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Analytical Modeling of the Forced Gravity Drainage GAGD Process

Madhav M. Kulkarni[1]

Marathon Oil Company, 5555 San Felipe Rd., Houston, TX.

Dandina N. Rao

The Craft and Hawkins Department of Petroleum Engineering, Louisiana State University and A & M College, 3516 CEBA, Baton Rouge, LA.

Abstract

Literature review on gravity drainage suggests that the fundamental understanding and modeling of the gravity drainage process still appears to be a challenge to the reservoir engineer, mainly because of the limitations of the reservoir simulation tools, to better include the physics of the process into improved reservoir management. This paper attempts to identify the fundamental forced gravity-drainage mechanisms, and possibly improve the mechanistic understanding of gravity-drainage processes by conducting: (i) mechanistic studies of the gravity-drainage process and (ii) employing analytical models to predict the recovery characteristics.

Mechanistic studies on gravity-drainage suggested that the existing models employed the Buckley-Leverett and gravity-drainage theories to model forced and free gravity-drainage, respectively. It appeared that neither of these theories holistically characterizes the Gas Assisted Gravity Drainage (GAGD) process, due to non-representative assumptions. A 'lumped' approach appeared to be preferable for GAGD modeling, and a new gravity-drainage mechanism has been proposed. Additionally, two 'lumped' mechanistic models, Richardson and Blackwell's analytical model (1971) and Li and Horne's empirical model for free gravity drainage (2003), were employed for validation of the proposed mechanism. The R&B model was validated against Hawkins Dexter field's gravity drainage flood data, and later employed to predict oil recoveries for 1-D and 2-D laboratory GAGD floods. The R&B model was found to predict the ultimate oil recovery within a 6.4% error band. The L&H model, used to predict the dynamic recovery characteristics due to R&B model limitations, was found to over predict the GAGD oil recoveries. To improve the capillary pressure modeling and incorporate the GAGD mechanisms into the model, the 'demarcator' concept of the original gravity

[1] Corresponding Author: Fax: (713) 296 4682; (O): (713) 296 3156; e-mail: MKulkarni@MarathonOil.com

drainage theory was introduced into the L&H model. This modification appears to have significantly and successfully improved the resulting model's ability to capture the multiphase mechanisms and fluid dynamics of gravity drainage processes.

1. Introduction

The Gas Assisted Gravity Drainage (GAGD) process was developed (Rao et al., 2004) as an alternative to the currently popular water-alternating-gas (WAG) process used for improving conformance during high mobility solvent injections, such as CO_2. Since the GAGD process is new, its analytical and conceptual coupling with the existing knowledge base is essential for better understanding of the fundamental multiphase mechanisms and fluid dynamics operational during its application. These mechanisms have been found to be important, to facilitate forecasting of the reservoir behavior and its oil recovery characteristics, one of the most important tasks of reservoir engineering. This paper attempts to identify the gravity drainage flow mechanisms, and help improve our mechanistic understanding of the forced gravity drainage GAGD process as well as predict the recovery patterns, by employing existing simple analytical models.

2. Literature Review

Schechter and Guo (1996) provided a comprehensive review of the gravity drainage literature and suggested that three different gravity drainage processes can occur in porous media, namely: (i) forced gravity drainage by gas injection at controlled flow rates into steeply dipping reservoirs, (ii) simulated gravity drainage by centrifuging (existing only in laboratory experiments), and (iii) free-fall (or pure) gravity drainage which takes place in naturally fractured reservoirs after depletion of oil from fractured or gas injection into a depleted fractured reservoirs.

Since only the first and third gravity drainage processes discussed above are relevant to the GAGD process being developed in this study, this literature review focuses on these two gravity drainage processes. The literature review summarizes: (i) displacement stabilities for gravity stable gas flow through porous media, (ii) gravity drainage fundamentals and traditional models, (iii) various laboratory studies on gravity drainage and (iv) various field applications of gravity drainage.

2.1 Displacement Instabilities for Gravity-Stable Gas Flow through Porous Media

The drainage of oil primarily under the influence of gravity forces (gravity drainage) has been found to be an efficient improved recovery method (Rao et al., 2004), since it can reduce the remaining oil saturation below that obtained after secondary recovery techniques. It is important to note that the literature review on the mechanistic characterizations of gas injection processes is applicable to all processes; however the emphasis of this review is on gravity stable gas injection.

The presence of viscous forces in a gas injection process may result in unstable flood fronts. Gas injection for EOR results in a finite viscous force acting on the gas-liquid interface. Because in any gas injection process (horizontal or gravity stable), the mobility ratio is typically unfavorable, the development of unstable fingers during gas displacements is imperative. The macroscopic and microscopic heterogeneities result in unequal displacement rates between the gas and in-situ fluids, thus magnifying this 'fingering' phenomenon. In horizontal mode floods, various modifications in gas injection protocol are followed to mitigate this phenomenon, but have met with limited success – mainly due to the unfavorable gravity forces (Kulkarni and Rao, 2004).

On the other hand, in vertical (gravity stable) gas floods, this unfavorable mobility ratio is generally attempted to overcome by reducing the viscous force magnitude (by decreasing the injection rates), and allowing the favorably acting gravity forces to stabilize the gas front. The maximum (vertical) gas injection rate allowable in a given reservoir to achieve a stable flood front is called as the 'critical rate'. Mechanistically, the critical rate represents the injection rate at which the favorable gravity force effects are overcome by the increased magnitude of viscous forces.

For miscible gravity stable flood, Hill (1952) derived a critical velocity expression (Equation 1) to predict the rates above which viscous instabilities can occur due to gravity forces being overshadowed by viscous forces. Equation 1 assumed a single interface contact between the injected and displaced phase with no mixing of solvent and oil behind the front.

$$V_C = \frac{2.741 \Delta\rho k Sin\theta}{\phi \Delta\mu} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Where:

V_C = Critical vertical injection rate (ft/d)

$\Delta\rho$ = Density difference (gm/cc)

k = Permeability (D)

θ = Dip angle (degrees – measured from horizontal)

ϕ = Porosity (fraction)

$\Delta\mu$ = Viscosity difference (cP)

Dietz (1953) proposed a method of analysis of stability of a vertical flood front with the following assumptions: homogeneous porous medium, vertical equilibrium of oil and water, piston displacement of oil by water, no oil-water capillary pressures, and negligible compressibility effects of rock and fluid. The Dietz equation is given by Equation 2 below.

$$\tan\beta = \frac{1 - M_e}{M_e N_{ge} Cos\theta} + \tan\theta \ldots\ldots \text{with } \beta > 0 \text{ being the stability criterion} \ldots\ldots\ldots\ldots (2)$$

Where,
M = Mobility Ratio
N_{ge} = Gravitational force

Dumore (1964) eliminated the limitation of the Hill (1952) equation which assumed that for vertical gas-liquid displacements, the solvent and oil do not mix, and derived a new frontal stability criterion (Equation 3). Interestingly, the Dumore stability criterion is more stringent than the Hill criterion, and for all rates lower than V_{st}; each infinitesimal layer of the mixing zone is stable with respect to each successive layer.

$$V_{st} = \frac{2.741 k Sin\theta}{\phi}\left(\frac{\partial\rho}{\partial\mu}\right)_{\min} \quad \text{……………………………..………...………...……………….....(3)}$$

Where
V_{st} = Critical velocity for stable vertical flow of gas (ft/D)

Rutherford (1962); Mahaffey et al., (1966) developed a stability criterion for miscible vertically oriented corefloods in laboratory (Equation 4).

$$(q/A)_{CRITICAL} = 0.0439\frac{k*(\rho_O - \rho_S)}{\mu_O - \mu_S} Sin(\theta) \quad \text{……….………………...……………….....(4)}$$

Where,
(q/A) = Critical velocity for stable flow (ft/D)
μ_O = Viscosity of Oil (cP)
μ_S = Viscosity of Solvent (cP)
θ = Advancing contact angle (degrees)

Brigham (1974) observed that the estimate of stability of a coreflood front could be obtained by measuring mixing zone length. The mixing zone length could then be used to calculate the effective mixing coefficient (α_e) an important reservoir simulation parameter. Perkins (1963) and Brigham (1974) solved the diffusion-convection equation and concluded that by measuring the mixing zone between 10% and 90% injected fluid concentrations at the core exit; the effective mixing coefficient (α_e) can be easily determined. Brigham (1974) suggested that in the absence of viscous mixing, the effective mixing coefficient (α_e) is a function of the porous medium only and typical values for Berea are 0.005 ft in laboratory scale systems.

Slobod and Howlett (1964) derived a critical injection velocity equation for gravity stable displacements' frontal stability in homogeneous sand packs and is given in Equation 5

$$V_C = \frac{k_o}{\Delta\mu}(\Delta\rho g) \quad \text{……..……..…………………………….………...…....………….(5)}$$

Among all the available analytical models in the literature to determine the critical gas injection rates (and promote stable displacement fronts) in gravity stable gas injection floods, the Dumore (1964) criterion appears to be the most popular in the industry. The Dumore criterion has been widely applied, in spite of newer models being available (Piper and Morse, 1982; Skauge and Poulsen, 2000; Pedrera et al., 2002; Muggeridge et al., 2005).

2.2 Gravity Drainage Fundamentals and Traditional Models

Gravity drainage is defined as a recovery process in which gravity acts as the main driving force and where gas replaces the voidage volume (Hagoort, 1980). Gravity drainage has been found to occur in primary phases of oil production through gas cap expansion, as well as in the latter stages wherein gas is injected from an external source. Muskat (1949) provides a detailed review on the effects of gravity forces in controlling oil and gas segregation during the primary-production phase of gas drive reservoirs. It was suggested that the most efficient type of gravity-drainage production would be an idealized case wherein no free gas is allowed to evolve in the oil zone by maintaining the reservoir pressure above its bubble point, or by pressure maintenance at current GOR levels (Muskat, 1949).

The literature employs the words ‘gravity stable gas injection’ and ‘gas gravity drainage’ interchangeably. Identification of the conceptual mechanistic differences between gravity stable gas injection, and ‘pure’ gas gravity drainage has been attempted in this study, and are detailed in following sections.

The importance of gravity drainage as an important oil recovery mechanism has been well recognized. Gravity drainage has been observed to occur during gas injection (Muskat, 1949) as well as in the stripper stages of volumetric reservoirs (Matthews and Lefkovits, 1956). Field and laboratory experience has shown that that gravity drainage, under certain conditions, can result in very high oil recoveries and also, that gravity drainage is one of the most effective mechanisms of developing an oil field (see Section 3.4 of Kulkarni, 2005).

Inspite of the fact that one of the earliest gravity drainage models appeared in 1949, the “…characterization and modeling of the (gravity drainage) process are still a great challenge (Li and Horne, 2003)”. This review attempts to provide a mechanistic understanding of the forced gravity drainage process, the fundamental mechanism involved in the GAGD process.

2.2.1 Drainage or Displacement?

Literature seems to use the words ‘gravity stable gas displacement’ and ‘drainage’ interchangeably. Many authors suggest the drainage process to be a type of displacement mechanism with the classical theories of Buckley-Leverett (1942), Darcy’s law, relative permeability, continuity equation, and decline curve analysis (material balance equation) to be applicable (Terwilliger et al., 1951; Hagoort, 1980; Li et al.; 2000).

However, Muskat (1949) suggested that although the classical theories of Darcy and Buckley-Leverett are relevant, the decline curve equation, applicable to most displacements, does not in itself provide any information regarding the gravity drainage phenomenon. The decline curve method represents only the thermodynamic equilibrium between the net liquid and gas phases in the reservoir and hence cannot characterize the mechanistic and fluid-dynamic aspects of the gravity drainage process. This statement of Muskat (1949) seems to be supported by many researchers (Cardwell and Parsons, 1948; Richardson and Blackwell, 1971; Pedrera et al., 2002; Li and Horne, 2003) who suggest that "Gravity drainage can be modeled by conservation equation, Darcy's law and capillary pressure relationship (Pedrera et al., 2002)".

Most of this confusion about gravity drainage characterization appears to stem from ignoring the injection gas pressure distribution as well as due to the application of 'pure' or 'free' gravity drainage theory (Cardwell and Parsons, 1948) to forced gravity drainage applications or vice-versa.

2.2.2 Gravity Drainage and Buckley-Leverett Displacement Mechanisms and Models

To facilitate the differentiation between displacement and drainage, the original Buckley-Leverett (1942) displacement theory and the gravity drainage theory (Cardwell and Parsons, 1948) have been examined and the resulting inferences are summarized in the following sections.

- **Classical Displacement Theory**

Buckley and Leverett (1942) first described the mechanism of displacement and also proposed an analytical model to determine the oil recovery by gas or water injection into a linear (horizontal mode) oil reservoir. The Buckley-Leverett (B-L) model (Equation 6) considers a small element within a porous medium and expresses the displacement rates in terms of accumulation of the displacing fluid (material balance theory is applicable).

The B-L displacement theory also suggests that after displacing phase breakthrough, the oil production rate changes (generally decreases) in proportional to its saturation. Since the oil saturation decreases continually after breakthrough, the oil production rate also drops with time. Additionally, for pure piston-like displacement (B-L displacement) in water-wet systems (ignoring the capillary pressure effects), water floods demonstrate a 'clear' breakthrough, i.e. no additional oil is produced after the water breaks through at the producing well. If the capillary pressure effects are included, the size of the oil bank increases with proportional decrease of the oil saturation from the leading to the trailing edge (Buckley and Leverett, 1942; Welge, 1952)

$$\left(\frac{\partial S_D}{\partial \theta}\right)_u = -\frac{q_T}{\phi A}\left(\frac{\partial f_D}{\partial u}\right)_\theta \qquad (6)$$

Where, S_D is the saturation of the displacing fluid, A is the cross-sectional area of flow, θ is the time, q_T is the total rate of flow through the section, u is the distance along the path of flow, ϕ is the porosity, and f_D is the fraction of flowing stream comprising of the displacing fluid.

However, in spite the fact that the original B-L model was hypothesized to be applicable to gas floods as well, the two assumptions used by B-L model, no mass transfer between phases and incompressible phases, result in severely limiting its application to GAGD type (gravity drainage) floods.

Buckley-Leverett's Perspective about Gravity Drainage

The original paper by Buckley and Leverett (1942) suggests that the gravity drainage phenomenon is "exceedingly slow" and is defined as the 'mechanism in which no other forces in the reservoir, except gravity, are available to expel the residual oil'. Although Buckley and Leverett (1942) suggest that the 'mechanism by which the area of high gas saturation invades the area of high oil saturation is very similar to that by which water encroaches into and displaces oil from a sand'; they also acknowledge that 'in gas displacing oil systems, simultaneous three phase flow in the reservoir results in non-piston like displacements and complete displacement never occurs!'.

Classical Gravity Drainage Theory

The earliest known analytical theory on gravity drainage was that of Cardwell and Parsons (1948), which derived a gravity drainage model based on hydrodynamic equilibrium equations in vertically oriented sand packs. The original theory assumed a free gas phase draining a single liquid phase, and suggested that the liquid recovery is equal to the percentage of the total area above the height versus saturation curve. One of the most important requisites to gravity drainage is the absolute pressure equilibrium between the gaseous and liquid phases. In other words, the gas zone does not exert a vertical pressure gradient on the gas-liquid interface.

Interestingly, Cardwell and Parsons (1948) acknowledge that only a slight pressure gradient in the gas zone is sufficient for the B-L theory to be applicable. This statement seems to be the reason for non-distinction between displacement and drainage, since in real oil-gas-water systems, reservoir pressure maintenance and gas injection result in a finite pressure gradient on the gas-liquid flood front.

A gravity drainage model similar to that of Cardwell and Parsons (1948) was proposed by Terwilliger et al. (1951). Terwilliger et al. (1951) applied the B-L immiscible displacement theory and the 'shock-front' technique (using fractional gas flow equations (Welge, 1952)) to match the steady state gravity drainage laboratory experiments (assuming steady-state relative permeability and static capillary pressure distribution). Terwilliger et al. (1951) also showed that recovery by gravity drainage is inversely proportional to production (conversely, injection) rates and recommended a "maximum rate of gravity drainage" or "gravity drainage reference rate" (Equation 7).

Equation 7 appears to be the theoretical basis for the “critical injection rate” and “frontal stability” equations developed by various researchers (Hill, 1952; Dietz, 1953; Perkins and Johnston, 1963; Dumore, 1964; Brigham, 1974; Moissis et al., 1987; Ekrann, 1992; Virnovsky et al., 1996) for commercial gravity drainage applications.

$$GRR = \frac{K_L A}{\mu_L} g \Delta \rho Sin\alpha \quad \text{..} (7)$$

where, K_L is the effective permeability to liquid at 100% liquid saturation, A is the cross-sectional area of flow, μ_L is the liquid viscosity, g is the gravitational constant, $\Delta\rho$ is the density difference between liquid and gas, GRR is gravity drainage rate and α is the angle of dip.

Traditional Gravity Drainage Models

Although Cardwell and Parsons (1948) and Terwilliger et al. (1951) models first presented the governing equations for the gravity drainage process, the non-linearity of the equations forced them to ignore two important parameters: (i) the capillary pressure variation with saturation and (ii) capillary pressure dependence on permeability.

Although, Nenniger and Storrow (1958) provided an approximate series solution (obtained from film flow theory) to predict the gravity drainage rates on a glass bead pack, the next important development in gravity drainage modeling was the generalization of the Cardwell and Parsons (1948) theory (Dykstra, 1978) by improving the capillary pressure representation in the governing equations. Using similar analysis and procedures, Hagoort (1980) also developed a theoretical analysis to predict forced gravity drainage recoveries, by simultaneously employing the B-L and Cardwell and Parsons (1948) theory. Although the model was significantly improved over the classical gravity drainage theory by modeling the capillary function as a Leverett J function, analytical solution of the model is not feasible due to the resulting non-linear governing equation.

Richardson and Blackwell (1971) presented a radically different ‘hybrid’ approach to predict gravity drainage recoveries for a variety of scenarios such as: vertical flow conditions, water under running viscous oils, gravity segregation of water banks in gas caps, and for control of coning by oil injection. They combine the Buckley and Leverett (1942), Cardwell and Parsons (1948) and Welge (1952) theories with the Dietz (1953) frontal stability criterion to predict the ultimate oil recoveries, when the injection rate is less than one-half of the Dietz’s (1953) critical rate.

Pavone et al. (1989) and Luan (1994) revisited the ‘demarcator’ concept introduced by Cardwell and Parsons (1948) to generate analytical models for gravity drainage in low

IFT conditions and fractured reservoir systems, respectively. The ‘demarcator’ is defined (Cardwell and Parsons, 1948) as the region of minimum gas saturation in the systems. They also showed that assuming the demarcator at the bottom (or outlet) of the reservoir, improves the model prediction.

Blunt et al. (1994) developed a theoretical model for three-phase gravity drainage flow through water-wet porous media based on a wide range of experiments, from molecular level to glass bead packs. These studies suggest that best tertiary gravity drainage efficiency in water-wet systems occurs when the oil spontaneously spreads as a layer between water and gas (under positive spreading coefficient conditions).

Li and Horne (2003) claim that “…the analytical models do not work well…” for gravity drainage recovery predictions, an empirical approach is more suitable. They proposed an empirical oil recovery model to match and predict oil production, which was tested against experimental, numerical and field data.

2.3 Gravity Stable gas Injection (Gravity Drainage) Laboratory and Field Scale Studies

Mechanistic reviews (provided earlier in Section 2.2) on pure gravity drainage and gravity stable gas injection processes suggest that they are the two ends of the gravity stabilized gas injection processes. This section therefore summarizes the laboratory experiments conducted for the characterization and optimization of the vertical gas injection process, since the forced as well as free gravity drainage processes are relevant to the GAGD process. The detailed literature review for the gravity stable gas injection laboratory and field projects is outside the scope of this paper and is available elsewhere (Kulkarni, 2005). This section will only summarize the important inferences made during the literature review.

2.3.1 Laboratory Studies Summary

1. Gravity stable gas injection and pure gravity drainage appear to be on the two extreme ends of the vertical gas injection EOR processes spectrum.
2. Literature does not attempt to mechanistically differentiate between these two processes, and the precise distinction between these two processes is not available.
3. Two different schools of thought are evident from the literature review on gravity stabilized gas injection: (i) the drainage process is a type of displacement mechanism with the classical theories of Buckley-Leverett, Darcy’s law, relative permeability, continuity equation, and decline curve analysis (decline curve equation) are applicable; and (ii) although the classical theories of Darcy and Buckley-Leverett are relevant, the decline curve equation, applicable to most displacements, does not in itself provide any information regarding the gravity drainage phenomenon.

4. Most of this confusion about gravity drainage characterization appears to stem from ignoring the injection gas pressure distribution as well as due to the application of 'pure' or 'free' gravity drainage theory to forced gravity drainage applications or vice-versa.
5. Characterization and modeling of the gravity drainage process is still a challenge.
6. Non-linear nature of the fundamental gravity drainage equation (Cardwell and Parsons (1948)) has prompted application of numerical and empirical techniques to gravity drainage process characterization. No single model to adequately define the gravity drainage process is available.
7. The forced gravity drainage process has been suggested to be consisting of two flow regimes: bulk flow and film flow, and a 'lumped' approach between the Buckley-Leverett (1942) and Cardwell and Parsons (1948) theory to accurately model forced gravity drainage has been advocated.
8. Characterization and quantification of conditions of displacement instabilities and critical injection rates are important for flood profile control and need to be evaluated using 3D physical models and / or reservoir simulation. Various models for the mitigation of these displacement instabilities in gravity drainage have been proposed.
9. Wettability influences on gravity drainage oil recoveries are not very clear. Although the literature appears to be in unison about the beneficial effects of oil spreading and film flow in water-wet and mixed wet systems, conflicting reports about the effects of wettability on gravity drainage recoveries in oil-wet systems have been found.
10. The effects of spreading coefficient (coupled with wettability) on gravity drainage performance in oil-wet systems are also not clear. However, most of the literature appears to agree that positive spreading coefficient in water-wet or intermediate-wet systems is beneficial to gravity drainage by promoting film flow.
11. Although, miscibility development has demonstrated improved oil recoveries in both water-wet as well as oil-wet systems; the screening criteria for miscible flood applications have not been defined.
12. The literature review on miscible gravity stable gas injection into depleted reservoirs (gas cap injection) yielded only a few studies. This is probably due to the notion that immiscible gravity drainage can eventually recover nearly 100% of the reservoir oil given enough drainage time. Further characterization and optimization of the miscible gravity drainage process presents an excellent future research opportunity.
13. Vertical coreflood displacement studies suggest the use of CO_2 over hydrocarbon gases due to the higher recovery efficiency and injectivity characteristics of CO_2; although economical and assured supply of CO_2 for EOR applications could be an issue in some cases.

14. Reservoir heterogeneity and fractures may not negatively influence the recovery characteristics of gravity drainage processes. Some studies suggest that the fractures may actually aid the gravity drainage process.
15. Gravity stabilized gas injection remains an active research area and has continued to demonstrate superlative oil recovery performance in laboratory applications inspite of the meager mechanistic understanding of the process.

2.3.2 Field Reviews Summary

The important characteristics of the field scale gravity drainage projects are:

1. Up dip or crestal gas injection into oil reservoirs is one of the most efficient methods to recover residual oil.
2. Gas gravity drainage process has been applied as secondary as well as tertiary recovery processes with encouraging results.
3. Gas gravity drainage process has been applied to all reservoir types, from extremely geo-complex reservoirs like Biomicrite / Dolomite to high quality turbidite (fluvial-deltaic sands) reservoirs.
4. Various field injectant gases such as Air, Nitrogen (N_2), Hydrocarbon (HC) and Carbon Dioxide (CO_2) have been successfully employed for the gas gravity drainage process.
5. Gas gravity drainage process is applicable to low permeability (110 mD) – low porosity (8.5%) reservoirs as well as high permeability (3400 mD) – high porosity (32.9%) formations, and is not greatly affected by the variation of common reservoir and fluid parameters such as reservoir heterogeneity, bubble point pressure, gas oil ratio (GOR), reservoir temperature and oil formation volume factor (FVF).
6. Gas gravity drainage process is best applicable to light oil reservoirs, low connate water saturations, positive spreading coefficient (to promote film flow), thicker formations, moderate-high vertical permeability, highly dipping or reef structured reservoirs, and minimal reservoir re-pressurization requirements (for miscible GAGD applications).
7. Corefloods and field investigations confirm that a large amount of incremental tertiary oil can be recovered using gravity assisted gas injection.
8. Recoveries as high as 85 – 95% OOIP have been reported in field tests, with the calculated average ultimate recoveries for all the field projects reviewed in this study being 77 %OOIP, and laboratory gas gravity drainage floods yielding nearly 100% recovery efficiencies.

3. Analytical and Conceptual GAGD Modeling

3.1 Inferences from Literature Review

1. Literature seems to use the words 'gravity stable gas displacement' and 'drainage' interchangeably.
2. Although, the original Buckley-Leverett model was hypothesized to be applicable to gas floods as well, the two assumptions used by Buckley-Leverett model, no mass transfer between phases and incompressible phases, result in severely limiting its application to GAGD type (gravity drainage) floods.
3. Buckley and Leverett (1942) theory suggests that the gravity drainage phenomenon is "exceedingly slow".
4. Terwilliger et al.'s (1951) model result in two inferences that appear to be relevant for the mechanistic description of the GAGD process: (i) as oil production rate approaches zero, the oil drains under its own weight, in the gas swept zone, fast enough to maintain the "static capillary saturation distribution" in the gas-oil contact transition zone; and (ii) at very high production rates, oil drainage under its own weight is negligible and recoveries approach those of horizontal gas drives.
5. It is interesting to note that Grattoni et al.'s (2001) studies on gas invasion under gravity-dominated conditions, to study the effects of wettability and water saturation on three-phase flow; reconfirm the first inference of Terwilliger et al.'s (1951) model, which states that there exists a critical height in the porous medium above which the oil saturation is negligible. The second inference, more relevant to the GAGD process, also seems to be supported from the first part of the scaled GSDH GAGD IRC # 1 experiment (Section 5.8 of Kulkarni, 2005) conducted to study the influence of injection rate on GAGD flood performance. Interestingly, the oil recovery (6.89% OOIP) obtained in the first part, wherein the gas injection rate far exceeded the critical injection rate, is very close to the average field scale horizontal mode immiscible CGI (or WAG) recoveries of about 6.4% OOIP (Christensen et al., 1998).

3.2 Application of Traditional Gravity Drainage Models to GAGD Process

All the limited number of existing models of the gravity drainage process seems to be limited by the fact that "…capillary pressure is usually neglected or considered inappropriately (Li and Horne, 2003)". To assess the applicability of various traditional models to the new GAGD process, two models were chosen after careful review: Richardson and Blackwell (1971) and Li and Horne (2003).

3.2.1 Richardson and Blackwell (R&B) Model

The R&B model was selected because of its simplicity and versatility. This model was applied to the following secondary mode GAGD experiments: (i) gravity stable displacement history secondary immiscible GAGD flood (GSDH GAGD # 1), gravity stable displacement history secondary miscible GAGD flood (GSDH GAGD # 3), non-gravity stable displacement history secondary immiscible GAGD flood (NSDH GAGD # 1), and non-gravity stable displacement history secondary miscible GAGD flood (NSDH GAGD # 3). The step by step procedures for calculating the oil recovery rates are available in the Richardson and Blackwell (1971) reference. The model application required some data that was not measured during regular experimentation. Therefore CMGL's Winprop® PVT simulator was used to generate some of the missing data. The GAGD experiments conducted in the laboratory used a gas injection rate of 10 cc/hr. This rate is less than one-half of the Dietz's (1953) critical rates; hence the R&B model was found to be applicable to these floods. The R&B model application procedure also requires the reservoir to be 'divided' into blocks of equal size. Since all the GAGD experiments were conducted on 1-ft Berea cores, six arbitrary divisions of 0.1667 ft each were used for the model prediction.

The data used for the prediction of oil production rates using the R&B model are included in Table 1. The calculated fractional flow of gas during GAGD experiments is summarized in Table 2. The calculated vertical drainage rates and gas interface height for each core block is plotted in Figure 1. Lastly the comparison between predicted and actual oil recoveries is summarized in Table 3.

The R&B model was validated against the Hawkins Dexter field data, and the model was found to under predict the ultimate oil recovery by 5.2% OOIP. From Table 3, it is clearly seen that the maximum error generated by this model's application to the GAGD floods is 6.4%. This makes the R&B model a good prediction tool for gravity drainage ultimate recoveries. However, since this model does not predict oil production rates, another model was required for this purpose. To facilitate prediction of production rates, another model by Li and Horne (2003) was employed, and the results are discussed in the following sections.

3.2.2 Li and Horne (L&H) Model

Since the R&B model did not predict the oil production rates, the Li and Horne (2003) empirical model was employed. The important feature of this model is the ability to incorporate capillary pressure data to improve gravity drainage recovery predictions. The capillary pressure data for the GAGD experiments and L&H model application was generated using the Brooks-Corey (1966) model.

To check the validity of this model as well as to calibrate the data, the L&H model was employed to predict free gravity drainage data generated from 2-D Hele Shaw physical model runs (Sharma, 2005). The experimental and predicted recovery data comparison for two free gravity drainage floods is summarized in Figure 2. It is important to note that the L&H model is applicable only to free gravity drainage floods. Application of this model to forced gravity drainage (FrGD) 1-D GAGD corefloods and 2-D physical models resulted in over-prediction of the oil production rates. This is intuitive, since the pure (or free) gravity drainage performance is usually better than the forced gravity drainage performance (Muskat, 1949).

Proposed Modification to the Capillary Pressure Model Incorporated in the L&H Model to Facilitate its Application to Forced Gravity Drainage

Sensitivity analysis of the L&H model application to the forced gravity drainage 1-D and 2-D scaled GAGD experiments suggested the inadequacy of the Brooks-Corey model for capillary pressure modeling. Furthermore, the insensitivity of the pore size distribution index (λ) as well as dimensionless length (Zc) of the model in production rate prediction; while the significant dependence on the depth corresponding to entry capillary pressure (Ze) data suggested the need for modification of the L&H model.

Further consideration of the 'demarcator' concept of Cardwell and Parsons (1948) to generate analytical models for gravity drainage in low IFT conditions and / or fractured reservoir systems as well as regression analysis of the GAGD data suggested that for improved GAGD recovery predictions, the Ze needs to be multiplied by a factor defined by Equation 8.

$$Ze^{*} = Ze\left(L - \frac{P_C^{(Entry)}}{Ps^{(Injection)}} \right) \quad \ldots\ldots(8)$$

Where, Ze^{*} is the modified Ze, Ze is the original depth corresponding to entry capillary pressure (Li and Horne, 2003), L is the equivalent length of the porous medium, $P_C^{(Entry)}$ is the entry capillary pressure calculated by Brooks-Corey model, and $P_S^{(Injection)}$ is the average system injection pressure (recorded during experimentation).

This modification is very similar to the 'demarcator' concept proposed by Cardwell and Parsons (1948), and is also more representative of the multiphase mechanics operational in the flood. And although the employment of this equation sometimes generates negative dimensionless length (Zc) values; it does reflect the physical phenomenon operational in the flood. For example, for coreflood experiments, Equation 8 generates a negative Zc value, physically suggesting that the entry capillary pressure effects (or capillary end effects) are insignificant. On the other hand, this value is found be zero or positive in free or forced 2-D Hele Shaw physical model runs, suggesting stronger capillary end effects, which are also supported by visual inferences (Sharma, 2005). Finally, the intentions to accurately represent capillary pressures and improved performance predictions of recovery characteristics for the GAGD scaled laboratory experiments have indeed been achieved through this modification.

Tables 4 and 5 summarize the data employed for the application of the modified L&H

model to the GAGD process's coreflood and physical model experiments. Comparison of the modified L&H model predictions and the experimental results is graphically depicted in Figures 3 and 4. As can be observed from Figures 3 and 4, excellent match between the experimental and model results has been achieved. Furthermore, this modified model appears to be more representative of the various multiphase flow phenomena (such as displacement, film flow and gravity drainage).

3.3 Proposed Forced Gravity Drainage Mechanism

The literature review on gravity drainage suggests that the fundamental understanding and modeling of the gravity drainage process is still a challenge to the reservoir engineer, mainly because of the limitations of the reservoir simulation tools to better include the physics of the process into improved reservoir management. This section summarizes the important mechanistic and dynamic characteristics of the gravity drainage process identified and also attempts to distinguish between displacement and drainage phenomena. Finally some recommendations for continued research on analytical modeling of the new GAGD process are also included.

3.3.1 Hypothesized Gravity Drainage Mechanism and its Possible Distinction from Buckley-Leverett Type Displacements

The literature review (Schechter and Guo, 1996) suggests that there are three distinct categories of the gravity drainage processes: (i) forced gravity drainage by gas injection at controlled flow rates, (ii) centrifuge simulated gravity drainage (not occurring in natural systems), and (iii) free fall gravity drainage occurring in a variety of cases, such as pressure depleted fractured and volumetric reservoirs, and gas injection (or pressure maintenance) into highly fractured reservoirs.

It appears that the displacement (classical definition) is an indivisible characteristic of the forced gravity drainage (GAGD) phenomenon. However, the displacement phenomenon appears to be one of the several distinct phenomena occurring during the GAGD process. Nevertheless, almost all the models used to characterize forced gravity drainage (relevant to the GAGD process), employ the Buckley-Leverett approach. Inspite of the inherent limitations of the B-L theory (imparted due to unrealistic assumptions from gravity drainage injection view-point: see Section 2.2), its application to a wide variety of scenarios with fair results, suggest it to be relevant and important to forced gravity drainage (therefore GAGD) applications. However, from a theoretical point of view, this argument appears to be valid only when there is little or no pressure variation within the gas chamber, which may be achievable for constant pressure type and low injection rate floods. Therefore, the B-L theory could be useful to model gravity drainage until gas breakthrough.

It is interesting to note that all the forced gravity drainage models that employ B-L approach appear to be valid only until gas breakthrough. This is a serious limitation, since the modified B-L theory (which includes the capillary pressure effects on oil recoveries and breakthrough times) suggests that in real reservoir systems (water-wet), the production rates decrease after breakthrough and this decrease is proportional to pore volume injection, residual saturation and the corresponding oil relative permeability; and therefore cannot be used to predict post breakthrough oil production rates. Furthermore, for pure piston-like displacements, in water-wet porous media (ignoring capillary pressure), 'clean' breakthroughs are observed, i.e. no oil production after water breakthrough. This statement is also supported by the scaled secondary waterflood data on realistic water-wet porous media (also reported in this study). GAGD experimental data (presented in Kulkarni, 2005) clearly demonstrate that GAGD oil production rates do not drop significantly even after gas breakthrough. This suggests that the spreading coefficient and oil film flow rates are important for GAGD oil recovery (especially after gas breakthrough) and must be incorporated into the GAGD analytical models. Gravity drainage literature review also seems to support this view.

It is hypothesized that the GAGD process operates in three distinct multiphase modes: (i) piston-like displacement (B-L theory, decline curve and continuity equation, and Darcy's law are valid), (ii) gravity drainage mechanisms (oil film flow under positive spreading coefficient conditions), and finally (iii) extraction mechanism. The lumped approach of Richardson and Blackwell (1971) and Pedrera et al. (2002) also seems to support this multi-level and multi-mechanistic approach.

The first multiphase mode is supported by many authors (Terwilliger et al., 1951; Hagoort, 1980; Li et al.; 2000) and is best depicted in Hagoort's (1980) schematic of the forced gravity drainage (gravity stable gas displacement) flood front (Figure 5). The second multiphase mechanism stems from the limitations of the B-L theory to accurately predict the oil production rates under forced gravity drainage (GAGD) floods. Scaled corefloods, physical model results as well as field reviews clearly demonstrate that oil production rates may not drop after gas breakthrough.

Additionally, the B-L 'shock-front' concept does not appear to be applicable to the forced gravity drainage process. The saturation shock (from initial oil saturation ahead of the flood front to residual oil saturation immediately behind the front) does not appear to be representative of the reservoir mechanics during forced gravity drainage (GAGD), attributable to the presence of oil films, which act as high-speed conduits for oil production. The laboratory studies on gravity drainage (see section 2.3) appear to support this view since they stress the importance of thicker and continuous oil films to promote improved film flow and consequently higher gravity drainage recoveries.

The last multiphase mechanism was not apparent from 'model' laboratory fluids used for scaled GAGD floods. This phenomenon was noticed during GAGD Yates corefloods, wherein the color of the produced crude oil started fading towards the end of the flood. The pictorial representation of this phenomenon is shown in Figure 6.

The reduced color intensity of the produced oil suggested the possibility of the 'in-situ' oil up gradation and increased API gravity of the produced oil during the GAGD process. The possibility of dilution of the produced oil by the injected solvent was limited, since this oil sample was recovered after the backpressure regulator (at ambient conditions. Since the injected solvent (CO_2) cannot exist in the liquid phase at ambient conditions, the dilution effect is probably not relevant in this scenario.

A fully compositional numerical simulation model which included the effects of molecular diffusion and interfacial tension (Darvish et al., 2004: Figure 7) reconfirms the presence of the two mechanisms during forced gravity drainage, film flow gravity drainage and extraction mechanism, and also attests that the film flow gravity drainage phenomenon does not become active (at a given point in the porous medium) until that point comes at the trailing end of the gas front.

3.3.2 Inferences and Recommendations

The above discussion clearly suggests that the characterization and modeling GAGD process is a multi-mechanistic approach. The modified L&H model and the proposed multi-step explanation of the GAGD flood mechanism (consisting of Buckley-Leverett flooding until gas breakthrough, film flow phenomenon and extraction mechanism), appears to be well supported by previous work. One of the critical limitations of the modified L&H model is its empirical nature, which significantly limits its scope of application. Additionally, there appear to be many smaller multiphase mechanisms operational during the GAGD process using CO_2 such as: extraction, molecular diffusion, non-linear film flow, solvent (CO_2) dissolution, viscous displacement, capillary retention etc. which need to be better understood. The next step to this work would be the characterization of the contribution of these individual mechanisms in the gravity drainage process and development of an analytical model of the phenomena.

4. Conclusions

1) Preliminary mechanistic and dynamic differences between the drainage and displacement phenomenon have been identified and a new mechanism to characterize the GAGD process fluid mechanics (consisting of Buckley-Leverett flooding until gas breakthrough, film flow phenomenon and extraction mechanism) has been proposed.
2) The Richardson and Blackwell analytical model was successfully applied to predict the ultimate oil recoveries for the GAGD process, within 6.4% error.
3) Since the Richardson and Blackwell model could not predict the dynamic GAGD behavior, an empirical Li and Horne model (developed for free gravity drainage

applications) was used. Although this model predicted the dynamic behavior of free GAGD process, it was found to over predict the forced GAGD oil recoveries.

4) A new parameter (Ze^*) was therefore introduced in the Li and Horne model for improved prediction of the dynamic GAGD flood behavior. The introduction of this parameter resulted in an accurate model (although empirical) to predict GAGD oil recoveries.

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Tables and Figures

Table 1: Data Used for R&B Model Application

Experiment Number	Type	GSDH # 1	GSDH # 3	NSDH # 1	NSDH # 3
Pore Volume (Vp) (cubic ft)	Expt. Data	0.0041	0.0041	0.0041	0.0041
Cross-Sectional Area (A) (sq. ft)	Expt. Data	0.0218	0.0218	0.0218	0.0218
Permeability (Darcy)	Expt. Data	0.2224	0.2440	0.1426	0.1176
Density Difference (lbm/ft3)	Winprop	38.3655	44.8946	38.3655	44.8946
Oil Viscosity (cP)	Winprop	0.9250	0.9250	0.9250	0.9250
Gas Viscosity (cP)	Winprop	0.0165	0.1879	0.0165	0.1879
Relative Permeability to Oil (Fraction)	Expt. Data	0.1001	0.1001	0.1001	0.1001
Relative Permeability to Gas (Fraction)	Expt. Data	0.0018	0.0500	0.0018	0.0500
Recovery (%OOIP)	Expt. Data	0.7544	1.0000	0.7387	1.0000
Connate Water Saturation (Swc)	Expt. Data	0.0194	0.0194	0.0452	0.0624
Residual Oil Saturation to Gas (Sor)	Expt. Data	0.3516	0.0000	0.3804	0.0000
Critical Rate (Dietz's Model) (ft3/D)	Calculated	4.3674	0.0786	2.7998	0.0379
Critical Rate (Dietz's Model) (cc/hr)	Converted	5152.9055	92.6803	3303.4372	44.6689
Gas Fraction of Flowing Stream (Fg)	Calculated	0.5546	0.8064	0.5358	0.7570
Actual Rate of Frontal Movement (ft/D)	Calculated	0.0812	0.0559	0.0841	0.0595
Time to Breakthrough (Days)	Calculated	12.3096	17.8986	11.8912	16.8010

Table 2: Calculated Fractional Flow of Gas for GAGD Floods

Kor	Kgr	Fg1 (GSDH # 1)	Fg2 (GSDH # 3)	Fg3 (NSDH # 1)	Fg4 (NSDH # 3)
0.1001	0.0000	0.0000	0.0000	0.0000	0.0000
0.0900	0.0020	0.6069	0.1105	0.5882	0.1043
0.0800	0.0040	0.7987	0.2187	0.7766	0.2077
0.0700	0.0060	0.8883	0.3246	0.8666	0.3102
0.0600	0.0080	0.9373	0.4282	0.9175	0.4116
0.0500	0.0100	0.9661	0.5294	0.9489	0.5122
0.0400	0.0120	0.9833	0.6283	0.9692	0.6117

0.0300	0.0140	0.9934	0.7248	0.9825	0.7102
0.0200	0.0160	0.9986	0.8189	0.9913	0.8078
0.0100	0.0180	1.0005	0.9106	0.9968	0.9044
0.0000	0.0200	1.0000	1.0000	1.0000	1.0000

Table 3: Comparison of Experimental and Predicted Ultimate Oil Recovery for Various GAGD Floods

Experiment	Experimental Recovery	R&B Model	Model Error
	%OOIP	%OOIP	Avg. Error: 5.6%
GSDH # 1	64.8%	75.5%	-16.5%
GSDH # 4	100.0%	94.2%	5.8%
NSDH # 1	62.3%	73.5%	-17.9%
NSDH # 4	100.0%	93.6%	6.4%

Table 4: Data Used for Modified L&H Model Application to 2-D GAGD Floods

Experiment Number	Type	FrGD # 1	FrGD # 2	FrGD # 3	FrGD # 4
Beta (β)	Calculated	0.016528	0.01552413	0.018871722	0.019756
Pore Volume (Vp)	Expt. Data	514.8	522	520	530
Recovery (%OOIP)	Expt. Data	0.675578	0.494708356	0.593096558	0.708109
Connate Water Saturation (Swc)	Expt. Data	0.203574	0.22605364	0.173076923	0.245283
Residual Oil Saturation to Gas (Sor)	Expt. Data	0.258378	0.391068629	0.336477847	0.220295
Initial Oil Production Rate (Qoi)	Calculated	4.578103	3.102686421	4.812883847	5.595865
Ultimate Oil Production by FGD (Npo Inf.)	Calculated	276.9869	199.8621759	255.0315198	283.2435
Average Residual Oil Saturation (Sor Avg.)	Calculated	0.258378	0.391068629	0.336477847	0.220295
Depth Corresponding to Entry Pc (Ze)	Expt. Data	0.35	0.35	0.35	0.35
Pore Size Distribution Index (λ)	Assumed	3	5	3	5
Dimensionless Length (Zc)	Calculated	0	0	0	0

Table 5: Data Used for Modified L&H Model Application to 2-D GAGD Floods

Experiment Number	**Type**	**GSDH # 1**	**GSDH # 3**	**NSDH # 1**	**NSDH # 3**
Beta (β)	Calculated	0.0010	0.0014	0.0016	0.0016
Pore Volume (Vp)	Expt. Data	116.2600	116.2600	116.2600	116.2600
Recovery (%OOIP)	Expt. Data	0.7544	1.0000	0.7387	1.0000
Connate Water Saturation (Swc)	Expt. Data	0.0194	0.0194	0.0452	0.0624
Residual Oil Saturation to Gas (Sor)	Expt. Data	0.2408	0.0000	0.2494	0.0000
Initial Oil Production Rate (Qoi)	Calculated	0.0881	0.1603	0.1304	0.1773
Ultimate Oil Production by FGD (Npo Inf.)	Calculated	86.0000	114.0000	82.0000	109.0000
Average Residual Oil Saturation (Sor Avg.)	Calculated	0.2408	0.0000	0.2494	0.0000
Depth Corresponding to Entry Pc (Ze)	Expt. Data	0.3500	0.3500	0.3200	0.3500
Pore Size Distribution Index (λ)	Assumed	3.0000	5.0000	3.0000	5.0000
Dimensionless Length (Zc)	Calculated	-0.1483	-0.1483	-0.0499	-0.1483

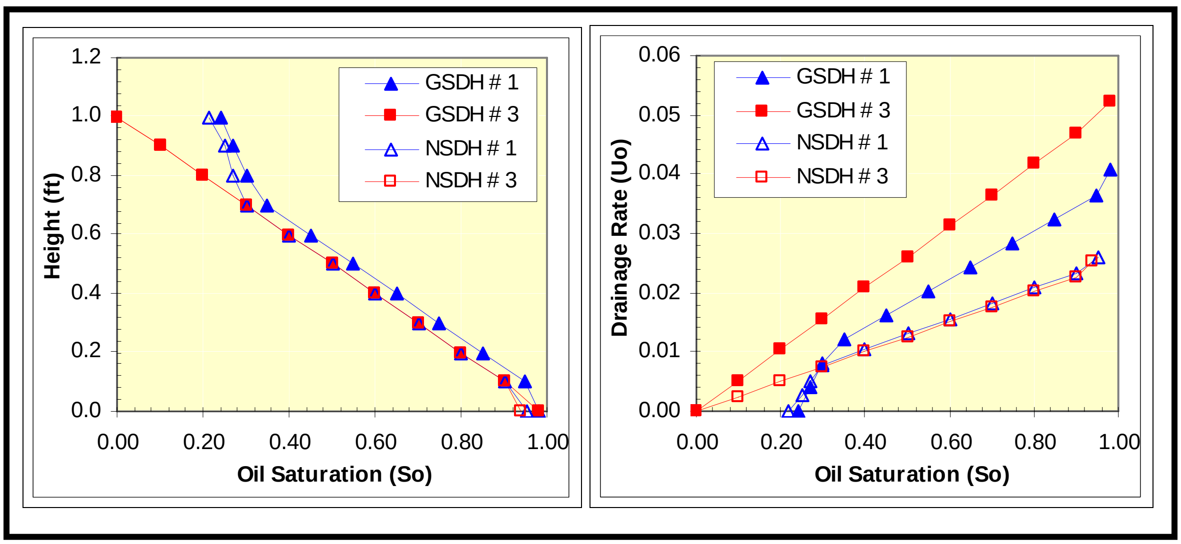

Figure 1: R&B Model Predicted Vertical Drainage Rates and Gas Interface Height for Each Core Block

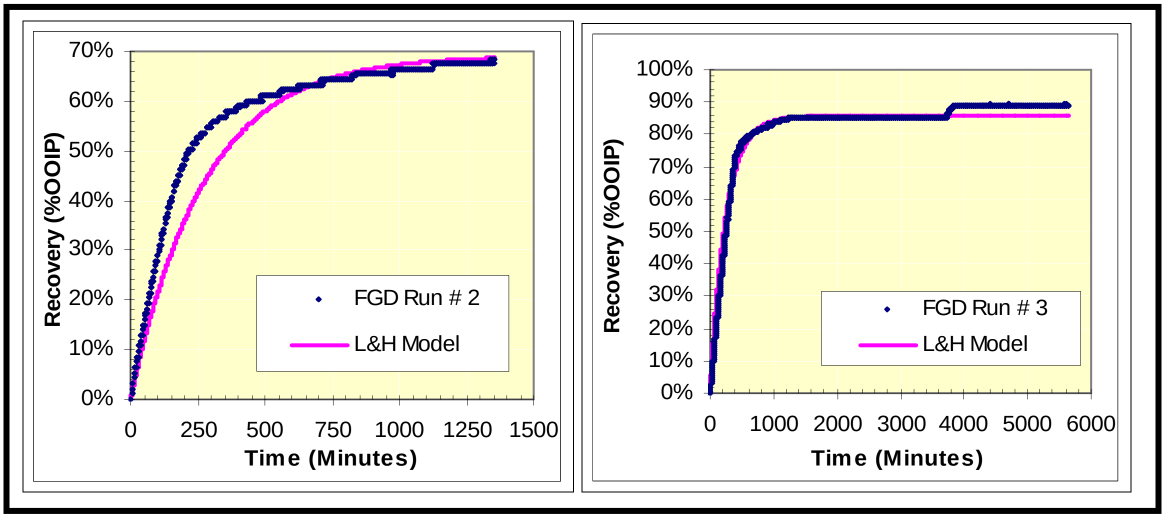

Figure 2: Comparison of Experimental and L&H Model Predicted Oil Production Rates for Two Selected Free Gravity Drainage Tests in a 2-D Physical Model

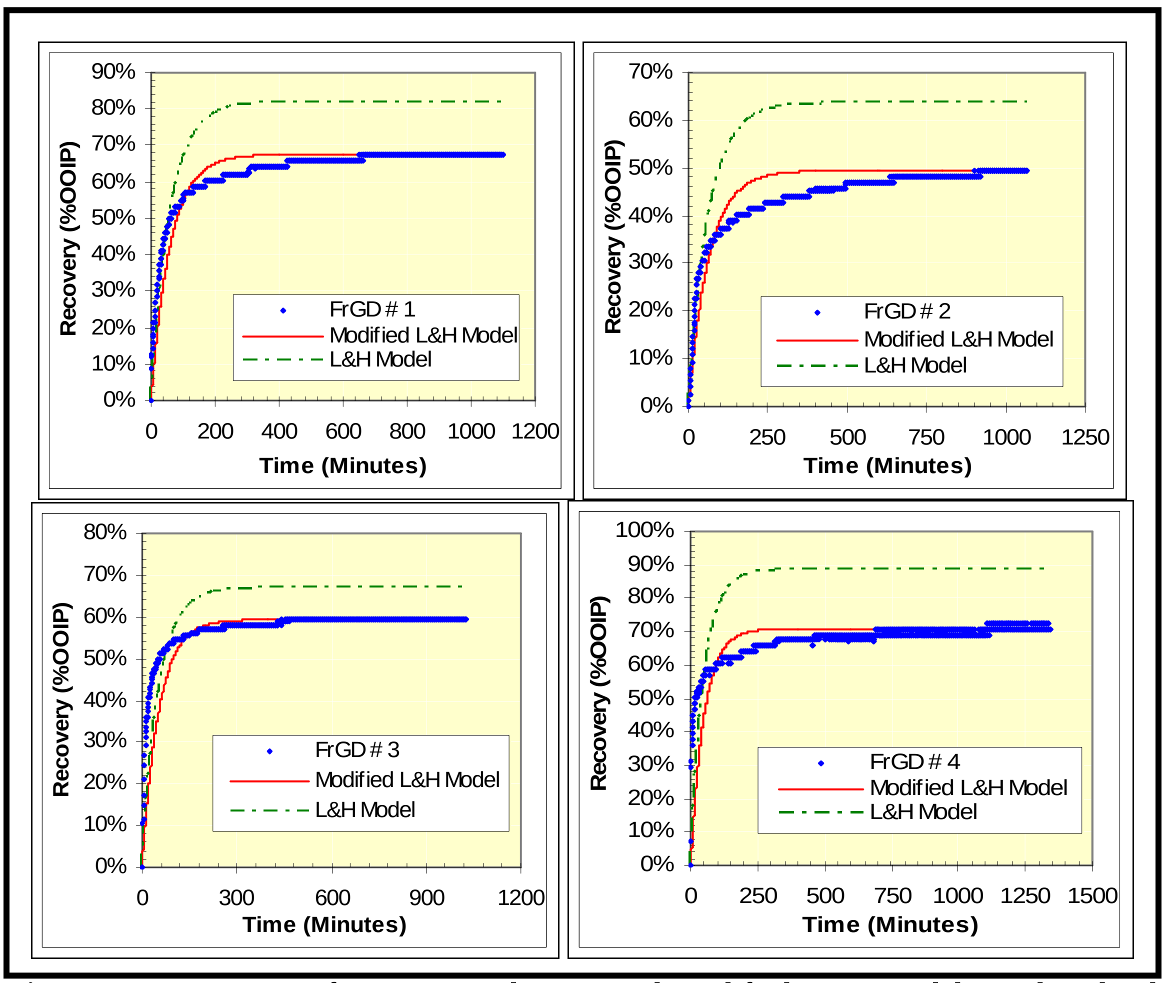

Figure 3: Comparison of Experimental, L&H and Modified L&H Models Predicted Oil Production Rates for Forced Gravity Drainage 2-D Physical Model GAGD Floods

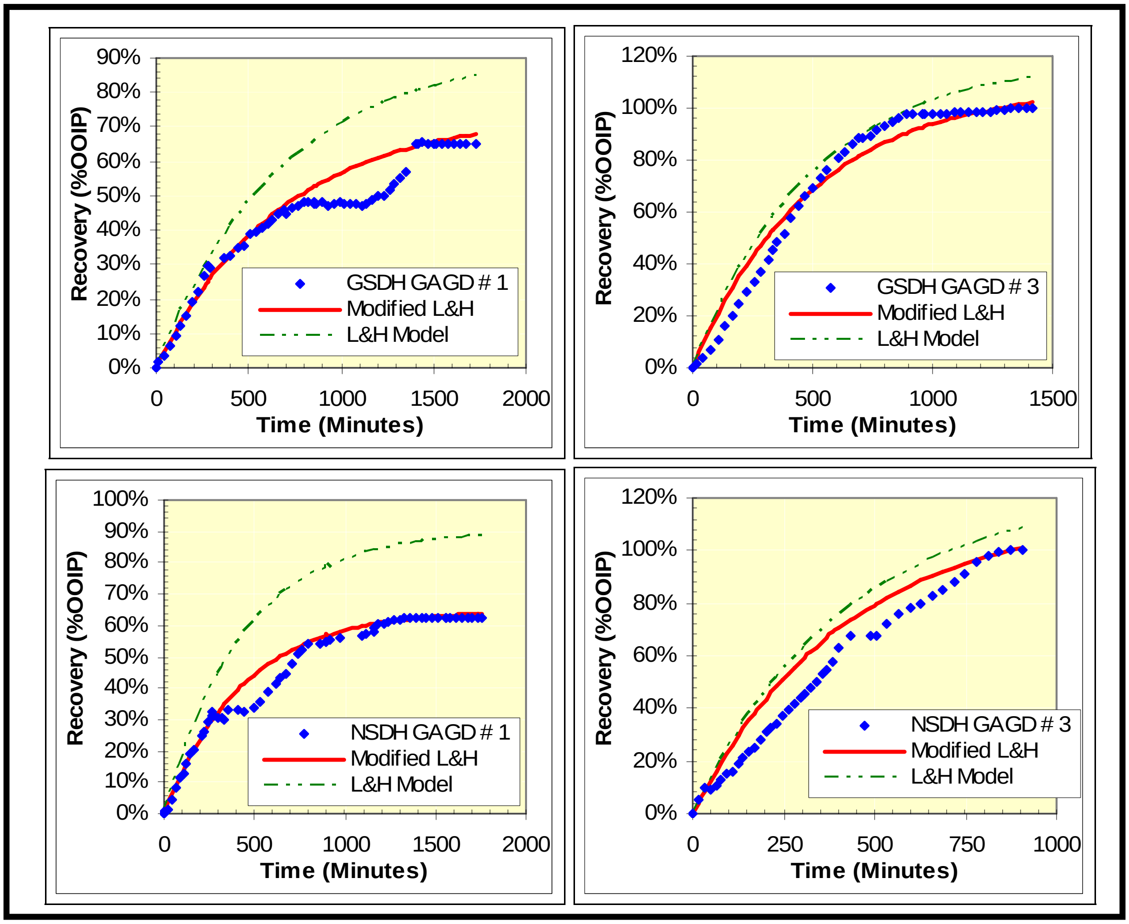

Figure 4: Comparison of Experimental and Modified L&H Model Predicted Oil Production Rates for Forced Gravity Drainage 1-D GAGD Corefloods

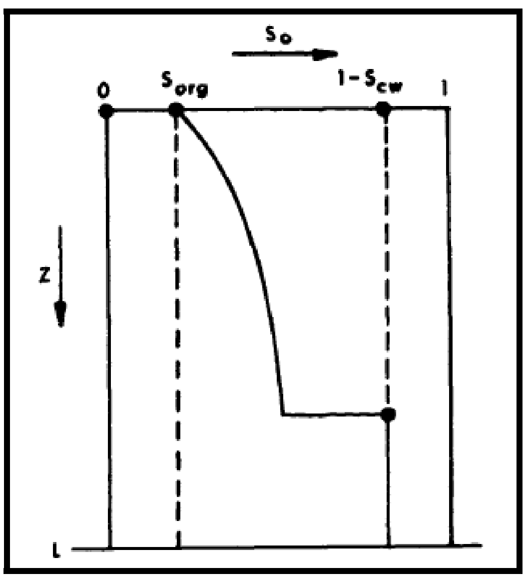

Figure 5: Buckley-Leverett Saturation Profile for Stable Downward Displacement (Hagoort, 1980)

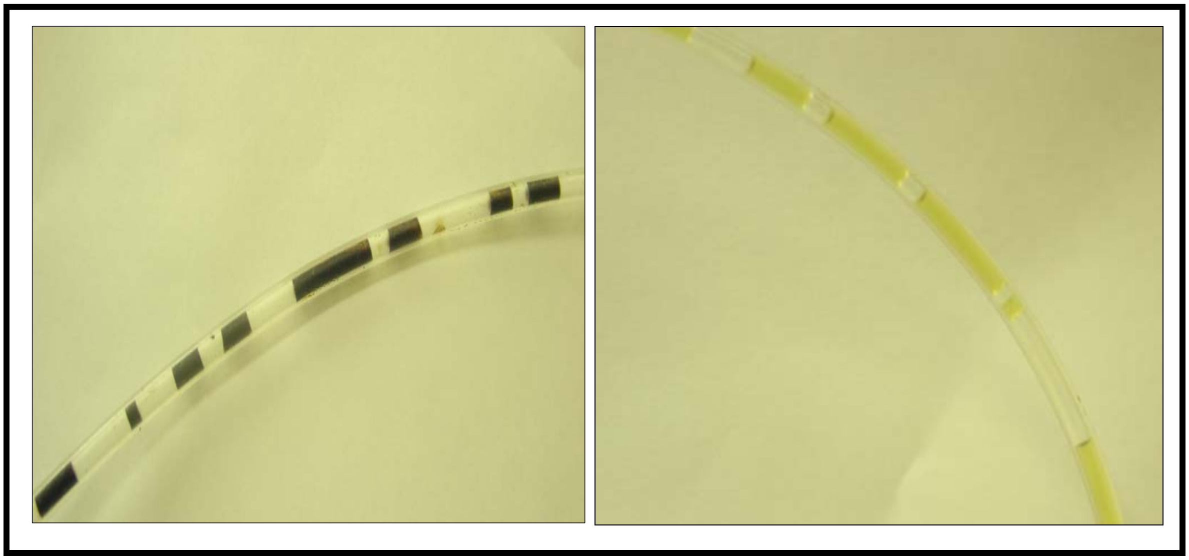

Figure 6: Gradual Color Fading of the Produced Oil for GAGD Yates Corefloods

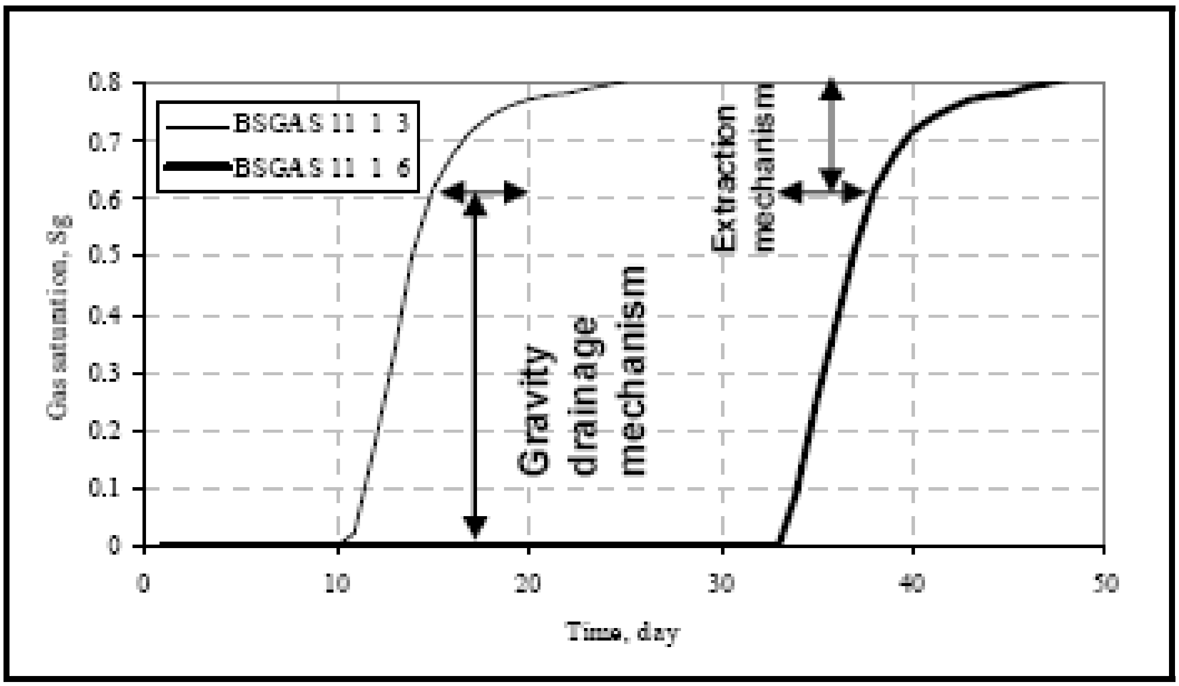

Figure 7: Numerical Simulations Demonstrating the Presence of Gravity Drainage Film Flow Mechanism and the Extraction Mechanism in Forced Gravity Drainage (GAGD) Type Flow (Darvish et al., 2004)