DIMENSIONLESS NUMBERS IN GAS-ASSISTED GRAVITY DRAINAGE PROCESSES

^a Bautista, E. V. ¹; ^b Barillas, J. L. M.; ^b da Mata, W.; ^b Dutra Jr, T. V.

^a Petrosynergy Ltda., Brazil

^b Universidade Federal do Rio Grande do Norte, Departamento de Engenharia de Petróleo, Brazil

ABSTRACT

Numerical simulations of Gas-Assisted Gravity Drainage (GAGD) processes were analyzed by using three dimensionless groups: Capillary Number (the ratio between viscous and capillary forces), Bond Number (the ratio between gravity and capillary forces), and Gravity Number (the ratio between gravity and viscous forces). The effect of each number on the oil recovery factor was evaluated. The simulation results indicated that higher oil recoveries were obtained with higher Capillary and Bond Numbers, and lower Gravity Numbers. At last, based on simulations, this work proposes that numerical simulations with dimensionless groups can be useful tools to predict the performance of Gas-Assisted Gravity Drainage processes.

KEYWORDS

simulation; gravity; capillary; viscosity; modeling

¹ To whom all correspondence should be addressed.

Address: Petrosynergy Ltda., Av. Comendador Gustavo Paiva, 2789, Mangabeiras, Maceió, Alagoas, Brazil
Zip Code: 57038-360 | Mobile phone: +55(82)9929-7721 | e-mail: ernesto.vargas@petrosynergy.com.br
doi:10.5419/bjpg2014-0014

1. INTRODUCTION

The Gas-Assisted Gravity Drainage (GAGD) process appeared as an alternative to conventional methods of gas injection, which are affected by fluid gravity and result in low oil recoveries. The GAGD process (Figure 1) uses existing vertical wells to inject gas into the top of a horizontal reservoir, and a horizontal producer well is located either at the bottom of the reservoir or above the oil-water contact (Rao et al., 2004).

The success of gravity-stable gas injection in dipping reservoirs encouraged the development of a GAGD process for horizontal reservoirs (Rao et al., 2004). Besides the evaluation of the effects of the operational and reservoir parameters on oil recovery, the search for individual effects of capillary, viscous, and gravitational forces has been an important component in developing the GAGD (Kulkarni et al., 2005).

Dimensionless groups such as Capillary Number (N_c), Bond Number (N_b), and Gravitational Number (N_g) have been used to describe the interplay among capillary, viscous, and gravity forces in the GAGD process (Kulkarni et al., 2005).

The Capillary Number (Grattoni et al., 2001), which describes the relationship between viscous and the capillary forces, is defined by Equation 1, as follows:

$$N_c = v\mu/\sigma \quad (1)$$

Where v is the Darcy velocity of the injected gas in m/s, μ is the viscosity of the gas injection in Pa.s, and σ is the interfacial tension in N/m.

The Bond Number (Edwards et al., 1998), which describes the relationship between gravity and capillary force, is calculated using Equation 2, as follows:

$$N_b = \Delta\rho g k / \sigma \quad (2)$$

Where $\Delta\rho$ is the density difference between the oil reservoir and the injected gas in kg/m³, g is the gravitational constant in m/s², and k is the vertical permeability in m².

The Gravity Number (Shook et al., 1992), which measures the relationship between gravity and viscous force, is defined by Equation 3, as follows:

$$N_g = \Delta\rho g k / (v\mu) \quad (3)$$

Figure 1. Conceptual diagram of GAGD (Bautista, 2010).

For the GAGD process, **Kulkarni (2005)** and **Sharma (2005)** conducted studies using a physical model and core floods to evaluate the effect of capillary, viscous and gravitational forces on the oil recovery through N_c , N_b , and N_g . The results obtained are considered good, if compared with field data. However, other studies failed to show a relationship between some dimensionless groups and the oil recovery in the GAGD process because the range of experiments was not sufficiently wide (**Mahmoud, 2006; Tham et al., 2011**).

A few studies on the numerical simulation models of the GAGD process have applied the dimensionless groups. They focus on the evaluation of operational (i.e., the gas injection rate, gas injection type, and well pattern) and reservoir parameters (i.e., fractures, permeability, oil viscosity, and wettability), which relate their effects on the oil recovery factor. However, the interplay among the capillary, viscous, and gravitational forces is yet to be evaluated in that type of model (**Akhlaghi et al., 2012; Bautista 2010; Jadhawar, 2010; Pinto, 2009; Tham et al., 2011**). Therefore, the objective of this work is to show the interplay

among the three forces using dimensionless groups. The work seeks to show the influence of dimensionless group over oil recovery factor before and after breakthrough takes place.

2. MATERIALS AND METHODS

2.1 Reservoir modeling

A two-dimensional numerical model was created using the simulator "GEM" from CMG (Computer Modelling Group, version 2007.11). The features of the simulator (i.e., the equation-of-state compositional simulator, which can simulate the gas injection process) make the GAGD process correctly modeled (**Jadhawar, 2010; Bautista, 2010**).

The properties of the Cartesian grid and the single porosity reservoir model (Table 1) used in this study are similar to those of a Brazilian sedimentary basin.

Table 1. Reservoir model.

Reservoir grid (i,j,k)	Cartesian 1 x 201 x 45
Grid size (m)	30 x 1 x 1
Grid top (m)	2652
Layer thickness (m)	1
Reservoir Temperature (°C)	104
Porosity (%)	0.21
Horizontal Permeability (mD)	10
Vertical Permeability (mD)	1
Reference depth (m)	2697
Reference pressure (kPa)	28370
Rock compressibility (1/kPa)	7.3×10^{-7}
Water-oil contact (m)	2743
Original oil in place (m ³)	25742

Table 2. Reservoir fluid model.

Pseudocomponent	Mol (%)
Nitrogen	0.16
Carbon Dioxide	0.91
Methane	36.47
Ethane	9.67
Propane	6.95
Iso-Butane & N-Butane	5.37
Iso-Pentane & N-Pentane	2.85
Hexane	4.33
Heptane Plus ^a	33.29

^a Molecular Weight = 218 and Specific Gravity = 0.8515

Table 3. Rock-fluid properties.

Connate water saturation (%)	0.35
Critical water saturation (%)	0.35
Residual oil saturation for water-oil table (%)	0.25
Residual oil saturation for gas-liquid table (%)	0.10
Critical gas saturation (%)	0.10
Gas relative permeability at connate liquid	0.60

A compositional fluid model was obtained using the CMG's WINPROP software. Table 2 shows nine pseudo-component fluid models. The PVT data was reported by **Danesh (1998)**. The API gravity oil is 35.1 at 15.5 °C. Pure carbon dioxide is used as injected gas. The CMG's WINPROP predicted the values of 18166 kPa and 34068 kPa for saturation pressure and minimum miscibility pressure, respectively.

The reservoir used in this study was a water-wet reservoir. A correlation was used to obtain the relative permeability curves (**Honarpour et al., 1986**). Table 3 lists the values used in the correlation. Capillary pressure effects were neglected in this study.

The injector well completion is located in the grid block 1,101,1. The producer well completion is located in the grid block 1,101,45. The simulation is terminated after 20 years.

3. RESULTS AND DISCUSSION

The results were obtained by running seven different simulations. The gas injection rate varied among the following values (in m³/d): 1.6×10^3 , 3.3×10^3 , 6.6×10^3 , 9.9×10^3 , 13.1×10^3 , 16.4×10^3 , and 19.7×10^3 , under standard conditions. The minimum miscibility pressure was not attained for any of the gas injection rates.

For each simulation case, Equations (1), (2) and (3) were used to evaluate the interplay of capillary, viscous, and gravitational forces on the numerical model of the GAGD process. The interplay of these forces was analyzed in terms of pore volume injected (PVI %) instead of time.

3.1 Effect of Capillary Number (Nc)

Figure 2 shows the effect of Nc on oil recovery. For the same PVI, the variation from lower to

Figure 2. Effect of the Capillary Number on oil recovery factor.

Figure 3. Comparison of the gas injection rate on oil saturation before the breakthrough time.

higher gas injection rate is plotted from left to right.

Note that in Figure 2, at constant gas injection rate, there is an increase in oil recovery with a decrease in N_c , which indicates that the capillary force is predominant over the viscous force. It is believed that when the gas injection rate is not sufficient to maintain or increase the reservoir pressure, the interfacial tension acts against the gas flow, and the injected gas does not have a good microscopy sweep efficiency to drain the residual oil. A similar behavior was observed by [Grattoni et al. \(2001\)](#).

At the same PVI, Figure 2 also shows that before the gas breakthrough (BT), higher oil recoveries were obtained at lower N_c , which indicates that, to increase the oil recovery, the capillary force should be predominant with a low gas rate. However, after BT occurs, a higher final oil recovery is obtained at a higher N_c . In this case, the magnitude of the viscous force is increased at higher gas injection rates.

Figure 3 shows the comparison between the lowest and the highest gas injection rates at 10% PVI before BT. Oil saturation is the parameter shown in the GAGD model section. In the case with a lower gas injection rate, the gas-invaded zone contacted more oil than the one with a higher gas rate. In other words, the injected gas leaves behind the residual oil, most likely because of the interfacial tension. Notice that the residual oil saturation in the gas-invaded zone is higher in the first case (0.25-0.4) than in the second one (0.15-0.25). However, the average oil saturation is lower in the first case than in the second case. Therefore, before the BT, the macroscopic sweep efficiency is better than the microscopic sweep efficiency to recover more oil when N_c is low in the GAGD process.

Figure 4 shows the comparison between the lowest and the highest gas injection rates at the 100% PVI after the gas BT time. Notice that, in the second case, the gas-invaded zone contacted more oil than the first case in the reservoir model. The injected gas displaced more oil because, at a higher N_c , the interfacial tension decreased reducing

Figure 4. Comparison of the gas injection rate on the oil saturation after the breakthrough time.

residual oil saturation. The residual oil saturation remains higher in the first case (0.2-0.35) than in the second case (0.15-0.25). It is believed that the microscopic sweep efficiency is better than the macroscopic sweep to improve oil recoveries at higher N_c after the BT. This behavior was also observed by [Kulkarni et al. \(2005\)](#) in the physical models and the core floods of the GAGD process, where a higher oil recovery was obtained at a higher N_c . These authors also concluded that a lower magnitude of the capillary force corresponded to a better efficiency of the injected gas to counter the capillary trapping and mobilize the residual oil.

3.2 Effect of Bond Number (N_b)

The effect of N_b on the oil recovery is illustrated in Figure 5. For the same PVI value, the variation from lower to higher gas injected rate is plotted from left to right. At a constant gas injection rate, one can observe that there is an increase in oil recovery with a decrease in N_b . This effect was not consistent with the experiments using the physical models performed by [Grattoni et al. \(2001\)](#). The authors described that there was an increase in oil recovery with an increase in N_b when the gas

injection rate was constant. The reason for this inconsistency can be that [Grattoni et al. \(2001\)](#) used N_b as a function of the average grain radius and not as a function of the permeability.

One can also observe in Figure 5 that, before the BT and at the same PVI, higher oil recoveries were obtained at a lower N_b . In other words, the capillary force is predominant to gravity to drain more oil at a lower gas injection rate. In this case, it is believed that the gas-oil density difference was insufficient to drain more oil at a lower N_b . If lower N_b improves the contrast between fluid densities to enhance the gravity drainage, it increases the interfacial tension between the same fluids. Similarly, at higher N_b , the interfacial tension can be reduced (miscible condition).

After the gas BT time, higher oil recovery is obtained at higher N_b . Thus, the magnitude of the capillary force loses predominance against the magnitude of gravity. In this case, the fluid densities were favored over the capillary effects at a higher gas injection rate. Similar results were obtained from the experiments of [Kulkarni et al. \(2005\)](#), where the final oil recovery is obtained at a higher N_b .

Figure 5. Effect of the Bond Number on the oil recovery factor.

3.3 Effect of Gravity Number (Ng)

The effect of N_g on oil recovery is shown in Figure 6. For the same PVI value, the variation from lower to higher gas injected rate is plotted from right to left.

Figure 6 depicts an increase in oil recovery with an increase in N_g at a constant gas injection rate, which indicates that gravity is predominant over the viscous force to recover oil. This result can demonstrate that gravity is one of the principal mechanisms to drain oil in the GAGD process. **Mahmoud (2006)** emphasized the importance of maintaining the dominance of gravity in the GAGD process. Nonetheless, the presence of the viscous force is also important to maintain the reservoir pressure and sweep more oil from the porous media in the GAGD process.

Figure 6 also shows that before the gas BT, a higher oil recovery is obtained at a higher N_g when the gas injection rate is low. In other words, gravity is predominant over the viscous force. When BT occurs, higher oil recovery is obtained at a lower N_g when the gas injection rate is high. Thus, the gravity magnitude decreases in relation to the viscous force. Nevertheless, the N_g value remains above 1, which implies that, after BT, gravity loses its dominance over the viscous force but its

magnitude remains slightly higher than the magnitude of the viscous force to drain the oil.

Similar performance was observed in the GAGD process experiments performed by **Mahmoud (2006)** and **Sharma (2005)**. The results of these experiments are shown in Table 4, which lists the N_g values as a function of the final oil recovery at different gas injection rates. One can observe that the higher final oil recovery is obtained at a lower N_g , when a higher gas injection rate is applied, which is consistent with the results of this study after the BT.

It is believed that gravity has predominance over viscous force in the GAGD process because of the gas front velocity. Figure 7 shows the effect of the gas front velocity on the oil recovery in a numerical model of GAGD. Notice that at the BT time, higher oil recoveries are obtained at a lower gas velocity. Because the viscous force is a function of the gas front velocity, its magnitude will decrease with respect to gravity. It is believed that, at lower gas velocities, there would be an increase in density difference between the oil reservoir and injected gas. Notice that, after the BT time, higher oil recoveries are obtained at slightly higher gas velocities. This result will help improve the magnitude of the viscous force, although the magnitude of gravity remains higher because the

Figure 6. Effect of the Gravity Number on the oil recovery factor.

Figure 7. Gas front velocity versus oil recovery.

reservoir pressure cannot be further increased. However, at this point, the viscous force must be increased to improve the microscopic sweep efficiency to drain the residual oil that is trapped by the capillary effects as observed in Figure 4.

Finally, from Figure 7, one can presume that, to obtain the highest oil recovery factor in the GAGD process, a lower gas injection rate should be

applied from the beginning of the process until before the BT, and that, after BT occurs, the gas injection rate should be increased. An optimization of this operational parameter should be evaluated to confirm this hypothesis. A future study will be developed to show the results. **Mahmoud (2006)** mentions that gas injection rate is one of the most important factors to be optimized for a successful GAGD process.

4. CONCLUSIONS

- The numerical simulation of the GAGD process coupled with the dimensionless groups, which is presented in this study, proves to be a notably useful tool to describe the interplay of capillary, viscous, and gravitational forces on the oil recovery factor.
- A numerical model of GAGD showed that higher oil recoveries are obtained at lower N_c and N_b , and at higher N_g before the BT. Nevertheless, higher oil recoveries are obtained at higher N_c and N_b , and at lower N_g after the BT time.
- Based on the analyses of the gas velocity parameter, it is hypothesized that, to obtain the highest oil recovery factor in the GAGD process, a lower gas injection rate should be applied from the beginning of the process to just before the BT. After the BT occurs, the gas injection rate should be increased.

ACKNOWLEDGEMENTS

The authors thank the *Laboratório de Estudos Avançados do Petróleo* (LEAP) of the Federal University of Rio do Grande do Norte (UFRN) for the support in the execution of this work. Moreover, EVB would like to express his sincere gratitude to Petrosynergy for the constant incentive to finish the work.

5. REFERENCES

Akhlaghi, N.; Rezaei, F.; Akhlaghi, N. Simulation study of GAGD process in one of Iranian fractured reservoir. **International Journal of Scientific Engineering Research**, v. 3(7), p. 1-6, 2012.

Bautista, E. V. **Análise paramétrica da simulação composicional do processo de drenagem gravitacional assistida por gás (GAGD)**. Dissertação de Mestrado, Departamento de Engenharia de Petróleo, Universidade Federal do Rio Grande do Norte, Natal, Brazil, 2010. (in Portuguese)

Danesh, A. **PVT and Phase Behavior of Petroleum Reservoir Fluids**. Amsterdam: Ed. Elsevier, 1998.

Edwards, J. T.; Honarpour, M. M.; Hazlett, M.; Cohen, A.; Membere, F.; Pebdani, C.; Clayton, C.; Al-Hussainy, R. Validation of gravity-dominated relative permeability and residual oil saturation in a giant oil reservoir. SCA 9903. In: **Proceedings of 1999 International Symposium of the Society of Core Analysts**, 1999.

Grattoni, C. A., Jing, X. D., Dawe, R. A. Dimensionless groups for three phase gravity drainage flow in porous media. **Journal of Petroleum Science and Engineering**, v. 29(1), p. 53-65, 2001. [http://dx.doi.org/10.1016/S0920-4105\(00\)00090-5](http://dx.doi.org/10.1016/S0920-4105(00)00090-5)

Honarpour, M.; Koederitz, L.; Harvey, A.H. **Relative Permeability of Petroleum Reservoirs**. Boca Raton: CRC Press Inc., 1986.

Jadhawar, P. **CO₂-assisted gravity drainage EOR: Numerical simulation and scaling models study**. Ph. D. Thesis, Australian School Pet., Adelaide University, Adelaide, Australia, 2010.

Kulkarni, M. M.; Sharma, A. P.; Rao, D. N. Use of dimensional analysis for scaling immiscible gas assisted gravity drainage (GAGD) experiments. SCA2005-50. In: **Proceedings of 2005 International Symposium of the Society of Core Analysts**, Toronto, Canada, 21-25 Aug, 2005.

Kulkarni, M.M. **Multiphase mechanism and fluid dynamics in gas injection EOR Processes**. Ph.D. Thesis. Department of Petroleum Engineering, Louisiana State University, 2005.

Mahmoud, T. N. N. **Demonstration and performance characterization of the gas-assisted gravity drainage (GAGD) process using a visual model** M. Sc. dissertation, Department of Petroleum Engineering, Louisiana State University and Agricultural and Mechanical College, Baton Rouge, LA, 2006.

Pinto, T. A. **Estudo paramétrico da recuperação de óleo no processo de drenagem gravitacional com injeção de CO₂**. Dissertação de Mestrado, Departamento de Engenharia de Petróleo, Universidade Federal do Rio Grande do Norte, Natal, Brazil, 2009. (in Portuguese)

Rao, D. N.; Ayirala, S. C.; Kulkarni, M. M.; Sharma, A. P. Development of the Gas Assisted Gravity Drainage (GAGD) Process for Improved Light Oil Recovery. SPE 89357. **Presented at SPE/DOE 14th IOR Symposium**, Tulsa, OK, 17-21 April, 2004. <http://dx.doi.org/10.2118/89357-MS>

Sharma, A. P. **Physical model experiments of gas assisted gravity drainage**. M. Sc. thesis, Department of Petroleum Engineering, Louisiana State University and Agricultural and Mechanical College, Baton Rouge, 2005.

Shook. M.; Li, D.; Lake, L. W. Scaling immiscible flow through permeable porous media by Inspectional analysis. **In Situ**, v.16 (4), p. 311-349., 1992.

Tham, B. K.; Mehmet Raif, B. D.; Mohd Saaid, I.; Abllah, E. The effects of kv/kh on gas assisted gravity drainage process. **Interational Journal of Engineering and Technology**, v.11(3), p. 138-163, 2011.