Retrograde Condensate Dropout Phenomena in Rich Gas Reservoirs—Impact on Recoverable Reserves, Permeability, Diagnosis, and Stimulation Techniques

D.B. BENNION, F.B. THOMAS, B. SCHULMEISTER
Hycal Energy Research Laboratories Ltd.

Abstract

Gas condensate reservoirs exhibiting classic "dew point" or retrograde condensate dropout behaviour exist in many areas in the world. These reservoirs are unique in that, as the reservoir pressure is decreased, a certain volume of the heavy end fraction of the gas is precipitated in liquid form from solution in the gas. This condensate liquid may be temporarily or permanently trapped in the reservoir, causing severe reductions in gas production rates and the permanent loss of a large portion of the volatile and valuable condensate liquids (due to capillary pressure-induced trapping effects in the porous media).

This paper reviews the basic theory of gas condensate dropout and describes, in detail, damage problems that may be associated with production of reservoirs of this type. Techniques for mitigating condensate dropout problems on a production basis, as well as stimulation techniques such as repressurization, lean and rich gas injection, surfactant and solvent injection, in situ combustion and water/gas injection, are reviewed, and the advantages and disadvantages of the techniques discussed.

Introduction

Rich gas or retrograde condensate gas reservoirs are common on a worldwide basis.

Figure 1 provides a pressure-composition diagram for a typical hydrocarbon system at a fixed temperature level. The shaded portion of this figure represents an area of two-phase equilibrium at the specified composition and pressure condition. This is generally a region where an immiscible hydrocarbon liquid and gas phase co-exist in thermodynamic equilibrium. Outside this area is a single phase region, where only one continuous and homogeneous uniform phase exists.

Potential Problems Associated with Rich Gas Condensate Systems

There are two main categories of problems commonly associated with rich gas reservoir systems:

1. Formation damage effects associated with the condensate dropout.
2. Permanent loss of valuable light condensate liquids due to trapping effects in the reservoir.

This paper addresses both of these issues and various techniques that can be used to reduce their impact on productivity and recovery.

Formation Damage Issues in Gas Condensate Reservoirs

The literature is replete with detailed discussions on formation damage(1-8). This paper does not address different types of damage which can occur during conventional drilling, completion and production operations, but concentrates solely on issues associated with condensate liquid dropout.

The primary damage mechanism resulting in a reduction in gas production rate in a rich gas-condensate reservoir is generally associated with capillary pressure-motivated phase trapping effects. These effects result in permanent reduction in the effective permeability to gas in the region affected by the condensate dropout surrounding the wellbore. This phenomenon is illustrated pictorially in Figure 2 and using a set of gas-condensate relative permeability curves in Figure 3.

As the condensate drops from solution in the gas while still in the porous media, capillary pressure effects are present [due to the generation of a second immiscible phase which has a finite interfacial tension (IFT) between it and the gas phase]. This capillary pressure traps the discrete drops of condensate in the central portion of the pore system and does not allow them to move until the saturation increases to the point where the individual droplets of condensed hydrocarbon liquid can accrete together and form a continuous condensate "film" in the porous media. Once this occurs, the condensate phase acquires finite relative permeability and can then flow as a separate and distinct phase in the rock. The value of the condensate saturation, which must build up before mobility occurs, is commonly referred to as the "critical" or "mobile" condensate saturation. It can have values ranging from less than 1% (at low IFT conditions and in high permeability rocks which have very low capillary pressure), to values in excess of 40% in poorer quality porous media.

Techniques to Avoid/Reduce Condensate Dropout Effects

Condensate dropout is a difficult problem to combat, simply because it is a natural thermodynamic property of the reservoir gas under consideration. As long as the reservoir temperature and gas composition remain constant, producing at a bottomhole pressure below the dewpoint will result in retrograde dropout.

One approach is pressure maintenance combined with reduced drawdowns and production rates such that the flowing bottomhole pressure around the production wells remains at all times above the dewpoint value. This is generally impractical in most operat-

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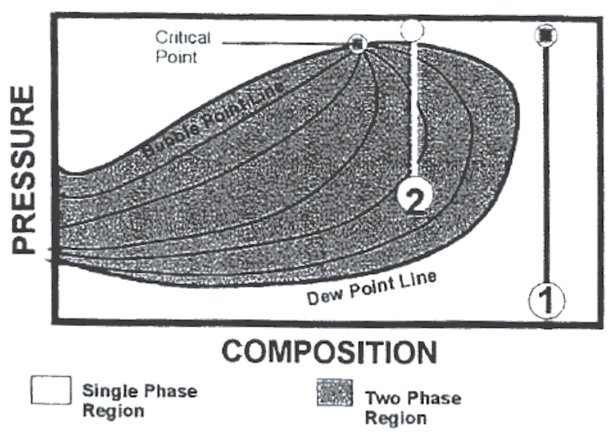

FIGURE 1: Illustration of typical pressure-composition.

ing situations, as many gas condensate reservoirs at discovery conditions are at or very near the dewpoint pressure of the gas. Even modest drawdowns applied in order to achieve economic production rates result in sub dewpoint pressure production around the producing wells.

Drawdown can be reduced in many cases by increasing effective bottomhole flow area through the use of high density perforating, open hole completions, horizontal wells and, in some cases, even by small fracture treatments (if fracturing will not result in water/oil production) in order to increase bottomhole flow area which can reduce drawdown and damage effects.

Mitigation Techniques

In most situations, a certain amount of damage due to condensate trapping is unavoidable. This is even the case in a gas cycling operation as, in general, although the bulk of the reservoir is maintained at some pressure above the dew point value, the area immediately adjacent to the wellbore is often subjected to high drawdowns which still result in localized condensate dropout. In good quality reservoirs where the value of the critical mobile saturation is low, this dropout may not appreciably affect flow rates (at least while reservoir pressure is high), and conventional primary production may be the economic and technical option of choice. In many cases though, periodic treatments to attempt to "remove" a portion of the trapped condensate liquids from around the wellbore are often used to try to increase production rates.

There are a number of potential techniques that have been suggested or used recently for this purpose with varying degrees of success. They include:

1. Static repressurization and imbibition
2. Lean gas injection
3. Rich gas injection
4. Solvent injection
5. Mutual solvent injection
6. In situ combustion
7. Water injection/displacement.

Static Repressurization and Imbibition

The tenant of this technique is based on the assumption of thermodynamic reversibility. Examination of Figure 1 indicates that, theoretically, if production from the well is halted (shut in) and if the bulk reservoir pressure is still high enough that over time the pressure in the depleted region around the wellbore is increased to above the original dew point pressure, the condensate liquids which are trapped in the pore system should be "re-vapourized" into the gas phase.

Unfortunately, this technique enjoys limited actual success in porous media due to the limited interfacial area, the revapourization process is extremely mass transfer limited (diffusion motivated) and hence very slow. Also, since such a limited volume of gas is in contact with a given volume of condensate in the pore space (the condensate which is trapped having been precipitated out of a huge volume of gas which has flowed through the pore space in comparison to the relatively small volume present in contact with it under static exposure), this once again severely limits the amount of revapourization that can occur.

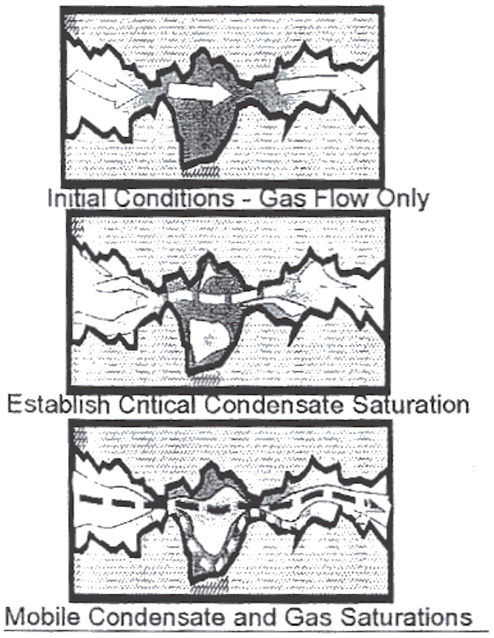

FIGURE 2: Pore scale mechanism of condensate trapping.

In a similar fashion, static imbibition (capillary pressure effects "wicking" the trapped condensate away from the wellbore deeper into the formation) are only effective if the reservoir exhibits strongly oil wet natural wetting tendencies. If the reservoir is neutral or water wet, there will be no spontaneous imbibition affinity present to move the trapped saturation away from the near wellbore region. Since many gas reservoirs do not contain a liquid hydrocarbon saturation initially, by default, in many cases, they are water-wet in nature, and hence this negates imbibition as a means of drawing retrograded condensate liquids away from the wellbore.

Examination of Figure 1 also indicates for some reservoir situations that if the pressure is dropped low enough, condensate begins to revapourize once again. In some instances, it is possible, at very low pressures and high temperatures, to pass completely out of the two-phase region (through the "bottom" dew point line as illustrated in Figure 1). Practically, once again, this method is limited in application. In most cases, the pressure at which substantive revapourization begins to occur is well below the economic abandonment pressure of the reservoir. Even if this is not the case, the re-vapourization process tends to be extremely slow and mass transfer-dominated when occurring in a static situation in porous media (in comparison to an agitated visual cell system in which the PVT measurements are normally conducted).

Lean Gas Injection

This technique enjoys more success, but generally requires relatively high bottomhole pressure in order to be successful. Lean gas injection is generally conducted using either dry methane or nitrogen gas and uses high pressure vapourizing miscibility to extract the trapped condensate from the injection region surrounding the wellbore. In this case, because the injection gas is lean in nature and contains no heavy end fraction, it has the capability of extracting a considerable amount of heavy ends from the system.

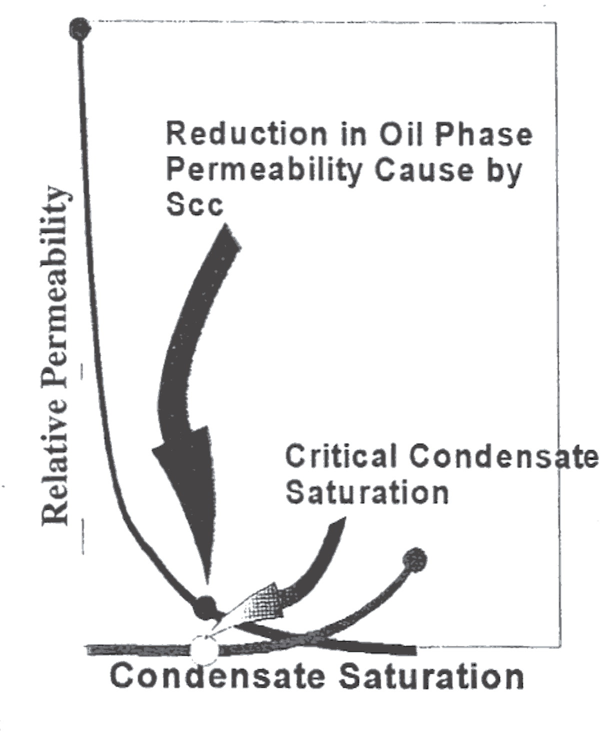

FIGURE 3: Typical gas-condensate relative permeability curve.

Since injection is occurring and new fluid is constantly moving through the pore system, convective and constant mass transfer is also possible in comparison to the previously discussed static shut in methods. Hence, more rapid mass transfer and vapourization effects are present.

The pressure required is highly dependent on the composition of the trapped condensate and specific temperature and gas properties. Generally higher pressures, usually in the 40 - 50 MPa region, are required for vapourizing miscibility with pure nitrogen gas. Methane tends to have lower vapourizing miscibility pressure with most condensates, often in the 30–40 MPa region.

This technique is commonly used as a periodic stimulation method in many gas cycling operations as a readily available source of lean gas and compression facilities are already present on-site. In many gas cycling operations, production wells are periodically stimulated for a few days by dry gas injection to remove accumulated condensate and increase production rates and reduce drawdown pressures.

Rich Gas Injection

In many reservoir situations, insufficient pressure is present to generate vapourizing miscibility with lean gas or nitrogen injection. In these cases, similar miscible extraction/displacement of the condensate can be effected by the use of a higher molecular weight injection gases such as ethane, propane or carbon dioxide which have much lower miscibility pressures with the trapped condensate. Although effective, these methods are fairly expensive to apply and concerns exist in some situations with respect to potential deasphalting of the condensate liquids by rich gas contact. Compatibility tests between the proposed injection gas and the reservoir condensate should be conducted to evaluate this issue prior to executing a treatment of this type.

Solvent Injection

This process consists of the injection of a liquid phase hydrocarbon solvent (generally toluene, xylene or distillate) into the formation. Although this method is often effective for removing wax/paraffin deposits that may be associated with condensate production in some wells, as a method for removal of "trapped" condensate, the method is normally ineffective as one simply substitutes one miscible hydrocarbon phase for another. In many cases, the IFT between the reservoir gas and an organic solvent, such a xylene, is actually higher than that between the trapped condensate and the reservoir gas, which may actually result in an increase in trapped hydrocarbon phase saturation.

Mutual Solvent/Surfactant Injection

This includes the injection of high molecular weight alcohols (i.e., butanol), other mutual solvents and surfactants. The objective is to reduce the gas-condensate IFT which makes it easier to recover the trapped condensate (e.g., lowers the value of the critical condensate saturation). Many alcohols have sludge and emulsion problems with condensates and careful compatibility testing should be conducted. Often with many agents of this type, the actual reduction in gas-oil IFT is relatively slight and the overall stimulation effect may be marginal. Careful IFT and lab screening should be conducted prior to execution to determine the effectiveness of any agent of this type for condensate removal.

In Situ Combustion

This is a fairly novel technique which attempts to use air injection to ignite and "burn" the trapped condensate saturation out of the region in the near wellbore area. Most condensates are volatile in nature and will spontaneously ignite at reservoir temperatures over about 120° C.

Concerns with this method include high bottomhole temperatures and cement degradation, effective propagation of the flood, corrosion concerns and well flashback (explosion) concerns if all of the injected oxygen is not consumed by combustion and LTO/HTO oxidation reactions with the in situ crude oil.

Considerable research work is currently underway evaluating the use of this method. Accelerated rate calorimetric studies(10) are a common screening method, coupled with combustion flow tests, to determine the suitability of this method for reservoir application.

Water Injection

This has long been proposed as a technique to recover trapped condensate liquids from a depleted gas condensate reservoir. The motivation is in many reservoir cases, the irreducible condensate saturation to water displacement is lower than the irreducible condensate saturation to gas displacement. It is thought that injected water may mobilize a portion of the trapped condensate saturation in the bulk reservoir matrix, allowing recovery of a portion of this "trapped" resource.

Practical experience indicates that the value of the trapped condensate saturation must be very high for this to be practical. In all cases where the author has evaluated this method as an EOR method, very limited recovery was observed on a bulk reservoir basis which suggests in most applications, the potential for success is marginal.

Water injection has been used as a stimulation method in some high permeability (10,000 mD plus) gas condensates to displace the zone of high mobile condensate saturation away from the bottomhole region in a situation where pressure has dropped to the extent that the wells are loading and self killing with condensate. This is then followed by gas injection to displace the water and re-establish high gas saturation and permeability with the "undamaged" portion of the reservoir. In lower permeability rocks, this method is not advised, as trapping and capillary pressure effects associated with the introduction of a water phase in the near wellbore region may create additional damage effects.

Duration of Stimulation

It should be noted that all of the aforementioned stimulation techniques do not solve the root cause of the damage, this being the retrograde nature of the gas. In many cases, these treatments must be repeated on a regular basis as, even though the condensate is removed from the near wellbore area, continued production below the dewpoint pressure results in the recurrence of accumulation problems. The economics of the treatment will thus be highly dependent on the magnitude and length of the "flush" production period that is created after the stimulation treatment is completed.

Conclusions

The mechanism of condensate dropout from rich gases has been discussed as one of the potential mechanisms reducing the production rate and recoverable reserves of condensate liquids. In general, the value of the critical condensate saturation in porous media varies from 1 – 40% and is affected by pore geometry, wettability, interfacial tension and capillary pressure and drawdown effects. In most situations, porous media with in situ permeabilities greater than 1,000 mD exhibit low (less than 5%) critical condensate saturation values. Formation damage and trapping issues are generally more severe in lower quality (sub-100 mD) formations which exhibit more adverse capillary pressure characteristics. Means of reducing dropout problems, as well as remediation techniques such as represurization, lean and rich gas injection, solvent injection and in situ combustion have been presented and the specific advantages and disadvantages of each method reviewed.

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Authors Biographies

Brant Bennion is Hycal's president and is a project engineer with over 20 years of domestic and international technical expertise in the area of formation damage and fluid flow in porous media. Brant has authored or co-authored over 170 technical papers on a variety of subjects, including multi-phase flow in porous media, formation damage, underbalanced drilling, fluid phase behaviour and enhanced oil recovery. Brant received his B.Sc. in chemical and petroleum engineering from the University of Calgary with distinction in 1984. Brant received Best Technical Paper of the Year awards from the Petroleum Society in 1993 and 1995. Brant is a director of the Petroleum Society and is also a member of APEGGA and SPE (registered P.Eng). Brant was also chosen to be a "Distinguished Lecturer" for the SPE for 2001.

Brent Thomas is Hycal's senior vice-president and is a project engineer working in the area of numerical simulation and gas injection. He received his Ph.D. from Washington University in chemical engineering. Brent has over 20 years of domestic and international experience in the area of numerical simulation, gas injection, phase behaviour, solids precipitation, and chemical and thermal application. He has authored or co-authored over 130 technical papers and received the 1992 Best Technical Paper of the Year award from the Petroleum Society (Experimental and Theoretical Studies of Solids Precipitation from Reservoir Fluids). He was selected as a "Distinguished Author" for the Petroleum Society in 1995.

Bernie Schulmeister is the engineering manager at Hycal. He brings with him 20 years of industry experience, 15 of which are directly focused on laboratory research and services. He maintains a strong technical background in the areas of petrophysics and formation damage assessment and control. Experienced in managing and conducting applied studies in all areas of advanced core analysis. Currently responsible for overseeing the engineering function of our integrated projects which includes special core analysis and phase behaviour. Bernie is a graduate of the Southern Alberta Institute of Technology with a diploma in petroleum engineering technology.