ESTIMATION OF RESERVES POTENTIAL FOR NEAR CRITICAL SYSTEMS
RESPONS II

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ABSTRACT

Rational management of the oil and gas reserves in Europe, and in North Sea more specifically, is of strategic importance for the European Community with respect to its energy policy. North Sea generates 90% of the EU hydrocarbon production and satisfies almost 35% of the demand. Giant fields (Elgin, Franklin) are in extreme pressure and temperature conditions (up to 1200bar, 120°C).

Confidence on the reserves estimation and on the recovery predictions is a key issue in the development policy of the petroleum industry. The technology developed within this project allows to set more correct cut-off values which constitute the limit for what can be considered as part of the reserves. It will also help in optimising the production scheme and the sizing of the surface facilities thus limiting flaring of excess gas and improving air quality.

The results will help increasing the level of expertise of the European oil and gas industry and of the related technical and consulting centers, and will ensure its competitiveness compared to the homologous North American.

This project investigated the relative importance of the physical processes, helped define their impact on near-critical fluids productivity and provided improved models for the prediction of gas condensate productivity.

Key technical results and breakthroughs were achieved in the following fields:

Description of thermodynamics and interfacial properties of near-critical fluids.

- Measurement of the bulk and interfacial properties for model and real gas condensate fluids. Innovating and efficient modeling to calculate liquid-vapor coexistence curves and IFT incorporating the singular behavior near the critical point and classical behavior far away from it.
- A thorough understanding of the wetting behavior of simple oils on water in presence of gas and demonstration that it does not obey the conventional picture. Modeling to predict the location of the different wetting states as a function of oil composition, brine salinity, presence of surface-active agents, temperature and pressure.

Modeling of fluid flow in low permeability reservoirs related to the porous medium structure and properties (far field and near-wellbore region).

- Dependence of the relative permeabilities on the capillary number even for very low values. Severe trapping of the condensate phase outside the critical point vicinity.
- An efficient model to calculate gas condensate relative permeability and critical condensate saturation as functions of the capillary number and the Bond number, the dimensionless parameters expressing viscous to capillary and gravity to capillary forces ratios.
- Examination of different approaches to model high flow rate effects and demonstration that the most promising one is to model inertial flow effects separately through the non-Darcy flow factor, in which case the relative permeability could be modeled as a function of capillary number.

1. EXECUTIVE SUMMARY

The general objective of this project was to improve modeling of gas condensate behavior and flow in tight reservoirs in the far-field and the near-wellbore region, in order to better estimate the reserves potential, and design appropriately their exploitation and recovery.

More specifically the technical objectives of the project were:
- Improving description of thermodynamics of near-critical fluids
- Improving understanding of physical phenomena dominating fluid flow in low permeability reservoirs and relating them to the porous medium structure and properties
- Improving the understanding of processes occurring in the near-wellbore region of a gas condensate reservoir.

In order to meet the objectives the project has been organized in two major tasks.
Task 1: Properties of reservoir fluids (densities, viscosities, interfacial and wetting properties)
Task 2: Transport parameters in porous media (far and near-wellbore conditions)

Task 1 consisted in studying bulk and interfacial properties of selected fluids at near-critical conditions in order to provide an appropriate that is needed to estimate the reserves in near-critical hydrocarbon fields and to describe the transport of high-rate condensate flow in tight porous media. Within this task:
- the bulk thermodynamic properties have been measured for multicomponent hydrocarbon mixtures and real gas condensate fluids. The phase envelops as well as the liquid dropout curves, the densities and compositions of the condensate and gas phases have been determined experimentally at appropriate ranges of pressure and temperature.
- experimental work with PNA (paraffin, naphthenic, aromatics) fractions has indicated that by varying the ratio of components from different PNA fractions it is possible to mimic the density and behavior of real petroleum fractions.
- a simple calculation procedure has been proposed for the thermodynamic behavior of near-gas condensates. It is based on a pressure and temperature shift by an amount equal to the difference between measured and calculated values. It can be easily implemented in reservoir simulators.
- a global crossover EOS has been obtained that incorporates the singular behavior near the critical point and classical behavior far away from the critical point for pure fluids. The asymptotic behavior satisfies universal scaling laws with universal critical exponents and universal amplitude ratios, which are very well established theoretically and experimentally.
- a mapping based on molecular type rather than boiling points has been proposed and tested for fluid mixtures. Only a few well-chosen components may be necessary to achieve a good mapping result. Phase behavior and density appear to map satisfactorily for the systems investigated.
- an experimental program has permitted acquisition of gas/oil interfacial tensions for real and synthetic gas condensates as a function of pressure and composition by using the pendant drop technique or the interface laser-light scattering spectroscopy. Values as low as 0.0058 mN/m have been determined with an overall accuracy better than 2%.
- the gradient theory of van der Waals has been combined with the Peng-Robinson equation of state to calculate bulk and interfacial properties of hydrocarbon mixtures. A satisfactory agreement with the experiments has been achieved.
- a mean field gvdW theory has been implemented to calculate liquid vapour coexistence curves and IFT for multicomponent mixtures of molecular fluids. The method has been used to study alkane mixtures pressurised with methane, nitrogen or carbon dioxide. Ternary mixtures and four component systems have also been studied. The gvdW-theory gives the IFT with an absolute accuracy of 0.3mN/m when the IFT is greater than 4mN/m and less than 0.3mN/m when the IFT is smaller than 4mN/m. It also gives good predictions remote from the critical point.
- a thorough understanding of the wetting behaviour of simple oils on water has been acquired. It has been demonstrated that the equilibrium wetting behaviour of oils on water in the presence of gas does not obey the conventional picture. In particular, the location of the different wetting

states can be predicted as a function of oil composition (alkane chain length), brine salinity, presence of surface active agents, temperature and pressure. This understanding arises primarily from ellipsometry measurements of equilibrium oil film thicknesses.

Task 2 consisted in studying and modeling flow properties of near-critical reservoir fluids to porous medium properties (structure, wettability, permeability) and to distance from wellbore. Concerning the flow far from the well the objective was to measure flow parameters, critical saturations and recovery, for near-critical fluid flow in porous media using the experimental set-ups developed within the REPONS project. Concerning the flow in the near-wellbore region the objective was to study the effect of operational parameters on the gas condensate behaviour in ordinary and tight formations. Within this task:

- core flood experiments were carried out in low permeability rocks (a 10 md sandstone and a 5.9mD limestone), with a 3-component and a 5-componant synthetic condensates that had been characterised by volumetric pVT experiments and interfacial tension measurements. The core flood experiments carried out were pressure depletion experiments, equilibrium gas injection, and co-injection of liquid and gas at different pressures.
- it was found that gas and condensate relative permeabilities depend on the capillary number even for capillary numbers as low as 10-7 and that both gas and condensate relative permeabilities increase with increasing capillary number.
- it has been demonstrated that outside the critical point vicinity, severe trapping of the condensate phase has been observed, accompanied by important hysteresis on the fluids mobility
- an experimental equipment has been designed to undertake near-wellbore measurements using a pseudo steady state method. Experiments were carried out above the dew point pressure to measure the inertial (non-Darcy) flow coefficient, and below the dew point pressure to measure the gas and oil relative permeability. They show both an increase in relative permeability with capillary number, and a reduction in effective gas permeability due to inertial flow. The capillary number effect is much more significant, so that the combined effect is to increase mobility for the flow rates in these experiments.
- flow rate and interfacial tension dependence of relative permeabilities have been explained on the basis of the competition between capillary and viscous forces. To account for that, a new capillary number is introduced. It includes, in addition to fluid properties, porous medium properties. This hypothesis has been validated by interpreting experimental results.
- a fractal model has been proposed to calculate gas condensate relative permeability and critical condensate saturation for mobility as functions of the capillary number and the Bond number, the dimensionless parameters expressing viscous to capillary and gravity to capillary forces ratios. The model takes into account the wetting/spreading characteristics of the system (rock & fluids). The model also includes the structure characteristics of the porous medium through its fractal dimension. The model, which predicts the modification of the relative permeability curves as the capillary number changes (velocity or interfacial tension changes), has been tested against experimental results, and a very satisfying agreement has been obtained, indicating that the major effects of the controlling parameters are correctly accounted for.
- different approaches to model high flow rate effects have been examined. The most promising approach was to model inertial flow effects separately through the non-Darcy flow factor F_{ND}, in which case the relative permeability could be modelled as a function of capillary number.
- history matching of both pVT and flooding experiments has shown that experimental data during depletion could not be reproduced with the same relative permeability curves as used to match equilibrium gas injection or co-injection. Equilibrium gas injection and co-injection could be matched with very similar relative permeability curves.

2. PARTNERSHIP

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3. OBJECTIVES

1) Industrial Objectives

New exploration techniques lead to the discovery of deep oil and gas fields, where the pressure and temperature is susceptible to attain very high values. These high pressure/ high temperature formations constitute a large proportion of the North Sea hydrocarbon reserves. Two well known examples are the Elgin and Franklin fields in North Sea with pressures up to 1100bars and temperatures as high as 200°C. Several other examples can be cited all over the world with pressures generally varying between 600 and 1200bars and temperatures ranging from 80°C to 200°C.

Of course the primary depletion of these fields is important and high production rates can be achieved as far as the fluid remains in one-phase state. However due to the depletion (gas or oil production) the fluid may turn near critical and the pressure may drop below the dew point. Then a new phase appears whose properties do not differ much from the other phase. Presence of two phases within the reservoir results in a modification of the flow properties of each phase far from or near the well bore, and may severely affect well productivity.

Some field experience suggests that the effect is less severe than expected from relative permeability measurements made in conventional laboratory studies. However field data in tighter formations show dramatic decrease of relative permeability and may lead to abandonment of the reservoir. In fact there exists a high uncertainty on whether the gas condensates in these tight material are producible or not and down to which permeability limit. Besides as most of these reservoirs are in deep sea, well interventions and regular well services are extremely expensive and would easily kill the economics of such development.

Confidence on the reserves estimation and on the recovery predictions is a key issue in the development policy of the petroleum industry. It is highly important to correctly predict the evolution of the response of near-critical reservoirs as a function of the pressure drawdown caused by their exploitation. This project aimed at developing know-how that would allow to set more correct cut-off values which constitute the limit for what can be considered as part of the reserves (recoverable oil and gas). Reliable knowledge of these cut-off values helps also in optimising the production scheme and the sizing of the surface facilities.

To this end a double objective has been set for the present project: to improve modelling of both the thermodynamic and the flow behaviour of near-critical hydrocarbon reservoirs. The developed modelling tools, implemented in reservoir simulators, permit to better forecast field productivity and design surface installations.

The main recipient of the results of this project is of course the **oil industry**. It concerns adequate simulations of primary recovery processes of volatile oil or gas condensates, as well as improved design of secondary recovery schemes (waterflooding of gas condensate reservoirs). However the results of the project may also have an **environmental** dimension. Good sizing of surface installations (separators, gas pipes) permit to limit flaring of excess gas thus having a strong impact on environment and air quality.

2) Technical Objectives

The general objective of this project was to improve modelling of the gas and oil behaviour and flow at near-critical conditions, in order to better estimate the reserves potential, and design appropriately their exploitation and recovery.

More specifically the technical objectives of the project are:

- Improving description of thermodynamics of near-critical fluids
- Improving understanding of physical phenomena dominating fluid flow in low permeability reservoirs and relating them to the porous medium structure and properties
- Improving the understanding of processes occuring in the near-wellbore region of a gas condensate reservoir.

In order to meet the objectives the project has been organised in two major tasks.

1. Properties of reservoir fluids (densities, viscosities, interfacial and wetting properties)
2. Transport parameters in porous media (far and near-wellbore conditions)

More and more gas condensates are explored at near-critical conditions for which experimental data of a variety of properties are not available. Phase behavior and interfacial phenomena need to be given more attention mainly when the critical point is approached. All classical models fail to describe/predict accurately these properties at near-critical conditions. The reason of this inadequate behavior of the models is that all of them suffer from the fact that intermolecular long-range fluctuations have not been taken into account. The last decade, significant progress was made in the understanding of near-critical phenomena and on the way to include them in the existing classical models. Within this project relevant and accurate experimental data have been obtained and refined models to describe fluid phase behavior and interfacial phenomena at near-critical conditions developed and tested.

The wetting properties of near-critical reservoir fluids are also a crucial issue as proven within the RESPONS project. It is now well established that wetting and spreading behaviour of the fluids highly affects their distribution within the porous structure, thus affecting displacement mechanisms, transport parameters and sweep efficiency. The transitions between partial and complete wetting for realistic oils and brines are delineated and analysed as a function of thermodynamic conditions (pressure, temperature, oil composition, brine salinity). These results provide the necessary information to interpret the experiments in porous media on a physical basis and to develop a more realistic modelling taking into account the physics of the displacement and the fluid interactions.

Finally the experiments in porous media permit to determine the core flow parameters for near-critical reservoir fluids far from the well and in the near-wellbore region. The effect of the porous medium structure and of the operational parameters is investigated: *critical fluid saturation* and *oil and gas relative permeabilities* are determined. Based on the experimental results, new models are developed for phenomena not taken presently into account in reservoir simulators.

3. TECHNICAL DESCRIPTION

The objective of this work was to provide an appropriate description of the fluid bulk and interfacial properties that are needed to estimate the reserves in near-critical hydrocarbon fields and to describe the transport of high-rate condensate flow in tight porous media. In order to achieve the technical objectives, which consist in developing experimental and theoretical tools (methodologies) to improve reserves estimate and flow description for near-critical reservoirs, the workprogramme had been divided into the following major tasks and subtasks:

Task 0: Selection of fluid/rock system

Task 1: Properties of reservoir fluids

- 1.1 Bulk properties of reservoir fluids
- 1.2 Oil/Gas interfacial tensions
- 1.3 Wetting properties of reservoir fluids

Task 2: Transport parameters in porous media

- 2.1 Effect of porous medium properties
- 2.2 Effect of near-wellbore conditions
- 2.3 Modelling and simulations

In what follows the work performed in Tasks 1 and 2 is briefly described.

Chapter 1 : PROPERTIES OF RESERVOIR FLUIDS

Within this task, determination of bulk and interfacial properties of selected fluids at near-critical conditions has been performed. Within the same task an important modelling part has been also developed. Details on the measurements and the theoretical concepts behind the models development are given below.

1.1 Bulk properties of reservoir fluids

Nowadays, the oil industry focuses more and more on the exploration and production of gas condensates much deeper than those currently in production. As a consequence that we are dealing with reservoirs at substantially higher temperatures and pressures, i.e., temperatures and pressures as high as 200°C and 1000-1400bars respectively are not rarely met. Due to these extreme conditions, the oil industry is facing a serious lack of basic data and knowledge of these fluids.
Even unexpected phenomena may occur during production of these gas condensates. For instance, during the production of a North-Sea high-pressure-high-temperature gas condensate reservoir, it was established that, although theoretically not impossible, a temperature increase of the produced condensate was observed at pressure release.
It has been also observed that sometimes the conditions of these high-temperature-high-pressure gas condensate reservoirs are such that criticality of the fluid may occur. This has the consequence that all traditional models for the prediction of thermodynamic properties fail because these classical models do not account for long-range fluctuations between the molecules. Another aspect related to the extreme conditions of the reservoirs is that due to the large cooling range of the fluid, there is a major enhancement in the probability of solid precipitation (wax, asphaltenes, and hydrates) during production and transportation.
Therefore, the primary objective of this task within the framework of the project was to provide experimental volumetric data (densities, fluid phase equilibrium, liquid dropout under a pressure drawdown) of some selected model gas condensates, with emphasis on the near-critical region, and to model them using different theoretical approaches. Also the effect on the phase densities of the mixture composition (different ratios of paraffin, naphthene and aromatic mimicking those found in real oils) has been determined.
Although the experimental information on the three component gas condensates is of major interest, for modeling purposes also experimental information on the subsequent binary mixtures is most

important. For instance, this experimental information on the composing binary mixtures can be used to calculate binary interaction parameters for the predictive models to be applied.
The experimental data obtained in this study have been modeled with three different approaches:

- A simple procedure based on a temperature and pressure shifting to correct some of the failures of the conventional EoS, namely the discrepancy between the measured and calculated saturation pressures and critical temperature.
- Simultaneous prediction of the fluid phase behavior and the interfacial tension using the Van der Waals square gradient theory in combination with the classical Peng-Robinson equation of state.
- Prediction of the fluid phase behavior with emphasis on the near-critical region applying a crossover Peng-Robinson equation of state.

1.2 Gas/Oil interfacial tensions

A special effort has been made to measure and model interfacial properties of the fluids. The interfacial properties of interest are the condensate/gas interfacial tension that govern capillary trapping and therefore residual condensate saturations, as well as the condensate and gas relative permeabilities. The interfacial tensions can vary by two or three orders of magnitude when the pressure and temperature conditions vary. Existing reservoir simulators fail in predicting accurately these variations mainly close to the critical point.

The work on this subject has been twofold: experimental and theoretical. An experimental program has permitted acquisition of interfacial tensions for real and synthetic gas condensates as a function of pressure and composition. A generalized van der Waals theory has been extended to complex hydrocarbon mixtures and real oils mapped onto a small number of pseudocomponents. Another modeling approach consisted in combining the gradient theory of van des Waals with the Peng-Robinson equation of state to calculate bulk and interfacial properties of hydrocarbon mixtures.

1.3 Wetting properties of reservoir fluids

The wetting behaviour of oils (condensates) on water in the presence of gas is expected to strongly influence the flow of oil (condensate) through porous media containing an irreducible water phase covering the rock surface. Thus, it is generally believed that oil drainage is more efficient under complete wetting of water by oil, due to the presence of the continuous oil film between water and gas. Under partial wetting conditions, however, a significant quantity of oil remains trapped in the porous medium after drainage, presumably under the form of disconnected oil lenses. For phases in thermodynamic equilibrium, the balance of interfacial tensions $S = \gamma_{wg} - \gamma_{wo} - \gamma_{og}$ (subscripts w, o and g stand for the water, oil and gas phases, respectively) controls the equilibrium wetting (or spreading) properties, with S<0 corresponding to partial wetting and S=0 to complete wetting.

An important question for this project, as it has an impact on porous media transport properties, was the following. Under what thermodynamic conditions (i.e., pressure, oil composition, etc.) do condensates wet water completely (S=0) or partially (S<0)? According to a classical argument due to Cahn (1977), near-critical condensates should completely wet water in a range of conditions « close enough » to the oil/gas critical conditions, while those « far enough » from the oil/gas critical point should only partially wet water. The transition that occurs between these two wetting states under a variation of thermodynamic conditions is referred to as a *wetting transition* : for practical purposes, it suffices to know the location of such transitions in the space of thermodynamic variables, or wetting phase diagramme. The initial purpose of this project was to identify and locate these transitions for oils on brines, starting with oils composed of pure alkanes such as the oil studied in Task 1.1 and utilized for the porous media experiments. An equilibrium wetting behaviour of the type described theoretically by Cahn in 1977 and subsequently found experimentally in many fluid systems was anticipated.

The most surprising outcome of this research is that the equilibrium wetting behaviour of oils on water in the presence of gas does not obey the conventional picture. It involves three, rather than two, different wetting states. Oils, at least those oils mostly composed of alkanes, display on water an intermediate wetting state between partial wetting (oil lenses) and complete wetting (thick oil film). This state, referred to as *frustrated-complete* wetting, consists of oil lenses coexisting at the surface of water with a mesoscopic (i.e., several tens of molecules, or around 100 Å -thick) oil film.

These studies provided a thorough understanding of the wetting behaviour of simple oils on water. In particular, the location of the different wetting states can be predicted as a function of oil composition (alkane chain length), brine salinity, temperature and pressure. This understanding arises primarily from ellipsometry measurements of equilibrium oil film thicknesses.

Chapter 2 : TRANSPORT PARAMETERS IN POROUS MEDIA

The objective of this work was to relate flow properties of near-critical reservoir fluids to porous medium properties (structure, wettability, permeability) and to distance from wellbore.

Concerning the flow far from the well the objective was to measure flow parameters, critical saturations and recovery, for near-critical fluid flow in porous media using the experimental set-ups developed within the REPONS project. Concerning the flow in the near-wellbore region the objective was to study the effect of operational parameters on the gas condensate behaviour in ordinary and tight formations.

2.1 Effect of porous medium properties on condensate mobility

Describing flow processes that occur both far from and close to the wellbore region is a major issue to accurately predict gas-condensate reservoir performance. When producing a gas condensate reservoir, the pressure draw-down leads to the build-up of a liquid bank which gets progressively mobile. Once mobile, this oil bank flows towards the producing wells that may thus experience impairment.

The retrograde condensation caused by this pressure draw-down is quite detrimental. Indeed, the liquid accumulation that occurs in the vicinity of the production wells tends to lower the deliverability of the gas by multiphase flow effects (relative permeability). In addition to that, the gas which is to be produced, due to condensation, tends to become lighter and therefore less marketable.

Predicting a gas condensate reservoir performance thus requires an accurate modeling of the flow behavior coupled with a correct thermodynamic modeling of the various processes.
Once the liquid segregates, the way the densities of the two phases start diverging and the gas/liquid interfacial tension builds up depends on the thermodynamic properties of the gas condensate system as seen in Task 1.
Depending on how close to the critical point the system will get when the pressure has decreased and the system has reached the phase envelope, the liquid accumulation, and then its production, is just ruled by the balance between three main mechanisms:

- gravity segregation
- capillary hold up
- viscous drag

A proper modeling of those three intricate mechanisms is quite complex. To reach that goal a number of experiments conducted in model porous media (micromodels) allowed to identify at the pore scale, the local events which are related to the liquid build up and its subsequent flow. Those experiments confirmed the great complexity of the various mechanisms that need to be accounted for.

For a long time only the effect of interfacial tension on the relative permeabilities has been studied, and relative permeability curves modification has been attributed to rapid interfacial tension changes near to the critical point. More recently the effect of flow velocity on the relative permeability curves has been acknowledged, and the investigations have been oriented toward a dependence of the relative permeabilities on a dimensionless number, the capillary number, that includes both the interfacial tension and the velocity.

Another parameter that has been extensively studied is the critical condensate saturation, S_{cc}. This saturation is the minimum liquid saturation above which the condensate starts being mobile, corresponding thus to a non-zero condensate relative permeability. There is quite a controversy about the determination of this value. Values ranging between zero and 50% PV have been reported. It has been largely recognized that the determination of the critical condensate saturation is of great importance to predict gas deliverability even though the condensate relative permeability takes very low values.

Another key factor is the wetting behaviour of condensate on the water phase, as complete wetting of the condensate on water favors its hydraulic continuity and allows to reach very low liquid saturations. As seen in subtask 1.3 there is theoretical and experimental evidence that for near-critical systems the condensate phase perfectly wets either the rock or the water phase covering the pore surface. However, as the pressure decreases in the near wellbore region a wetting transition may occur which would render the condensate phase only partially wetting. This would affect its hydraulic continuity and favor its trapping by capillary forces.

Core flood experiments were carried out in low permeability rocks (a 10 md sandstone and a 5.9mD limestone), with a 3-component and a 5-componant synthetic condensates that had been characterised by volumetric pVT experiments and interfacial tension measurements. The core flood experiments carried out were pressure depletion experiments, equilibrium gas injection, and co-injection of liquid and gas at different pressures.

2.2 Effect of near-wellbore conditions

The study is tailored specifically to near well gas condensate productivity, but the research may also be applicable to oil reservoirs below the bubble point pressure. The objective was to develop a proven method to determine near well relative permeability data and numerical model(s) to accurately predict well deliverability in gas condensate reservoirs.

The results from this project could be packaged to offer the industry a “routine service” to measure near well relative permeability and predict more reliably wellbore deliverability. The potential cost saving to the industry may be huge, since current simulation tools tend to under predict gas deliverability (and hence more wells may be drilled than necessary). More accurate well deliverability prediction will also enable better sizing of surface handling installations. The potential improvements in predictive tools, resulting in a more reliable and accurate forecasting, will allow improved planning and reduced risks for operators.

An experimental equipment has been designed to undertake near-wellbore measurements using a pseudo steady state method first outlined by Fevang & Whitson. The objective was to measure gas relative permeability (k_{rg}) as a function of the 'fractional flow' (the ratio of k_{rg} / k_{ro},) at high flow rates typical of the near wellbore region.

2.3 Gas–condensate mobility : Modelling and simulations

The objective was to propose a model for the relative permeabilities and the critical condensate saturation based on a physical description of the porous medium (geometry of the pore-space, rock permeability) and the fluid/rock interactions, and to test effectiveness of existing models for predicting condensate build-up and productivity.

In fact, as it is the case for any gravity segregation process, the low values of the condensate relative permeability, which are very difficult to determine experimentally, control the gas-condensate segregation and impact the phase distribution and the condensate ring buildup. This is particularly relevant for near-critical gas condensate reservoirs for which the liquid dropout can reach quite high values. A predictive model to calculate relative permeabilities, to feed the reservoir simulators for sensitivity analyses or large scale predictions, is of utmost importance.

The model proposed within this project takes into account all the relevant parameters. The pore structure, the fluid/rock interactions (wettability and spreading), and the relative importance of viscous, capillary and gravity forces.

More specifically, three configurations can be identified:
1/ near wellbore region : high velocity, high interfacial tension (high Ca, low Bo) ;
2/ reservoir : low velocity, intermediate interfacial tension (low Ca, high Bo) ;
3/ near-critical reservoir : low velocity, low interfacial tension (high Ca, high Bo).
where the capillary number (Ca) is defined as the ratio of the viscous to the capillary forces (predominant close to the well) and the Bond number (Bo) is defined as the ratio of the gravity to the capillary forces (predominant far from the well).

4. RESULTS AND CONCLUSIONS

PROPERTIES OF RESERVOIR FLUIDS

Bulk properties of reservoir fluids

The main conclusions of this experimental work are:

- The bulk thermodynamic properties have been measured for multicomponent hydrocarbon mixtures and real gas condensate fluids. The phase envelops as well as the liquid dropout curves, the densities and compositions of the condensate and gas phases have been determined experimentally at appropriate ranges of pressure and temperature (TUD, AEA).

- For two condensates with the same components and different molecular weights it has been seen that the phase envelope of the lower molecular weight (28.0 g/mol) gas condensate reaches a higher pressure maximum than the phase envelope of the high molecular weight (40.5 g/mol) gas condensate. On the other hand, the phase envelope of the higher molecular weight gas condensate reaches a higher temperature maximum than the phase envelope of the low molecular weight gas condensate. A significant observation is that the critical points of the three component mixtures show a rapid increase in temperature with increasing molecular weight (TUD).

- Experimental work with PNA (paraffin, naphthenic, aromatics) fractions showed that the density of the gas phase remains almost unaffected by changing the PNA ratio, while the liquid phase density is very dependent on it. There have been also indications that, by varying the ratio of components of PNA fractions, it is possible to mimic the behavior of real petroleum fractions (Univ. Liverpool).

The main conclusions of the modeling work are:

- A simple calculation procedure has been proposed for the thermodynamic behavior of near-gas condensates. It is based on a pressure and temperature shift by an amount equal to the difference between measured and calculated values. The proposed procedure, which requires experimental determination of saturation pressures and critical temperature, provides reasonable values for the quantities of reservoir engineering interest, except for the oil-gas interfacial tensions (IFP).

- A global crossover EOS has been obtained that incorporates the singular behavior near the critical point and classical behavior far away from the critical point for pure fluids. The asymptotic behavior satisfies universal scaling laws with universal critical exponents and universal amplitude ratios, which are very well established theoretically and experimentally. The shape of the top of the coexistence curve is repaired correctly and the "classical" critical point is shifted to its actual position. The value of the compressibility factor Z_c of the crossover Peng-Robinson equation is equal to the experimental value. The crossover behavior is controlled by only one non-universal system-dependent parameter related to the range of intermolecular forces. This parameter can be found from experimental data.
  The crossover approach would give better results if we adopted a classical equation that yielded a more accurate representation of the thermodynamic properties far away from the critical point (TUD).

- For fluid mixtures a mapping based on molecular type rather than boiling points has been proposed and tested. Only a few well-chosen components may be necessary to achieve a good mapping result. A major advantage of such a mapping is that the mapped fluid consists of real components rather than the pseudofractions arising from boiling point characterisations of petroleum fluids, and may prove of value in designing fluid for experimental study (Univ. Liverpool).

- Phase behaviour and density appear to map satisfactorily for the systems investigated. However, further work is necessary to establish the range of validity of the mapping process (Univ. Liverpool).

Gas/Oil interfacial tensions

The main conclusions of this work are:

- An experimental program has permitted acquisition of gas/oil interfacial tensions for real and synthetic gas condensates as a function of pressure and composition by using the pendant drop technique or the interface laser-light scattering spectroscopy. Values as low as 0.0058 mN/m have been determined with an overall accuracy better than 2% (IKU/SINTEF, AEA).

- The gradient theory of van der Waals has been combined with the Peng-Robinson equation of state to calculate bulk and interfacial properties of hydrocarbon mixtures. A satisfactory agreement with the experiments has been achieved. The advantage of this approach is that especially the predictions of the interfacial tensions are more accurate than those obtained from an empirical approach as the Parachor method. The reason is that gradient theory is a physically sound theory, i.e., this theory provides a generally valid expression for the Helmholtz energy through the interface. The results obtained from this theory are affected by the shortcomings of the equation of state used, in this case the Peng-Robinson equation of state (Univ. Liverpool, TUD).

- A mean field gvdW theory has been implemented to calculate liquid vapour coexistence curves and IFT for multicomponent mixtures of molecular fluids. By introducing state dependent effective pair potentials that map molecular interactions onto spherically symmetric forms, the theory can be used to calculate liquid-vapour coexistence curves and surface thermodynamics for alkanes as well as mixtures of alkanes and a small solute such as methane, nitrogen or carbon dioxide. In order to introduce an additional adjustable parameter the Lennard-Jones potential has been replaced by a square well potential. The latter potential gives the same phase diagram as the Lennard-Jones potential but it contains an extra parameter, the width of the square well that can be used to fit the IFT.

  The method has been used to study alkane mixtures pressurised with methane, nitrogen or carbon dioxide. Ternary mixtures and four component systems have also been studied. The components of the mixture need not necessarily be real components but can be pseudo components. This makes it possible to apply the method to more complicated systems (such as gas condensates or complex mixtures) by mapping these onto a smaller number of pseudocomponents. The gvdW-theory gives the IFT with an absolute accuracy of 0.3mN/m when the IFT is greater than 4mN/m and less than 0.3mN/m when the IFT is smaller than 4mN/m. It also gives good predictions remote from the critical point. The best results have been obtained for real binary mixtures. To calculate the IFT of real gas condensate systems it is recommended that that they are mapped onto pseudobinary components to take advantage of the better performance using binary systems (Univ. Liverpool).

Wetting properties of reservoir fluids

The main conclusions of this work are:

- The equilibrium wetting behaviour of oils on water in the presence of gas does not obey the conventional picture. It involves three, rather than two, different wetting states. Oils, at least those oils mostly composed of alkanes, display on water an intermediate wetting state between partial wetting (oil lenses) and complete wetting (thick oil film). This state, referred to as *frustrated-complete* wetting, consists of oil lenses coexisting at the surface of water with a mesoscopic (i.e., several tens of molecules, or around 100 Å -thick) oil film (ENS).
- Through these studies a thorough understanding of the wetting behaviour of simple oils on water has been acquired. In particular, the location of the different wetting states can be predicted as a function of oil composition (alkane chain length), brine salinity, temperature and pressure. This understanding arises primarily from ellipsometry measurements of equilibrium oil film thicknesses (ENS).
- The study of the effect of surface active agents (impurities, asphaltenes) on the wetting behaviour has also been realised. Presence of surfactant changes the equilibrium wetting state of partial wetting into the frustrated-complete wetting state. In presence of the surfactant, progressive addition of small amounts of sodium chloride (NaCl) allows to change the oil-water interfacial tension over several orders of magnitude (ENS).

TRANSPORT PARAMETERS IN POROUS MEDIA

Effect of porous medium properties on condensate mobility

Core flood experiments were carried out in low permeability rocks (a 10 md sandstone and a 5.9mD limestone), with a 3-component and a 5-componant synthetic condensates that had been characterised by volumetric pVT experiments and interfacial tension measurements (IFP, IKU/SINTEF).

The core flood experiments carried out were pressure depletion experiments, equilibrium gas injection, and co-injection of liquid and gas at different pressures. It was found that

- Depletion experiments were rather insensitive for the determination of relative permeability as a function of saturation, because very little liquid was produced from the core.
- Steady-state co-injection experiments yielded gas and liquid mobilities at saturations relevant for gas condensate blockage.
- Gas and condensate relative permeabilities depend on the capillary number even for capillary numbers as low as 10-7.
- Both gas and condensate relative permeabilities increase with increasing capillary number.
- Outside the critical point vicinity, severe trapping of the condensate phase has been observed, accompanied by important hysteresis on the fluids mobility.

Effect of near-wellbore conditions

- An experimental equipment has been designed to undertake near-wellbore measurements using a pseudo steady state method first outlined by Fevang & Whitson. The objective was to measure gas relative permeability (k_{rg}) as a function of the 'fractional flow' (the ratio of k_{rg} / k_{ro},) at high flow rates typical of the near wellbore region (AEA).

- Experiments were carried out above the dew point pressure to measure the inertial (non-Darcy) flow coefficient, and below the dew point pressure to measure the gas and oil relative permeability. A water saturation of about 5% was present in the core during these experiments. The most important conclusion from these experiments is that they appear to show both an increase in relative permeability with capillary number, and a reduction in effective gas permeability due to inertial flow. The capillary number effect is much more significant, so that the combined effect is to increase mobility for the flow rates in these experiments (AEA).

- A laboratory model was designed, built and tested. It is based on pressure depletion configuration, where two vessels of different pressures are connected via a porous medium. It is shown that the device can be used to obtain parameters that are useful to quantify well impairment by liquid drop out. In its present configuration it can be used to obtain (useful) experimental data on two-phase flow. Tests were limited to the situation far from the critical point. It is expected that the device will be less suitable very near to the critical point as an initial pressure difference of the order of 0.1-1 bar must be applied to obtain useful pressure readings. It is, however, an excellent device to measure inertia factors in low permeable cores at near well bore conditions i.e. far from the critical point (IKU/SINTEF).

- An acoustic measuring cell (for petrophysical interpretations) has been adapted to measure permeabilities by application of oscillating gas flows. The principle ideas were demonstrated on two- phase flow tests far from the critical point and show highly promising results (TUD).

Gas–condensate mobility : Modelling and simulations

Modelling of gas-condensate relative permeability and critical gas saturation in the far field (IFP)

- Flow rate and interfacial tension dependence of relative permeabilities have been explained on the basis of the competition between capillary and viscous forces. Relative permeabilities are shown to deform and approach straight lines when viscous forces overcome capillary forces. This can be achieved either by decreasing the interfacial tension or increasing the flow rate. To account for that, a new capillary number is introduced. It includes, in addition to fluid properties, porous medium properties. This capillary number allows to precisely define the flow rate (respectively interfacial tension) threshold above (respectively below) which relative permeabilities start to deform. This hypothesis has been validated by interpreting experimental results that were obtained either by modifying the interfacial tension or the flow rate.
- A fractal model has been proposed to calculate gas condensate relative permeability and critical condensate saturation for mobility as functions of the capillary number and the Bond number, the dimensionless parameters expressing viscous to capillary and gravity to capillary forces ratios. The model takes into account the wetting/spreading characteristics of the system (rock & fluids). The model also includes the structure characteristics of the porous medium through its fractal dimension.
- The model predicts the modification of the relative permeability curves as the capillary number changes (velocity or interfacial tension changes).
- A threshold condensate saturation, S_{tc}, can be predicted below which the condensate mobility is extremely reduced, even though finite. S_{tc} may be very high in highly fractal (very clayey) sandstones. It decreases with increasing capillary number.
- The critical saturation for condensate mobility, S_{cc}, increases with increasing interfacial tension (decreasing Bond number) and fractal dimension. Non-spreading condensate would be subject to severe trapping, increasing with increasing fractal dimension and decreasing spreading coefficient.
- The model has been tested against experimental results reported in the literature and a very satisfying agreement has been obtained, indicating that the major effects of the controlling parameters are correctly accounted for.
- Percolation theory together with the effective medium approximation is a simple and powerful tool to understand relative permeability behaviour in terms of pore size distributions and topological effects. The effective medium approximation takes the percolation threshold into account. The theory shows the importance of fluid distribution and the pore size distribution on the behaviour of the relative permeability curves. Percolation thoery is more flexible than the empirical relations by Brooks Corey or Van Genugten. The predictions of percolation theory are, however, only qualitative and must be validated with experiments of the kind described above.

Modeling og high velocity gas condensate flow (AEA)

- Modelling of the experimental results depends on the definition of gas relative permeability. The most promising approach was to model inertial flow effects separately through the non-Darcy flow factor F_{ND}, in which case the relative permeability could be modelled as a function of capillary number. The relative permeability data could be fitted either through a correlation of k_{rg} as a function of capillary number and the ratio k_{rg} / k_{ro}, or by a correlation of k_{rg} and k_{ro} as functions of saturation and capillary number.
- The model for k_{rg} and k_{ro} in terms of saturation and capillary number gave fair agreement with the in-situ saturation measurements. The model supported the observation of condensate saturation increasing with capillary number at a fixed value of the ratio k_{rg} / k_{ro}.
- The Whitson-Fevang 2-parameter model gives a reasonable match to the high-rate data, with parameters which are similar to those reported by Saeverid et al. Therefore, this correlation should provide a reasonable 'first guess' of the capillary number effect where no measured data are available. These results could be used in a pseudopressure calculation to estimate well

productivity, but only if the simulation models were changed to accommodate data in the form of k_{rg} versus capillary number and the ratio k_{rg}/k_{ro}.

Numerical Simulations of flow experiments (IKU/SINTEF)

- History matching of both pVT and flooding experiments with the SRK EOS based Eclipse simulator has been performed.
- Due to the reasonable volumetric description, the development of absolute pressure was well matched with the simulator.
- Differential pressure and liquid production during depletion could not be reproduced with the same relative permeability curves as used to match equilibrium gas injection or co-injection, respectively.
- Equilibrium gas injection and co-injection could be matched with very similar relative permeability curves.
- Gas wet relative permeabilities were found to be required to match the experiments.

5. EXPLOITATION PLANS AND ANTICIPATED BENEFITS

The project resulted in a appropriate methodology and numerical models to improve reserve estimates and to obtain the flow parameters for gas and condensate at near-critical conditions. The results from this project could be packaged to offer the industry a tool or a “routine service” to measure gas condensate relative permeability and predict more reliably well bore deliverability.

Two main types of results are acquired within this project:
Advanced models for phase behaviour and thermodynamic properties of hydrocarbons and hydrocarbon mixtures near the critical point. For any model(s) incorporated into commercial codes it will be appropriate to protect them through licences or patents.
Experimental methodologies to determine transport parameters in porous media in near-critical conditions and improved models/interpretation techniques based on the advanced tools described previously. Experimental methods are generally discussed quite openly among interested parties in the Oil and Gas R&D community. It may be appropriate to patent advanced experimental equipment and techniques if commercialisation for the market is intended.

- ***Direct applications***

The potential cost saving to the industry may be huge, since current simulation tools for PVT behaviour cannot accurately predict near critical phase behaviour and properties ; besides reservoir simulation tools tend to underpredict gas deliverability (and hence more wells may be drilled than necessary). Better well deliverability prediction may also enable better sizing of surface handling installations. Improvements in predictive tools, resulting in a more reliable and accurate forecasting, will potentially reduce risk for the Operators. In off-shore production a good estimation of the sizing of surface installations is crucial for the project viability. Good sizing of the surface installations (separators, gas pipes) will also have a strong impact on environment because it suppresses the flaring of excess gas, thus preserving air quality.
This research may also be applicable to oil reservoirs below the bubble point pressure.

- ***Potential indirect applications***

As possible indirect applications outside of the Oil & Gas industry can be considered those having an environmental and public safety component. Improvement of the thermodynamic models for phase equilibria may have an impact on applications related to gas storage in depleted reservoirs. The quantity of gas that can be pumped out and of course its quality, of high importance for the consumers' safety, are of prime interest.
In the same domain, all the knowledge acquired within the present project on the wetting and spreading transitions of various pure hydrocarbons and mixtures can be used to rapidly and accurately estimate the extent of groundwater pollution by organic pollutants. Also more efficient remediation processes may be designed.

- ***Exploitation strategy***

Exploitation will be implemented in four areas:

- dissemination through publications and conferences
- attracting further research funds and contractual studies
- building closer links with industry and
- forging collaboration links with other research entities.

Each one of the different partners involved in the project has his particular exploitation strategy according to the nature of the activities.
For IFP the industrial strategy of exploitation of the results is achieved by taking patents for protection of commercially important innovations and then licensing the technology to service and oil companies. Improved numerical modelling may be incorporated into commercial codes constituting marketable products.
AEA technology provides consultancy services to the oil industry. The techniques developed may be offered to the market as an alternative, more cost effective approach to acquiring relevant reservoir engineering data. Improved numerical modelling of near well behaviour may be incorporated into commercial code(s), in-house Company software, or stand alone “tool kits”.

SINTEF provides consultancy services to the Norwegian government and to oil and gas companies operating in the Norwegian Shelf. They have already high level competencies on gas condensate reservoirs related problems. Fulfilment of the objectives of the present project will consolidate their position in this area.
TUD has a dual role. Providing research services to industrial enterprises and assuring training and continued education through Ph.D. studies mainly focused on industrial needs.
The University of Liverpool will develop its contacts with the industrial enterprises and other research laboratories, and will develop marketable softwares.
ENS is a national state university. The work within this project will help in improving collaborations with partners performing applied research.

ANNEXE

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