USE OF DIMENSIONAL ANALYSIS FOR SCALING IMMISCIBLE GAS ASSISTED GRAVITY DRAINAGE (GAGD) EXPERIMENTS

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ABSTRACT

Characterization of multiphase mechanisms and fluid dynamics operational in commercial gas injection processes and their duplication in the laboratory, forms an important component of the development of the Gas Assisted Gravity Drainage (GAGD) process. Dimensional analysis not only provided a good starting point to elucidate the mechanisms and dynamics associated with the gravity stable gas injection processes, but also helped as a fulcrum for effective experimental design. Literature review suggested the use of capillary number (ratio of viscous to capillary forces) and Bond number (ratio of gravity to capillary forces) to characterize the wide spectrum of the operational forces in field gas injection projects. The range of these dimensionless numbers calculated for nine commercial gravity stable gas injection projects, was reproduced in the coreflood and physical model tests, by selecting proper fluids and operating conditions of displacement rate and grain size of the bead pack.

In this experimental study, eight dimensionally-scaled immiscible secondary GAGD experiments were conducted at various operating conditions using a Hele-Shaw type physical model and a high-pressure Hassler-type coreholder. The physical model experiments were conducted at near-ambient pressures under both constant pressure and constant rate injection modes. The constant rate corefloods were conducted at higher pressures (500 psi), to include the effect of operating pressure on immiscible GAGD recoveries.

The oil recoveries increased linearly with increasing Bond and capillary numbers, indicating the strong influence of gravity and viscous forces on immiscible GAGD recovery. These results reaffirm the lower oil recoveries in capillary dominated gas injection projects. However, deciphering the individual effects of gravity and viscous dominated flows was not feasible using the Bond and capillary numbers alone. Hence the Gravity number (ratio of buoyancy to viscous forces) was used to study these individual effects and also effectively characterize the dominant flow mechanisms. When the oil

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recovery data from the field projects, the corefloods as well as the physical model were plotted against the Gravity number a single correlation resulted, signifying the capture of underlying displacement and drainage mechanisms in the simple laboratory tests. These experimental results and field findings indicate operating under gravity dominated flow regimes helps maximize oil recoveries in immiscible gas injection projects. Furthermore, this correlation could serve as an effective tool for preliminary oil recovery estimates as a function of operating conditions in gas injection projects.

INTRODUCTION

Enhanced Oil Recovery (EOR) surveys [1] from 1980-2004 show that gas injection projects have been rapidly increasing. EOR by gas injection currently accounts for about 48% of total enhanced production and for the majority of light oil enhanced production. The petroleum industry has been trying to improve gas injection EOR performance for several years to overcome problems due to unfavorable flood mobility ratios such as gas gravity override and premature gas breakthroughs. The Water-Alternating-Gas (WAG) process, introduced by Caudle and Dyes [2], is the most widely used gas flood conformance control tool in horizontal type gas injection projects. Inspite of WAG being a sound concept to counter gas gravity override and its reasonable performance in the laboratory tests, industry experience [3] shows that the incremental oil recovery (over primary depletion or after secondary waterflood) by WAG application has only been between 5 to 10% IOIP. On the other hand, gravity-stable gas injection floods, predominantly applied in dipping reservoirs and pinnacle reefs, have demonstrated recoveries in the range of 40 to 95% Residual Oil in Place (ROIP) field incremental oil recoveries [4].

The Gas Assisted Gravity Drainage (GAGD) Process

Gravity has long been recognized as one of the three important natural reservoir drive mechanisms for extraction of oil from the reservoir rock, besides natural water drive and solution gas drive [5] It is believed that if drainage was occurring, those wells lowest in the structure should recover the highest amount of cumulative oil [6]. During the early life of the reservoir below the bubble point, the reservoir tends to produce by solution gas drive, depending upon how much pressure drawdown is available. The force of gravity is believed to provide sufficient mechanical energy to drain a large percentage of oil from the rock. However, the major concern is not how much potential mechanical energy the reservoir can supply to facilitate gravity drainage but how effective this mechanical energy would be in displacing and mobilizing the reservoir oil [7, 8].

The success of gravity-stable gas injection in dipping reservoirs and pinnacle reefs has encouraged the development of Gas-Assisted Gravity Drainage (GAGD) process [9], to facilitate its application to horizontal type reservoirs. The GAGD process [9] uses several existing vertical gas injectors to inject gas in the crest of the reservoir, whereas the horizontal producer placed at the bottom facilitates production of drained oil. The

GAGD process [9] utilizes the natural density contrast between the injected gas and the reservoir oil to enhance the drainage of oil towards the horizontal producer. This gravity stable displacement results in significantly improved volumetric sweeps, consequently resulting in lower residual oil saturations [4].

The development of the GAGD process is underway through laboratory core floods and physical model experiments at Louisiana State University (LSU). Coreflood experiments were designed to study the performance of GAGD process at reservoir conditions. Coreflood experiments using 1-ft and 6-ft Berea cores have been conducted at miscible as well as immiscible conditions. Several 2-D physical model experiments to investigate the effects of operating forces such as gravity, capillary and viscous forces on oil recovery characteristics have been conducted using a Hele-Shaw type physical model packed with glass beads as the porous media. Both the coreflood and physical model experiments were characterized using dimensionless variables to capture the operative mechanism in the reservoir during gravity drainage. These experiments have been partially scaled to field scale using data from nine gravity-stable commercial and pilot projects.

DIMENSIONAL ANALYSIS OF THE GAGD PROCESS

Traditionally, dimensional analysis has been an extremely useful tool for scaling of the laboratory experiments to large scale operations and vice versa. This section summarizes the dimensional analysis work completed for the GAGD process to facilitate the identification of the key operating variables and their scalability to field applications.

Selection of Dimensional Variables for Gravity Drainage

Dimensional analysis is a powerful tool that can be used to reduce the number of experimental variables required for the adequate description of the relationship among controlling variables. In many applications of science and engineering, especially experimental work, the mathematical relationship between the variables of a system is unknown [10]. Experimental evaluation and verification of all the variables for a particular process is not always feasible or sometimes even impossible. In such cases dimensional analysis becomes indispensable for fair and reasonably accurate process performance evaluation.

Studies for dimensional analysis and model studies of gravity drainage applications are sparse. Geertsma et al.'s [11] derivation via inspectional analysis is important in that it not only generates dimensionless groups for solvent injection, but also helps generate a connecting link between dimensionless numbers in other engineering sciences and porous media flow commonly used in chemical and mechanical engineering. Further consideration of this relation, suggests that six commonly used dimensionless groups could also describe gravity drainage, namely Reynolds, Schmid, Weber, Froude, Lewis and Grashoff numbers.

Grattoni et al. [12] studied gas invasion under gravity-dominated conditions, for examining the effects of wettability and water saturation on three-phase flow. Analysis of the results using dimensionless groups helped define a new dimensionless group by combination of gravity and viscous to capillary forces. Characterization of these three forces is facilitated by the use of dimensionless numbers such as the capillary number, Bond number and Grattoni et al.'s [12] gravity number.

The capillary number plays a very important role in establishing the stability of the gas/oil displacement process. The viscous forces during gravity drainage are characterized using the capillary number for a given gas-oil interfacial tension. The capillary number [12] describes the balance between viscous and interfacial forces and is defined (for a water-wet system), where v is the Darcy velocity, μ is the viscosity of the displacing phase, and σ is the interfacial tension.

$$N_C = \frac{v.\mu}{\sigma} \tag{1}$$

The Bond number measures the relative strength of gravity (buoyancy) and capillary forces [12] as described by Equation 2, where, Δρ is the density difference between the displacing and displaced phase, g is the acceleration due to gravity, σ is the interfacial tension between the displacing and displaced phase, ϕ is the porosity of the reservoir and k the absolute permeability.

$$N_B = \frac{\Delta\rho_{(oil-gas)}\, g\left(\frac{k}{\phi}\right)}{\sigma_{og}} \tag{2}$$

The gravity number, which is a combination of the Bond and capillary number, is a measure of the relative strength of the gravity forces over the capillary forces. It is defined [12] by Equation 3 below.

$$N_G = \frac{\Delta\rho_{(oil-gas)}\, g\left(\frac{k}{\phi}\right)}{\mu_o v_d} \tag{3}$$

Scaling of Laboratory Experiments using Dimensional Analysis

The use of these dimensionless numbers not only reduces the number of parameters to be studied through the experiments but also facilitates in effectively capturing the multiphase mechanisms and fluid dynamics operative in these processes. This reduction is particularly useful in designing experimental work where the minimization reduces the number of experiments [13]. The relationship shown in Equation 4 has to be satisfied in the process of designing an experiment to reflect similar performance at field scale [14].

In Equation 4, γ refers to the ratio of dimensionless numbers at field scale to that of the experimental model.

$$\gamma\left(\frac{v\mu}{\sigma}\right)=\gamma\left(\frac{\Delta\rho_{(oil-gas)}g\left(\frac{k}{\phi}\right)}{\sigma}\right)=\gamma\left(\frac{\Delta\rho_{(oil-gas)}gk}{\mu_o v_d}\right)=1 \tag{4}$$

Dimensionless numbers obtained from nine gravity-stable field projects identified by Kulkarni [15] formed the basis for the experimental design for this study. All the experiments in this study are designed to mimic or resemble the multiphase mechanisms operative in the field processes by keeping synonymous dimensionless values obtained from the field projects.

The grain size of the glass beads and fluid properties in the experimental model are selected to generate similar values of the selected dimensionless numbers. Variables in the dimensionless numbers were varied to capture the entire spectrum of dimensionless number values obtained from the field projects. From Equation 2 we can see that, the Bond number (N_B) is directly proportional to the absolute permeability of the porous medium and the density difference between the reservoir fluids. Absolute permeability of a consolidated porous medium is a strong function of the grain diameter and is given by the Carman-Kozeny [16] equation:

$$k=\frac{{D_P}^2\phi^3}{72\tau(1-\phi)^2} \tag{5}$$

In Equation 5, D_P is the grain diameter, τ is the tortuosity and ϕ is the porosity of the porous medium. However, it is out of the scope of this study to experimentally measure the tortuosity of the porous media, hence a typical value of 1.5, was assumed in this analysis. Moreover, permeability decreases weakly with tortuosity, and tortuosity does not vary vastly [17]. In order to obtain favorable and realistic Bond numbers, fluid-fluid interaction parameters (interfacial tension) are also important. For example, the effect of Bond number on GAGD oil recovery was studied by using glass beads of varying grain sizes and the same fluid-fluid system (Decane-N_2) in the physical model (Table 1).

On the other hand, different capillary numbers were obtained by varying the fluid-fluid systems, for example Decane-CO_2 and Paraffin-CO_2 in the physical model. However, the ranges of capillary number obtained through selection of different fluid-fluid system were not as large in comparison to the ranges obtained through selection of different gas injection rates. Therefore different gas injection rates, using a mass flow controller, were used to generate capillary numbers of various orders of magnitude. Table 2 summarizes some of the experiments conducted using the physical model to study the effect(s) of capillary number variation on GAGD oil recoveries. The gravity number, a combination of the Bond and Capillary numbers, was also found to be useful for gravity drainage performance characterizations in core flood experiments, physical model experiments as well as real field operations (discussed later).

EXPERIMENTAL STUDIES

The effect of physical and dimensionless parameters on the performance of the Gas Assisted Gravity Drainage (GAGD) Process was investigated by conducting experiments in 1-D Berea cores and on a 2-D visual physical model (shown in Figure 1). The main features of the model are the ability to visually verify the stability and movement of the gas-oil displacement front.

Coreflood Experimental Procedure

The immiscible secondary mode GAGD experiments were conducted in 1-ft and 6-ft Berea sandstone cores using model fluids to ‘scale’ the corefloods as well as duplicate the multiphase mechanisms and fluid dynamics operational in field scale projects. The GAGD tests consisted of the following steps: saturation with brine, determination of pore volume and absolute permeability, oil flood to connate water saturation, end point oil-permeability measurement, and gas flood in GAGD mode. It is important to note that only the gas flood step was conducted in a gravity-stable manner, to duplicate the actual GAGD implementation in the field. The step-wise details of the coreflood experiments are provided elsewhere [15]. The experimental data are then processed to investigate the dependence of recovery characteristics on the selected dimensionless groups studied.

Physical Model Experimental Procedure

A Hele-Shaw type 2-D physical model was used for studying the displacement and drainage phenomenon occurring in GAGD as well as the effect of the dimensionless variables on its performance. Visual experiments were carried out using different fluids and packing, in order to obtain dimensionless numbers that fall in the same ranges as observed in some of the field projects. A vision system is incorporated in the setup (shown in Figure 1) to obtain images of the oil column in the separators. The data acquisition system records the production over the entire time of the run.

The data is then processed to investigate the dependence of total recovery on the dimensionless groups studied in the specific experiments. The step-wise details of the experimental procedure are provided elsewhere [18].

RESULTS

This section summarizes the experimental results and the investigation of their dependence on selected dimensionless groups. This section also demonstrates the development of a correlation between oil recovery by the GAGD process and the dimensionless groups. This correlation could be helpful to predict immiscible GAGD recoveries if the reservoir and injection fluid properties are known.

Effect of Bond Number on GAGD Immiscible Oil Recovery

Coreflood and physical model experimental runs were conducted to investigate the effect of Bond number on GAGD oil recovery. The Bond number variations were obtained by varying the fluid-fluid and porous medium properties and maintaining the Capillary number relatively constant. Figure 2 summarizes the effect of Bond number value on ultimate oil recovery.

Figure 2 clearly demonstrates the logarithmic dependence of immiscible GAGD oil recovery on Bond number. To determine the limits of this dependence, a miscible coreflood data-point [15] was plotted on the same graph. It is interesting to note that this correlation appears to effectively span both operating modes of immiscible and miscible GAGD applications. Hence, this correlation provides a good predictive tool to help estimate GAGD performance under immiscible as well as miscible applications.

Effect of Capillary Number on GAGD Immiscible Oil Recovery

Similar to the Bond number study, experiments to investigate the effect of capillary numbers, at constant Bond numbers, on GAGD oil recovery were carried out by varying the injection rate to obtain a large range of operating flood capillary numbers. The results from these runs are summarized in Figure 3. As expected, higher GAGD oil recoveries are obtained at higher capillary number(s). This suggests that the lower the magnitude of capillary forces, the better would be the efficiency of the injected fluid to counter capillary trapping and mobilize the residual oil. Similar to the Bond number study, a good logarithmic correlation for the entire operating range of the possible GAGD applications is also obtained.

Statistical Analysis of Experimental Results

A multiple regression analysis was performed on the experimentally measured results (coreflood and physical model) and gravity-stable field data using the Statistical Analysis Software (SAS) [19]. The results from this analysis are shown in Figure 4. The regression model fits two-thirds of the experimental and field data well and the remaining third fall within ±20% error range. Results from the statistical analysis indicate that while GAGD oil recovery depends on both capillary and Bond numbers, the effect of Bond number is significantly higher than that of capillary number. This is indicated by the value of the ‘probability of significance’ factor, which is significantly lower for the Bond number (0.0084) compared to the capillary number (0.0234).

Scaling of Time

In order to scale-up the laboratory run time to a given prototype field, the following dimensionless time expression was used. The expression for the dimensionless time (t_d) for gravity drainage processes was obtained from the literature [20] and is expressed as:

$$t_d = \frac{k k_{ro}{}^{o} \Delta\rho (g / g_c)}{h \phi \mu_o (1 - S_{or} - S_{wi})} t \qquad (6)$$

where k is the absolute permeability of the porous medium, K^{o}_{ro} is the end-point relative permeability to oil, $\Delta\rho$ is the density difference between the displaced phase and the displacing phase, g is the acceleration due to gravity, h is the thickness of the porous medium, ϕ is the porosity, μ_o is the oil viscosity, S_{or} and S_{wi} are the residual oil and connate water saturation respectively, t_d is the dimensionless time, and t is real time.

Equation 6 enables the scale-up of the run time (in minutes) in the experimental models to time required in a prototype reservoir to reach similar recoveries. A prototype gravity drainage field project (Dexter Hawkins) was identified and its data [18, 21] were used to scale the experimental run time from the physical model. Results indicate that an experimental run time of 10 minutes corresponds to about 69 - 127 days in a field project, depending upon the experimental operating conditions listed in Equation 6. Most of the production in the 2-D experiments was observed during the first 100 minutes [18], which corresponds to about 2 - 4 years in the field.

The production data for the Dexter Hawkins Field is available elsewhere [18, 21]. The experimental data obtained from the physical model GAGD studies predict the gravity drainage flood performance of the Dexter Hawkins reservoir reasonably well. This clearly indicates that the ‘scaled’ GAGD experimental studies are capable of capturing and reproducing the mechanisms operational in the field scale projects.

Comparison of Laboratory Experimental Results to Field Data

The results obtained from the physical model and immiscible core flood experiments were compared with data obtained from the gravity drainage field projects. For effective comparisons, as well as to account for the relative variations of the Bond and Capillary numbers in each of these floods, a single comparison parameter was required.

The gravity number is a combination of Bond and capillary numbers, and incorporates the relative variations of the major reservoir forces, namely the gravity, capillary and viscous forces. Therefore, the Gravity number appeared to be more appropriate for the comparison of laboratory and field data. Therefore the results for all the laboratory experiments (both the physical model and corefloods) and the field recovery data were plotted against the gravity number in Figure 5.

From Figure 5, it can be seen that there is a good logarithmic relationship, with very low data dispersion, between the GAGD recovery characteristics and the Gravity number. This is very encouraging, since the data for this comparison are obtained from vastly varied sources, such as from the atmospheric pressure, homogeneous 2-D sand packs, to the highly heterogeneous and high-pressure field flood projects. These findings indicate that the performance of the GAGD process appears to be well characterized by the use of the gravity number.

CONCLUSIONS

1. Coreflood and 2-D physical model experiments, coupled with dimensionless analysis have proven to be a useful tool for capturing the multiphase mechanisms and fluid dynamics operative in the field into the laboratory.
2. The performance of the GAGD process and the process run times have been effectively characterized using dimensionless numbers such as the Bond, Capillary and gravity number, and a dimensionless time expression.
3. A straight-line relationship between the total recovery and the natural log of Bond and capillary number is obtained from the experiments. This correlation fits well to both immiscible and miscible experiments. This indicates that, immiscible experimental results could be extrapolated to predict oil recoveries under miscible flood conditions.
4. A multi-variable regression model to fit the experimental and field data has been obtained. This analysis suggests that the Bond number has greater influence on ultimate GAGD oil recovery compared to the capillary number.
5. A logarithmic relationship between gravity number and oil recovery is observed when results from the physical model, core floods and field data are compared. It is very interesting to note that the recovery data from all the scales of operation corroborate well with this relationship.

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TABLES AND FIGURES

Table 1: Experimental Design to Study the Effect(s) of N_B on GAGD Oil Recovery

Expt. No.	Fluid-Fluid System	Grain Size	Injection Rate	Bond Number	Capillary Number	Bond Number Field Ranges [15]	
CR1	Decane-CO_2	0.5 mm	0.043 PV/min	3.50E-04	5.35E-08	Minimum Value: 2.80E-07	Maximum Value: 1.20E-05
CR2	Decane-CO_2	0.15 mm	0.043 PV/min	3.60E-05	5.35E-08		
CR3	Decane-N_2	0.15 mm	0.043 PV/min	3.50E-05	6.43E-08		
CR4	Decane-N_2	0.065 mm	0.043 PV/min	7.07E-06	6.43E-08		

Table 2: Experimental Design to Study the Effect(s) of N_C on GAGD Oil Recovery

Expt. No.	Fluid-Fluid System	Grain Size	Injection Rate	Bond Number	Capillary Number	Capillary Number Field Ranges [15]	
CR3	Decane-N_2	0.15 mm	0.043 PV/min	3.50E-05	6.430E-08	Minimum Value: 1.20E-09	Maximum Value: 4.20E-08
CR5	Decane-N_2	0.15 mm	0.109 PV/min	3.00E-05	1.331E-07		
CR6	Decane-N_2	0.15 mm	0.011 PV/min	3.10E-05	1.602E-08		
CR7	Decane-N_2	0.15 mm	0.870 PV/min	3.10E-05	1.280E-06		
CR8	Decane-N_2	0.15 mm	0.434 PV/min	3.21E-05	6.430E-07		
CR9	Decane-N_2	0.15 mm	0.652 PV/min	3.50E-05	9.640E-07		

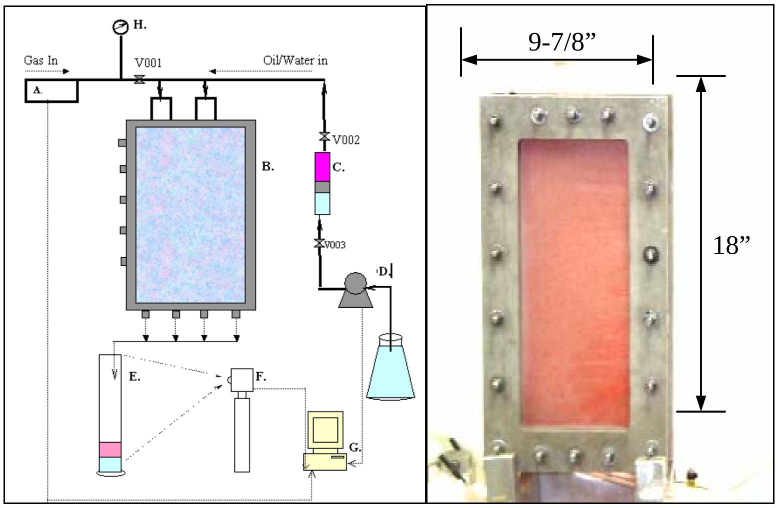

Figure 1: Schematic of the Hele-Shaw Type Physical Model [18]

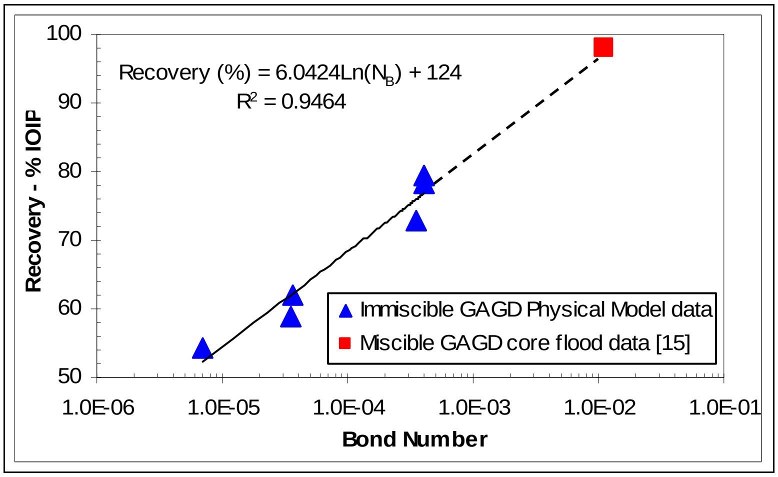

Figure 2: Correlation of Bond Number with Cumulative Oil Recovery

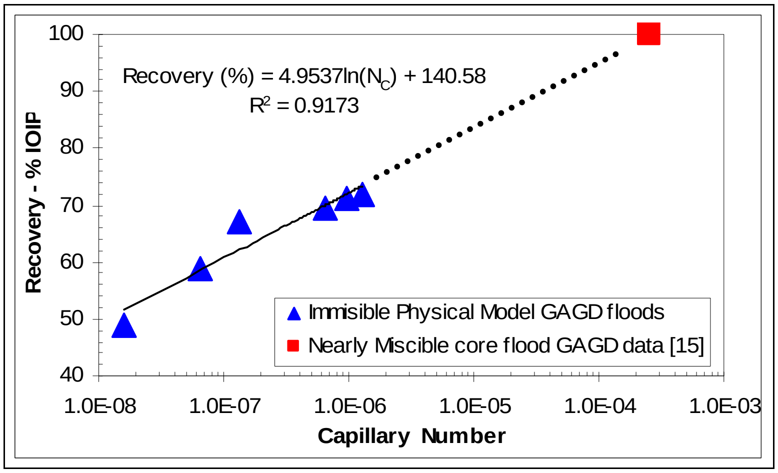

Figure 3: Correlation of Capillary Number with Cumulative Oil Recovery

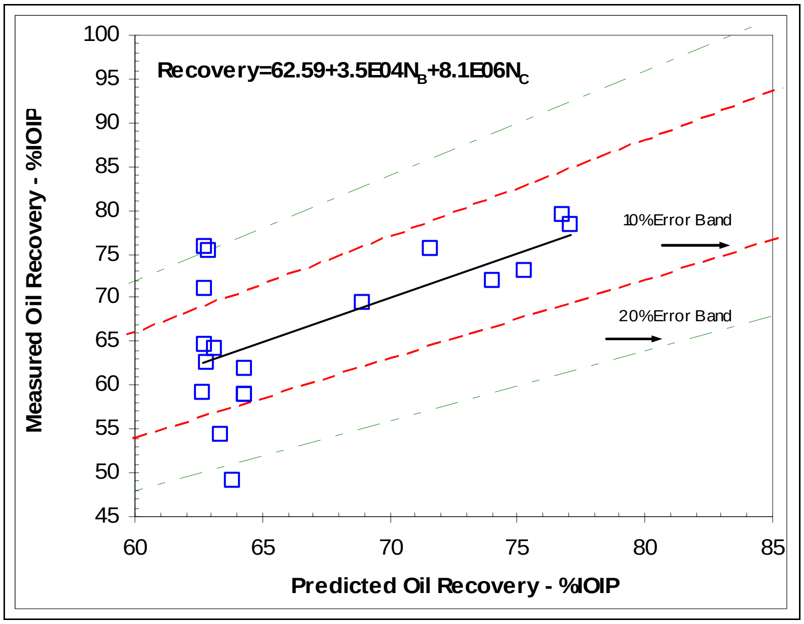

Figure 4: Multi-variance Regression Model for Correlating and Predicting Cumulative GAGD Immiscible Oil Recovery

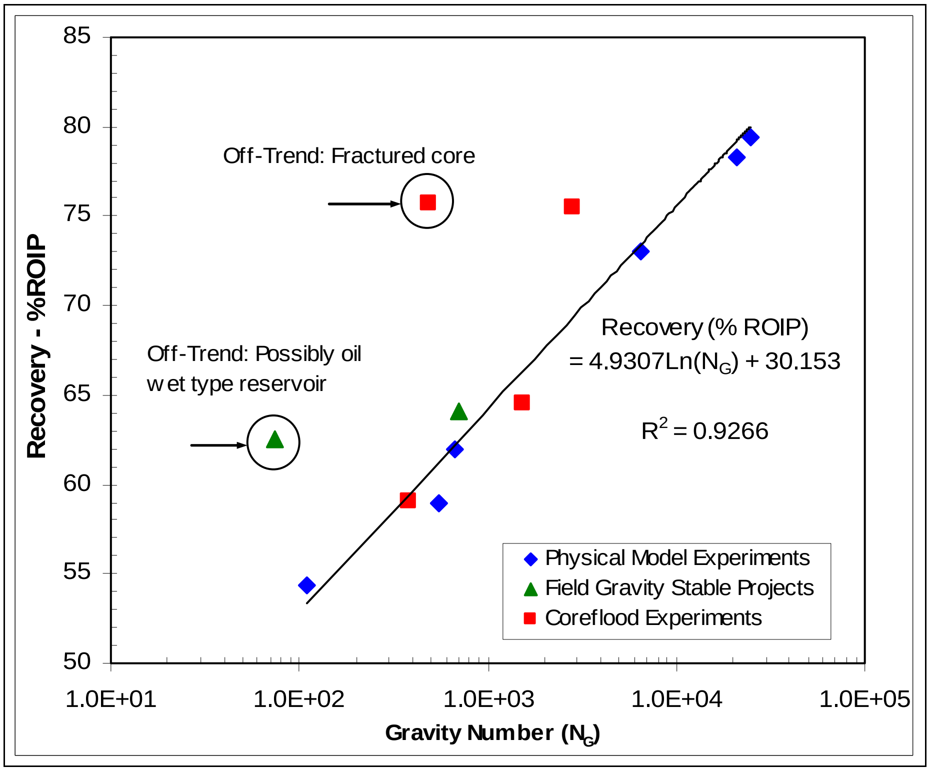

Figure 5: Comparison of GAGD Laboratory Experimentation and Field Gravity Drainage Projects' Performance versus Flood Gravity Number