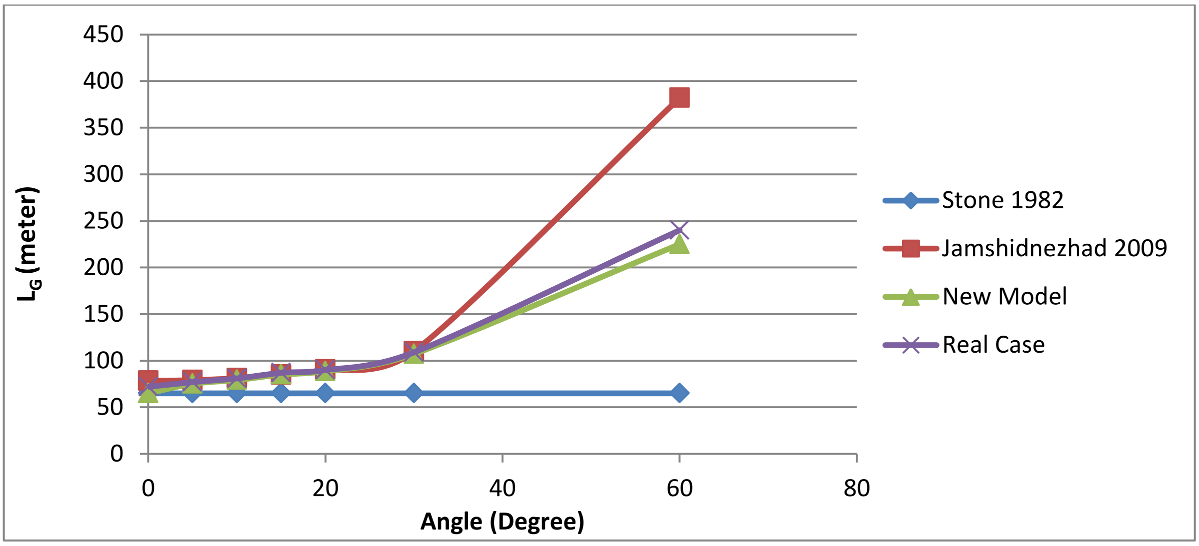

Fig. 4: L_G versus slop of reservoir, Prediction Results of different models

4. Conclusions

By taking advantage of theoretical formulas such as Darcy law's of motion in porous media, Buckly-Levert's theorem and material balance equations we were able to enhance Stone-Jenkins' equation for characteristic length of segregation in an WAG IOR process. Our generated formula is applicable for a broader range of flow and reservoir conditions. Furthermore, we investigated the effect of inclination angles on a complete segregation length in a gas improved oil recovery process. We concluded that the length of segregation point elongated with increasing inclination of the reservoir. This means that Tilting lags the complete length of segregation and so co-injection of gas and water recovers more oil in tilted reservoirs in comparison to horizontal reservoirs.

Moreover, Due to the practical nature of Jamshidnezhad's correlation it is not efficient for a variety of mobility values which the injected fluid can retain.

From previous formulas we can deduce that the length of segregation is a function of water mobility, gas fractional flow, density difference between water and gas, relative permeability of displacing phases, and of course the slope of reservoir (tiltness).

References

[1] Blackwell, R. J., Terry W. M., Rayne, J. R., Lindeley, D. C. and Henderson, J. R. , *Recovery of oil by Displacement with Water-Solvent Mixtures,* Trans., AIME ,1960: 219-293.

[2] Candle, B. H. and Dyes, A.B. *Improving Miscible Displacement by Gas-Water Injection*, Trans., AIME, 1958: 213-281.

[3] Holt, T., and Vassenden, F. Skjaeveland, s. m., Skauge, A., Hindraker, L., and Sisk, C. D. *Physical Gas/Water Segregation Mode*, RUTH 1992-1995 Program Summary, Norwegian Petroleum Directorate, Stavanger. 1996: 75-84.

[4] Stone, H. L.Vertical, *Conformance In An Alternating Water-Miscible Gas Flood*. SPE Annual Technical Conference and Exhibition, 26-29 September, New Orleans, Louisiana, SPE-11130-MS, 1982.

[5] Jenkins, M. K., *An Analytical Model for Water/Gas Miscible Displacements*, SPE 12632, presented at the 1984 SPE/DOE Symposium on Enhanced Oil Recovery, Tulsa, OK, 1984. April 15-18

[6] Shi, J,-X.,and Rossen, W,R. *Simulation of Gravity Override in Foam Processes in Porous Media*, SPEREE1,1998: 148-154.

[7] Cheng, L., Reme, A. B., Shan, D., Coombe, D. A., and Rossen, W. R. *Simulating Foam Processes at High and Low Foam Qualities*. SPE 59287, presented at the SPE/DOE Symposium on Improved Oil Recovery, Tulsa, OK, 2000. 3-5 April.

[8] Holt, T., and Vassenden, F. *Reduced Gas-Water Segregation by Use of foam*. Presented at the European Symposium on Improved Oil Recovery, The Hague, The Netherlands, 1997: 20-22.

[9] Jamshidnezhad. *Gravity Segregation in Gas improved Oil Recovery of Tilted Reservoirs*, SPE119996, 2009.

[10] Rossen, W.R. & Duijn, C.J. van. *Gravity segregation in steady-state horizontal flow in homogeneous reservoirs*. Journal of Petroleum Science and Engineering, 2004; 43(1-2): 99-11