Miscibility Variation in Compositionally Grading Reservoirs
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Abstract
Minimum miscibility conditions of pressure and enrichment (MMP/MME) have been computed using an equation of state (EOS) for a number of reservoir fluid systems exhibiting a compositional gradient with depth due to gravity/chemical equilibrium. MMP/MME conditions are calculated using a multicell algorithm developed by Aaron Zick, where the condensing/vaporizing (C/V) mechanism of developed miscibility is used as the true measure of minimum miscibility conditions, when it exists. The Zick algorithm is verified by detailed 1D "slimtube" simulations with elimination of numerical dispersion. The miscibility conditions based on the traditional vaporizing gas drive (VGD) mechanism are also given for the sake of comparison, where it is typically found that this mechanism overpredicts conditions of miscibility.

Significant variations in MMP and MME with depth exist for reservoirs with typical compositional gradients, and particularly for near-critical oil reservoirs and gas condensate reservoirs where the C/V mechanism exists. An important practical implication of these results is that miscible displacement in gas condensate reservoirs can be achieved far below the initial dewpoint pressure. The requirement is that the injection gas (slug) be enriched somewhat beyond a typical separator gas composition and that the C/V miscibility mechanism exist. This behavior results in many more gas condensate reservoirs being viable candidates for miscible gas cycling than previously assumed, and at cycling conditions with lower cost requirements (i.e. lower pressures) and greater operational flexibility (e.g. cyclicig only during summer months).

Introduction
Considerable work on miscible gas injection in oil and, to a less extent, gas condensate reservoirs can be found in the literature. The phenomena of compositional variation with depth due to gravity and thermal effects has also been studied in detail the past 20 years. However, almost nothing in the literature can be found on the variation of miscibility conditions with depth in reservoirs with compositional gradients.

Intuitively it is difficult to picture the variation of MMP with depth for a reservoir with varying composition and temperature. This study shows that a simple variation does not exist, but that certain features of MMP variation are characteristic for most reservoirs.

For example, the simplest variation in MMP with depth is for a lean injection gas like nitrogen where minimum miscibility conditions developed by a purely vaporizing gas drive (VGD) mechanism. Here the MMP is always greater than or equal to the saturation pressure. In the oil zone, MMP may be (and usually is) greater than the bubblepoint pressure, while in the gas zone the MMP is always equal to the dewpoint.

The MMP variation with depth can be considerably more complicated when the injection gas contains sufficient quantities of light-intermediate components (C₂-C₅) or CO₂. Here, developed miscibility is usually by the condensing/vaporizing mechanism, but it may be purely vaporizing in some depth intervals of the reservoir. When the C/V mechanism exists, MMP may be and often is less than the saturation pressure, even for gas condensate systems.

This study quantifies the variation of MMP with depth for several reservoir fluid systems, and we try to understand the reasons for seemingly "complicated" MMP variation. Perhaps the most important result of our study has been to show that miscible gas injection in gas condensate reservoirs can exist far below the dewpoint. Economic application of enriched gas injection in partially-depleted gas condensate reservoirs may be achieved by slug injection, with slug sizes of 10% or less (similar to miscible slug injection projects in oil reservoirs).

Calculating Minimum Miscibility Pressure
Miscibility between a reservoir fluid and an injection gas usually develops through a dynamic process of mixing, with
component exchange controlled by phase equilibria (K-values) and local compositional variation along the path of displacement. The exact process of mixing is not really important to the development of miscibility – e.g. the relative mobilities (permeabilities) of flowing phases are unimportant. However, to obtain the correct MMP it is important to follow a "physically-realistic" path of developed miscibility, and not assume apriori how the path to miscibility occurs.

**Single-Cell Algorithms.** Historically, prior to 1986, it was assumed that developed miscibility followed one of two paths: (1) forward contact, or vaporizing gas drive (VGD), where the injection gas becomes enriched in C2+ by multiple contacts with original oil and, at the gas front, eventually develops miscibility with the original oil; or (2) backward contact, or condensing gas drive (CGD), where the injection gas continuously enriches the reservoir oil in C2-C5 at the point of injection until the injection gas and enriched reservoir oil become miscible.

Either process can be modeled with a single-cell calculation algorithm\(^6,7\), whereby the critical tie-line is located by appropriate multiple contacts of injection gas and reservoir oil. For gas condensates, the vaporizing mechanism has always been assumed to exist in miscible gas cycling projects and the VGD MMP is readily shown to equal the original dewpoint pressure.

For reservoir oils, it is usually assumed that the VGD mechanism exists for "lean" injection gases, while the CGD has been assumed to describe miscible displacement for enriched gas injection. Using a single-cell calculation algorithm, the calculated VGD MMP is almost always lower than or equal to the CGD MMP, unless the gas is highly enriched.

**Condensing/Vaporizing Mechanism.** Zick\(^8\) showed that a mixed mechanism involving both vaporization and condensation describes the actual development of minimum miscibility conditions for many systems. He showed that the location of "miscibility" (i.e. near-100% recovery efficiency) was located not at the displacement front (VGD) or the point of injection (CGD), but in between. He also showed that the true minimum conditions of miscibility could be significantly lower than predicted by the VGD and CGD mechanisms. These findings have been verified by numerous publications during the past 10 years\(^9,12\).

Based on Zick’s findings and his description of the mixed condensing/vaporizing (C/V) mechanism, it is clear that the true MMP (or MME) can be calculated only if the path of developed miscibility is modeled properly. Several authors have suggested methods to calculate the C/V MMP.

**Slimtube (1D) Simulation.** Both experimental slimtube measurements and properly interpreted slimtube simulations provide reliable determination of minimum miscibility conditions for a system, without assuming anything about the displacement mechanism or path of developed miscibility. The major problem with this type of miscibility test is severe case-dependent dispersion (physical or numerical).

Stullkup\(^1\) suggests a procedure for using slimtube simulations to estimate dispersion-free MMP. Oil recovery at a fixed pore volumes injected (e.g. RF\(_{1.2}\) at PV\(_{100\%}\)=1.2) is tabulated for a number of simulations with varying numbers of grid cells. These data are plotted versus the inverse of grid cell numbers (1/N or 1/√N), with the extrapolation providing an estimate for dispersion-free recovery (RF\(_\infty\)).

Dispersion-free recoveries are plotted versus pressure and the data are used to define the "breakpoint" where RF\(_\infty\) stabilizes at 100%. This point defines the MMP. We have found that this method provides an estimate of MMP within 5-15 bar for the systems studied (MMP ranging from 210-520 bara), the uncertainty depending on (a) the curvature in RF\(_{1.2}\) versus 1/√N at large N and (b) the maximum number of grid cells used. Figs. 1 and 2 show the determination of MMP by this method, where a dry gas is injected into a slightly volatile oil system.

Without taking into account grid effects, slimtube simulation results can overestimate MMPs severely and with a large degree of subjectivity. Even using the approach described above to eliminate grid effect, numerical dispersion can be a serious problem for gas condensate systems exhibiting the C/V mechanism.

**Zick Multicell Algorithm.** Zick\(^13\) has developed an efficient algorithm that mimics the development of miscibility as it appears in a slimtube simulation. The approach uses a series of PVT cells similar to what has been proposed by Cook et al.\(^14\) and Metcalfe et al.\(^15\). Zick, however, tracks the path of developed miscibility using a physical parameter describing the distance from criticality in each cell (e.g. density difference). By interpreting the historical minimum of this parameter for each cell (which decreases at increasing cell number), results are extrapolated to infinite grid cells and a dispersion-free value for the distance parameter. An automated algorithm determines the pressure (or enrichment) where the miscibility distance parameter approaches zero. Our estimates indicate that the Zick algorithm is 20-100 CPU times faster than multiple slimtube simulations, and with practically no manual interpretation of results.

We have tested the Zick algorithm for many reservoir fluids and injection gases, and we have compared results with slimtube simulations. Results are very similar, as shown in Table 1 and Fig. 3. An important feature of the Zick algorithm for the study of MMP variation with depth was its consistent procedures for data interpretation and extrapolation, thereby providing smooth and continuous MMP variation with depth.

**Tie-Line Algorithm.** Wang and Orr\(^16\) present a method for calculating MMP based on tie-line analysis and the method of characteristics. The method promises to be very useful if the numerical solution can be handled efficiently and consistently. Preliminary results presented by Jessen and Michelsen\(^17\) indicate that the Wang-Orr MMP calculation using an efficient algorithm is 50-100 times faster than the solution published by...
Wang and Orr (the original Wang-Orr method is apparently similar in computational speed to the Zick multicell algorithm).

Review of Compositional Grading
The composition of reservoir fluids can vary as a function of depth due to gravity and temperature gradients. The simplest model assumes isothermal conditions throughout the reservoir, with a resulting compositional variation described by the following monotonic property changes with increasing depth: (1) increasing C₇⁺ mole fraction and heavier C₇⁺ properties, (2) decreasing C₁ mole fraction (and GOR), (3) increasing dewpoint, and (4) decreasing bubblepoint. Monotonic changes in intermediate (C₂-C₆) components and CO₂ are also usually found.

The properties mentioned above are the most important to miscibility conditions. In this paper we present results only using the isothermal gradient model. Höser¹⁸ also gives results for non-isothermal gradient models, including the variation in MMP with depth for these systems.

Including a temperature gradient in addition to gravity results in somewhat different composition and property variations with depth compared with the isothermal model. Thermal diffusion consistently counteracts gravity in reservoir gases, thereby reducing compositional gradients. For reservoir oils, thermal diffusion can either counteract or enhance gravitational segregation, depending on the estimated sign and magnitude of thermal diffusion ratio (Soret effect). Significant uncertainty exists in the estimation of thermal diffusion ratios, and none of the available thermal diffusion models¹⁹-²² have been "verified" by data on reservoir fluid systems.

For the isothermal model, compositional and property variations are approximately linear except when the reservoir fluids are "near critical". Near-criticality can be loosely defined in this context by mixtures with GORs ranging from 300-1000 Sm³/Sm³ for reservoir fluids which are not highly undersaturated.

MMP Variation with Depth
Fluid Systems. In this paper we present results for three reservoir fluid systems: (1) a saturated slightly-volatile oil (SVO) with a somewhat lean gas cap; (2) a near-critical oil (NCO) with saturated transition to a very rich gas condensate; and (3) an undersaturated volatile oil (VO) with continuous (critical) transition to a rich gas condensate. The undersaturated volatile oil is based on the Ekofisk sample and EOS published by Belery and da Silva.²²

The majority of calculations are based on the two injection gases A and B shown in Table 2. Rich gas B is used to enrich lean gas A, where enrichment level E is given as mole fraction of the total gas mixture (e.g. E=0.25 indicates 0.25 moles of solvent gas B and 0.75 moles of lean gas A). Fig. 4 shows gas molar compositions as a function of enrichment.

Lean Gas Injection in Saturated Gas/Oil Reservoir. The simplest variation in MMP with depth is found for injection of a lean gas into a saturated oil with gas cap. Miscibility is developed by the vaporizing gas drive mechanism in this example, where VGD MMP is greater than or equal to the bubblepoint pressure in the oil zone. MMP may be significantly higher than the bubblepoint (and reservoir pressure), and the expected trend is increasing MMP with depth due to increasing amount and heavier properties of the C₇⁺ fractions in the oil. In the gas cap the VGD MMP is always equal to the dewpoint pressure.

Fig. 5 shows MMP variation with depth for the saturated slightly volatile oil and its overlying gas cap for lean injection gas A. Notice the discontinuity of MMP at the gas-oil contact, typical of saturated oil/gas systems far from critical behavior.

A saturated oil/gas system with near-critical transition at the gas-oil contact results in a more gradual transition in the VGD MMP across the GOC. This behavior is shown in Fig. 6 for the near-critical oil system with lean injection gas A (E=0). The VGD MMP in the oil zone is still greater than the bubblepoint pressure, but the MMP approaches the bubblepoint pressure as the gas-oil contact is approached. The VGD MMP increases monotonically at increasing depths in the oil zone, and the VGD MMP is (as it must be) equal to the dewpoint pressure in the gas cap.

Enriched Gas Injection in Saturated Gas/Oil Reservoir.
With an injection gas sufficiently enriched to develop miscibility by the condensing/vaporizing mechanism results in MMP variations with depth which are no longer related to or "limited" by the saturation pressure gradient. Consider the near-critical oil system shown in Fig. 6. VGD MMP behavior for the lean gas was discussed in the previous section.

The mixed C/V MMP behavior for an enrichment of E=0.4 is also shown in Fig. 6. Deep in the oil reservoir the C/V MMP is greater than the bubblepoint pressure. At shallower depths approaching the GOC we find the MMP decreasing monotonically, crossing the bubblepoint pressure gradient in a smooth and continuous manner.

At the gas-oil contact, the MMP drops significantly on the gas side of the GOC. This C/V MMP is typically the lowest MMP in the reservoir. At shallower depths within the gas zone we see an increase in the C/V MMP. As the reservoir gas becomes sufficiently lean (due to compositional grading) the condensing part of the miscibility mechanism disappears and the true MMP equals the VGD MMP (equal to the dewpoint pressure).

MME Variation with Depth in Oil Zone. Fig. 7 shows a plot of MMP versus enrichment level at a fixed depth in the oil zone. For lean injection gases the condensing/vaporizing mechanism does not develop and the true MMP is the VGD MMP. At increasing enrichment levels, a critical enrichment level (E*) is finally reached when the C/V mechanism is initiated and the true MMP drops below the VGD MMP.

As seen in Fig. 7, the C/V MMP continues to drop below the bubblepoint pressure in a smooth and continuous manner. This behavior, combined with the observation that E* is more-or-less independent of depth in the oil zone (Fig. 8a) suggests that the C/V MMP is independent of bubblepoint pressure (an
observation made previously by Zick).

However, the minimum miscibility enrichment (MME) for a fixed reservoir pressure is a function of depth in the oil zone (Fig. 8b). In the upper part of the oil zone we see that miscibility is developed by the VGD mechanism with the lean injection gas (E=0). At some depth D* the oil becomes sufficiently “heavy” that enrichment is required to maintain miscibility (at the fixed pressure). The required enrichment level at this depth is MME=E*, and the MME increases at greater depths.

At another reservoir pressure, the MME variation with depth will be similar to that described above, where the main difference is the depth D* where enrichment is required to maintain miscibility. MME at D* is more-or-less constant, independent of reservoir pressure, and the variation in MME below D* is similar (to that shown in Fig. 8b) for different reservoir pressures.

**Gas Injection in Undersaturated Gas/Oil Reservoir.** Transition from oil to gas through an undersaturated critical gas-oil contact is shown in Figs. 9 and 10. The dashed lines show saturation pressure variation with depth, where the maximum saturation pressure is (as always) a critical point defining the GOC. Characteristic of these fluid systems is that VGD MMP for a lean gas is always greater than the bubblepoint in the oil zone and always equal to the dewpoint in the gas zone. The VGD MMP at the GOC is equal to the critical pressure of the GOC mixture.

For systems with the developed condensing/vaporizing mechanism, MMP increases monotonically downwards through the oil zone. In the gas zone the C/V MMP is non-monotonic, where: (1) it continues to decrease above the GOC MMP, then (2) as the reservoir gas becomes leaner a minimum C/V MMP is reached, (3) the C/V MMP increases at shallower depths where reservoir gas continues to get leaner, and finally (4) the condensing part of developed miscibility disappears and the MMP gradient equals the dewpoint pressure gradient.

Systems with an undersaturated "critical" transition from gas to oil represent a potential for gravity stable updip miscible gas injection using any gas. In these systems all fluids throughout the reservoir are initially first-contact miscible with their neighboring fluids. Up-structure gas injection in a gravity-stable displacement should therefore result in fully miscible recoveries even for down-dip oils which are not miscible with the injection gas.

The only limitation for the success of such a gravity-stable process would be premature breakthrough of injection gas due to coning or dispersion. In the event of coning, miscibility will be lost only in the cone region. Away from the cone where displacement is still gravity stable the reservoir should experience miscible recoveries.

**Miscibility in Gas Condensate Reservoirs**

Historically it has been assumed that any gas cycling project in a gas condensate reservoir was miscible only by the vaporizing gas drive mechanism. Consequently, the MMP has always been assumed equal to the dewpoint pressure. Cycling projects where reservoir pressure dropped below the dewpoint were considered "inferior" because only partial vaporization of the retrograde condensate could be expected. For most separator injection gases these traditional assumptions are valid.

Our studies show that miscible displacement of gas condensates can be obtained at pressures far below the dewpoint for injection gases sufficiently enriched with NGLs (C₂-C₅).

**Condensing/Vaporizing Mechanism.** The development of miscible displacement by the condensing/vaporizing mechanism in gas condensate reservoirs has not been discussed previously in the literature. We give a short discussion of this process, its development, and properties of the process which are particular to gas condensate systems.

Fig. 11 (symbols) shows development of the oil saturation profile in a one-dimensional displacement for a gas condensate below its dewpoint (with approximately 15% liquid dropout at the time of injection). An oil bank develops quickly and increases in size at increasing pore volumes injected. Oil saturation behind the front approaches zero if the system is at or above the C/V MMP.

Fig. 12 (solid lines) shows the characteristic behavior of the C/V mechanism with an "hour-glass" shape of oil and gas densities, where the miscible (near-critical) front is located at the "bottleneck" in phase properties. The miscible front is located on the "back side" of the saturation bank (dashed line), leaving behind a near-zero oil saturation.

The size of the oil bank increases with time as shown in Fig. 11, but the absolute size at a given time (e.g. 0.5 PV injected) depends on the saturation and composition of the retrograde condensate ahead of the front -- e.g. a lean gas condensate will have a narrower oil bank than a rich condensate.

**Conditions of Developed C/V Miscibility.** Whether an oil bank develops with a near-critical C/V miscible front for a gas condensate depends on (1) pressure, (2) composition of the injection gas, (3) composition of the retrograde condensate ahead of the front, and (4) dispersion (numerical or physical). Although the same conditions also must be met for a C/V displacement of a reservoir oil, the conditions (3) and (4) are particularly important for gas condensates.

Below, we chose the near-critical near-saturated NCO system to discuss miscible gas cycling below the dewpoint because (a) the reservoir gases are rich and represent a prime target for gas cycling, (b) oil recovery loss due to retrograde condensation is severe for rich condensates, and (c) partial pressure maintenance with voidage replacement by produced gas only is inefficient for rich gas systems (resulting in significant reservoir pressure drop below the initial dewpoint).

**MME Variation with Depth in Gas Condensates.** The C/V MMP variation with depth in a gas condensate reservoir with compositional grading depends strongly on the level of enrichment. This behavior is shown clearly in Figs. 13 and 14a for the saturated NCO system. Converting results given in
Fig. 14a to a plot of MME versus depth at a fixed pressure (Fig. 14b), we see that enrichment is required to maintain miscibility at depths below D*. The limiting condition at D* is that the "fixed" pressure (reservoir pressure during gas cycling) equals the dewpoint pressure. Above D* the fixed pressure is greater than the dewpoint and miscibility is guaranteed with any gas (e.g., E=0).

At any depth below D*, enrichment is required to ensure miscibility at the system pressure (which is below the depth's original dewpoint). A varying degree of retrograde condensation has occurred at depths below D*, and the degree of condensation varies accordingly, with lower enrichment requirements at greater depths (Fig. 14b). The enrichment variation with depth below D* is related to the composition of retrograde condensate.

Miscibility Dependence on Retrograde Condensate Alone. For one-dimensional slumtub simulations of miscible displacement in gas condensate reservoirs below the dewpoint, we have found that the condensate composition ahead of the front (i.e., the initial retrograde condensate at the start of gas injection) controls the dispersion-free MMP. Experimentation has shown that the C/V MMP of the two-phase gas-plus-retrograde-condensate system is equal to the C/V MMP of the retrograde condensate alone. This is the justification for condition (3) above. We also have found that the same condition applies to reservoir oils where the C/V MMP is less than the bubblepoint.

Numerical Dispersion Effects. Fig. 15 shows the effect of grid size on the development of a near-critical front (and associated oil bank) for a leaner condensate with 10% liquid dropout ahead of the front. With 1000 and 3000 grid cells the oil bank does not fully develop as it does with 5000 cells. Also, oil recoveries at a given number of pore volumes injected (after breakthrough) are slightly higher for the 5000 cell simulation, even though saturations behind the front are near zero for 1000- and 3000-grid simulations.

The practical consequence of severe numerical dispersion in the C/V mechanism for leaner gas condensates is shown Fig. 16 where RF at 1.2 PV inj is plotted versus pressure for simulations with varying numbers of grid cells. Fig. 17 plots the same RF data versus 1/N for extrapolation to a dispersion-free recovery. At pressures approaching the C/V MMP we find that a large number of grid cells are required for simulations to provide recovery factors which can be reliably extrapolated to a dispersion-free result. Using only 100, 200, and 500 grid-cell simulations, for example, may result in an interpretation of MMP which is considerably higher than the true MMP. This is because the C/V mechanism is not sufficiently developed in the simulations with too-few grid cells (the actual width of the C/V front is smaller than 1/N).

Finally, the severe grid sensitivity of C/V displacement in depleted gas condensate systems leads to the question of how to model miscible displacement (below the dewpoint) on a field scale with large grid sizes. Though the same issue exists for modeling C/V displacement of oil reservoirs, the problem is more severe for gas condensates.

Physical Dispersion Effects. If the C/V front in a lean gas condensate system is sufficiently small then physical dispersion also can "destroy" the miscible displacement mechanism. This might be expected for lean gas condensates, but such systems would not be viable candidates for enriched gas cycling.

Slug Injection. Miscible gas cycling below the dewpoint in a gas condensate reservoir using continuous injection of an enriched gas has little chance of proving economic. The costs associated with using NGLs for enrichment would be prohibitive unless the NGLs were readily available and without a market. Consequently, we have evaluated the possibility of using slug injection of enriched gas, followed by a lean chase gas.

Simulations show that developed C/V miscibility conditions (MMP and displacement behavior) are practically identical for slug injection and continuous injection. Fig. 11 and Fig. 18 compare miscible displacements at the C/V MMP for continuous injection and slug injection of a 0.12-PV slug size.

The "identical" behavior of continuous and slug injection is found only if the slug size is larger than the "dispersion" size between the enriched gas and the chase gas (Fig. 19). If the chase gas breaks through the slug and contacts the reservoir gas-condensate system directly, miscibility will be lost. A similar limitation in slug size exists for miscible flooding in oil reservoirs.

Conclusions
1. Miscibility variation with depth due to gravity-induced compositional gradients can be significant, and the variation depends strongly on the mechanism of developed miscibility (vaporizing or condensing/vaporizing mechanism). If the C/V mechanism exists, the true MMP will always be less than the VGD (vaporizing) MMP.
2. In oil reservoirs, MMP always increases with depth, both for vaporizing and condensing/vaporizing mechanisms. VGD MMP is always greater than or equal to the bubblepoint pressure, while the C/V MMP can be greater than or less than the bubblepoint pressure.
3. In gas condensate reservoirs, MMP variation with depth follows exactly the dewpoint variation with depth only when miscibility develops by a purely vaporizing mechanism.
4. For enriched gas injection in a gas condensate reservoir the C/V MMP can be significantly lower than the dewpoint pressure.
5. MMP variation with depth in gas condensate reservoirs where miscibility develops by the condensing/vaporizing mechanism has the following general features:
   (a) MMP on the gas side of the GOC is less than or equal to the MMP on the oil side of the GOC; (b) MMP may decrease slightly at depths above the GOC until a minimum is reached, where at shallower depths,
(c) MMP increases until the condensing part of the mechanism disappears and the MMP equals the dewpoint (VDG MMP) variation with depth.

6. Dispersion has a strong influence on the development of miscibility by the C/V mechanism for lean gas condensates.

7. For a depleted retrograde condensate reservoir, the composition of the retrograde condensate at the start of a cycling project controls the C/V MMP.

8. Slug injections as small as 10% PV of enriched gas in depleted gas condensate reservoirs can develop miscibility at the same conditions as continuous enriched-gas injection.

Nomenclature

D* = depth requiring enrichment to obtain miscibility (by the C/V mechanism)
E = enrichment level
E* = minimum enrichment level required for a given reservoir fluid (at a given depth) to develop the C/V miscible displacement mechanism
K = equilibrium K-value ratio
N = number of cells in a multi-cell MMP calculation or slimtube simulation
PV = cumulative pore volumes injected
RF = stock-tank oil recovery factor after 1.2 PV inj
RF∞ = dispersion-free STO recovery factor after 1.2 PV inj

Acknowledgement

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References


### TABLE 1 – SUMMARY OF FLUID SYSTEMS, INJECTION GASES, AND MMP CALCULATIONS.

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### TABLE 2 – INJECTION GAS COMPOSITIONS.

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<td>F₅ (C₁₁⁻)</td>
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Fig. 1 — Extrapolation procedure for interpreting slimtube simulation results using varying grid numbers.

Fig. 2 — Recovery factor versus pore volume injected for slimtube simulations using varying grid cell numbers, and extrapolation to the dispersion-free RF (i.e. “infinite” grid cells).

Fig. 3 — Comparison of calculated MMP’s using the Zick multi-cell algorithm (symbols) and slimtube simulations with different methods to eliminate numerical dispersion (error bars). See Table 1.

Fig. 4 — Injection gas compositions as a function of enrichment.
Fig. 5 — Vaporizing MMP variation with depth for a dry injection gas in a saturated slightly volatile oil/lean gas condensate reservoir.

Fig. 6 — MMP variation with depth in a saturated near-critical oil/gas reservoir, showing MMP behavior for a lean gas (VDG mechanism only) and an enriched gas (C/V and VGD mechanisms).

Fig. 7 — MMP variation with enrichment at a specific depth in an oil zone, showing characteristic VGD and C/V MMP behavior.

Fig. 8 — (a) MMP variation with enrichment for oils at a number of depths; and (b) conversion to a plot of minimum miscibility enrichment (MME) versus depth in an oil zone.
Fig. 9 — MMP variation with depth for a slightly-enriched gas (E=0.47) injected in an undersaturated volatile oil-rich gas condensate reservoir.

Fig. 10 — MMP variation with depth for a highly-enriched gas (E=0.7) injected in an undersaturated volatile oil-rich gas condensate reservoir.

Fig. 11 — Development of an oil bank during injection of an enriched gas in a depleted gas condensate, comparing continuous injection with slug (0.12 PV) injection followed by methane.

Fig. 12 — Development of the condensing/vaporizing mechanism of miscibility in a depleted gas condensate (initially with retrograde condensate at the start of injection); snapshot at 0.7 PV_{inj}. 
Fig. 13 — Variation of MMP with depth in a saturated near-critical oil/gas system for injection gases with varying levels of enrichment; in particular, showing low MMP’s in the gas zone.

Fig. 14 — (a) MMP variation with enrichment at a number of depths in a gas cap; and (b) conversion to a plot of minimum miscibility enrichment (MME) versus depth in a gas cap.

Fig. 15 — Grid sensitivity for the development of a condensing/vaporizing miscible mechanism in a depleted gas condensate system.

Fig. 16 — Slimtube displacement STO recoveries for a gas condensate using varying number of grids, exhibiting large numerical dispersion which can not be readily eliminated.
Fig. 17 — Slimtube displacement STO recoveries at 1.2 PVs injected for a gas condensate using varying number of grids; large numerical dispersion can not readily be eliminated by extrapolation.

Fig. 18 — Comparison of gas densities during the development of an oil bank when injecting an enriched gas in a depleted gas condensate; continuous injection versus slug (0.12 PV) injection.

Fig. 19 — Slimtube displacement compositional profile at 0.97 PV injected initialized with enriched gas, and displaced with pure methane; numerical dispersion size is approximately 0.1 PV (250 grids / 3000 grids).