Invitation to join a Research Consortium on:

WELL PRODUCTIVITY IN GAS-CONDENSATE AND VOLATILE OIL RESERVOIRS: DIAGNOSIS AND ENHANCEMENT

(PHASE 3)

from

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Well Productivity in Gas-Condensate and Volatile Oil Reservoirs: Diagnosis and Enhancement (Phase 3)

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EXECUTIVE SUMMARY

Wells in gas condensate reservoirs usually exhibit complex behaviours due to condensate deposit as the bottomhole pressure drops below the dew point. The formation of this liquid saturation can lead to a severe loss of well productivity and therefore lower gas recovery. A similar behaviour is observed in volatile oil reservoirs below the bubble point. Understanding these behaviours and extracting values of controlling parameters is necessary to evaluate well potential and design effective programmes to improve productivity.

The Centre of Petroleum Studies at Imperial College London has been involved in research in these areas since 1997, sponsored mainly by consortia of oil companies. Results from this work have already greatly improved the understanding of well behaviour in gas condensate and volatile oil reservoirs and the ability to interpret well tests in such reservoirs.

Work to-date has focused on vertical and horizontal wells in sandstone reservoirs. Much work remains to understand the behaviours of fractured wells and wells in naturally fractured reservoirs.

The objective of this proposal is to complete the work performed to-date in sandstone reservoirs and to extend it to new well and reservoir characteristics, in order to develop a better understanding of near-wellbore effects in gas condensate and volatile oil reservoirs from well testing, and to use this understanding to develop new methods for predicting and improving well productivity in such reservoirs.

The work will be performed by staff, MSc and PhD students from the Centre for Petroleum Studies at Imperial College, with input and guidance from industry partners.

BENEFITS

- Access to the results of Phase 2 (2002-2005) of the research programme on “Well Test Analysis in Gas-Condensate Reservoirs”
- A comprehensive and systematic interpretation of typical well test data from different gas condensate reservoirs from industry partners and corresponding well test analysis reports.
- New understanding of near-wellbore pressure behaviour in gas condensate and volatile oil reservoirs, with various well and reservoir characteristics.
- Development of a single well compositional model and of a well multiphase flow model able to reproduce and predict the well test behaviour of gas condensate wells, including wellbore phase redistribution.
- Development of methods for predicting and improving well productivity and evaluating the effectiveness of different remediation solutions.
- Annual forum at Imperial College to review progress and provide input into research directions.

RESEARCH AREA

Wells in gas condensate reservoirs usually exhibit complex behaviours due to condensate deposition as the bottomhole pressure drops below the dew point. When this happens, three regions are created in the reservoir, with different liquid saturations[1-4]. Away from the well, an outer region has the initial liquid saturation; next, there is an intermediate region with a rapid increase in liquid saturation and a corresponding decrease in gas relative permeability. Liquid in that region is immobile. Closer to the well, an inner region forms where the liquid saturation reaches a critical value, and the effluent travels as a two-phase flow with constant composition (the condensate deposited as pressure decreases is equal to that flowing towards the well).

The formation of this liquid saturation can lead to a severe loss of well productivity[5-7] and therefore lower gas recovery. Regions 1 and 3 can be identified from well test data, where they create a two-region composite behaviour[8] and appear as two different mobility zones on the pressure derivative.

Laboratory experiments on cores, however, have shown that low interfacial tensions at high rates yield a decrease of the liquid saturation and an increase of the gas relative permeability[2-7,11] (capillary number effects[10-11]). This suggested that the damage due to condensate deposit may not be as bad as previously suggested.

The Centre for Petroleum Studies at Imperial College London started a research project in 1997, with the objective of identifying capillary number effects from well test data, and more generally, of investigating the conditions of the existence of the different mobility zones due to condensate drop-out.

This research was performed in two phases: it first concentrated on the Britannia field, and was sponsored by Britannia Oil Limited (BOL). It was then extended in 2002 to include a number of other fields worldwide, in a JIP that included Anadarko, Burlington, BHP Billinton, Britannia Operator Ltd, ConocoPhillips, Gaz de France, Total and the UK Department of Trade and Industry (DTI). The total number of different fields studied exceeds twenty.

A total of twenty-six MSc theses have been produced between 1998 and 2004 (see Appendix). In addition, six PhD projects have been initiated, with five still in progress. Results have also been presented in SPE papers (five to-date)[12-16] and in a SPE Distinguished Lecture[17].

In parallel, research work has been pursued on “Well Deliverability Improvement in Gas Condensate Reservoirs by Wettability Alteration”, in cooperation with the Reservoir Engineering Research Institute (RERI, Professor A. Firoozabadi), sponsored by the UK DTI and the oil companies sponsoring RERI. One PhD student is involved on Imperial side.

The starting assumption for our investigations was that capillary number effects should create a fourth mobility region in the immediate vicinity of the well (Fig. 1):

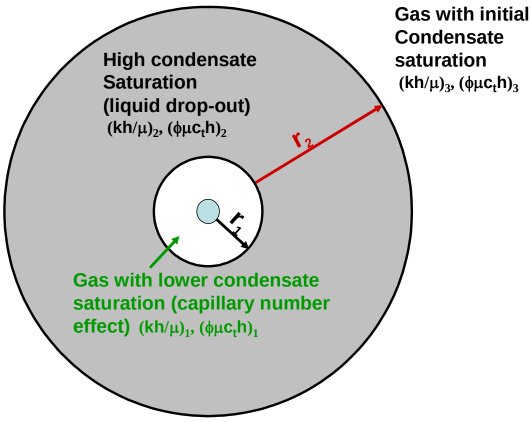

Figure 1: Schematic of three-region radial composite model

and that Regions 1, 3 and 4 should yield a three-region composite behaviour[12] in any given flow period of a well test, characterised by three different radial flow stabilisations on a log-log plot of the derivative of the pressure with respect to the logarithm of a function of the elapsed time (Fig. 2):

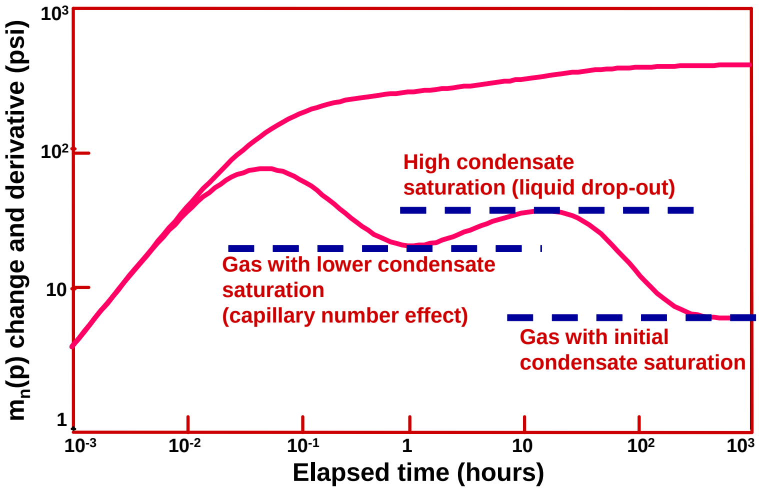

Figure 2: Three-mobility zone radial composite well test behaviour for vertical gas condensate wells below the dew point

The methodology was to analyse well test data from many different gas condensate fields with different characteristics in order to verify the capillarity number effect assumption and to correlate the condensate bank characteristics to the various reservoir properties. Our initial investigations concerned non-fractured vertical wells in sandstone reservoirs only.

We found[12] that capillary number effects can indeed be seen on the pressure derivative (Fig. 3), provided the condensate saturation is high enough and there is no other effect hiding them, such as high wellbore storage, wellbore phase redistribution, noisy data, or boundary and other reservoir effects:

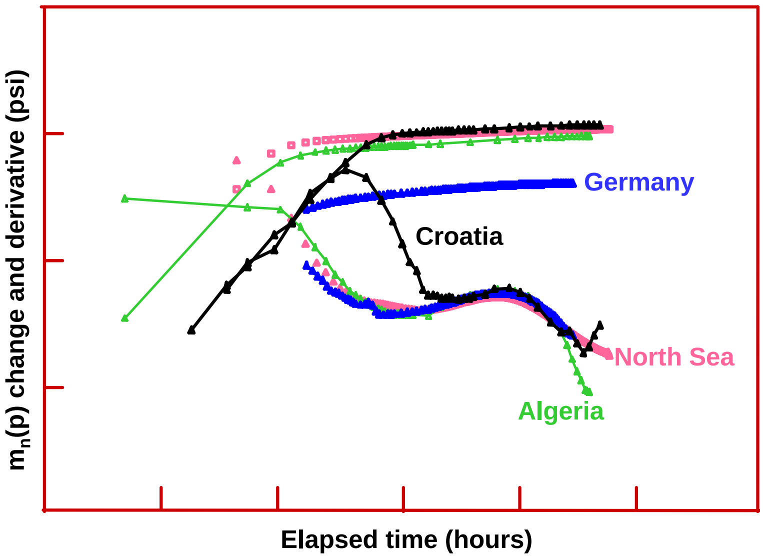

Figure 3: Examples of three-mobility zone radial composite well test behaviours in various vertical gas condensate wells below the dew point

Capillary number effects often compensate for condensate blockage and inertia[14]. As a result, the total skin, instead of increasing with increasing gas rates, may be constant or even decrease with increasing rates. Capillary numbers must therefore be taken into account for history matching and prediction; otherwise well damage and pressure drops would be overestimated[13].

We also found that, whereas the derivative stabilisations shown in Fig. 2 do yield the mobilities of the various regions, the storativity ratios cannot be un-coupled from the radius between two adjacent regions because analytical well test analysis methods can only account for one set of PVT data. A procedure to calculate the storativity in the condensate drop out region was therefore developed based on the total compressibility ratio between the two zones, taking into account the mass exchange between the reservoir liquid and vapour phases at reservoir conditions[14]. This procedure ensures that the condensate bank characteristics obtained from well test analysis are consistent with those from compositional simulation.

Our inspection of many well test data sets indicated that in practice, the derivative stabilisation representing the reservoir effective permeability in Fig. 2 is only seen in DST's, and it is usually not reached in production tests, because the flow periods at constant rate that can be analysed are not long enough[17]. This is illustrated in Fig. 4, where only the stabilisations due to the capillary number effect and the condensate bank are visible. Fortunately, experience shows that, at least in sedimentary reservoirs, core average permeability provides a good estimate of the reservoir effective permeability and this can be used to estimate the final derivative stabilisation if it has not been reached (Fig. 4):

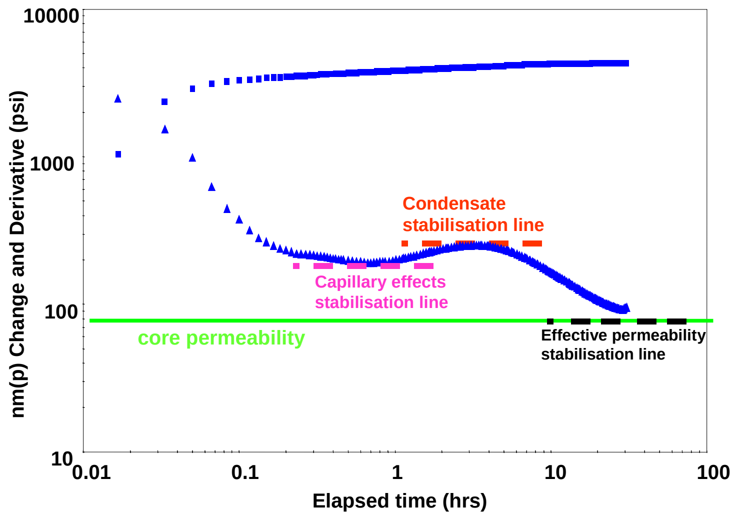

Figure 4: Example of analysis of gas condensate well test data

This is not the case in carbonate reservoirs and there, the analysis of production tests remains rather difficult. This adds to the challenges of interpreting well tests in gas condensate reservoirs, which include the difficulty of distinguishing between reservoir effects and fluid behaviour. Another challenge is that the well test behaviour often changes with time, from condensate dominated behaviour to boundary dominated behaviour. As a result, forward modelling must be performed with different analytical and numerical tools to investigate the possible causes of the various derivative shapes seen on the data[13].

We also investigated wellbore phase redistribution which often dominates drawdown or build-up data in gas condensate wells. The corresponding increasing wellbore storage may last up to one hundred hours and therefore may dominate the entire test. Furthermore, wellbore phase redistribution may yield derivative shapes that can be easily mis-interpreted for reservoir behaviour, because they are similar to what would be obtained with double porosity, partial penetration or composite behaviours. It is important to be able to model the conditions of existence of phase redistribution in the wellbore in order to design tests that are free from phase redistribution. We are developing a numerical wellbore flow model which takes direct account of the flow patterns within the well during both drawdowns and build-up's and leads to a code for predicting drawdown and build-up behaviours as a function of reservoir and fluid characteristics. In view of the uncertainties, experimental work has also been initiated. This uses a tall column where simulated shut-in can be carried out. Using a control system, the rate of fluid entry at the bottom of the pipe can be controlled to be proportional to the difference in pressure between the bottom of the pipe and a fixed pressure representing the reservoir. These experiments will be used to validate the principal features of the numerical model. Work is still in progress.

The composite behaviour described by Fig. 2 is obtained when the data are analysed in terms of a single phase pseudo-pressure[18], thus treating the gas as the dominant phase. A two-phase pseudo-pressure can be used instead[19-24], which transforms the two phases in the reservoir (gas and condensate) into a single phase equivalent. This eliminates the composite behaviour due to the condensate bank obtained with the single-phase pseudo-pressure and yields a derivative stabilisation corresponding to the reservoir effective permeability instead, thus potentially solving the problem with production tests mentioned before. Two-phase pseudo-pressures, however, require the evaluation of the saturation profile (i.e., the relationship between condensate saturation and pressure) at the beginning of the shut in period in all the different mobility regions in the reservoir. To this end, we developed a formulation relating condensate saturation to pressure that includes the region away from the well where a condensation occurs but the condensate is immobile until a critical saturation is reached. Our formulation tends to give better results that the ones that include two mobility regions only (mobile gas and condensate, and initial gas), or that account for three mobility regions (mobile gas and condensate, immobile condensate and initial gas) but use CVD experiments to calculate the condensate saturation vs. pressure in the region where the condensate is immobile. These methods for calculating the two-phase pseudo-pressure tend to over- or under-correct the data.

One limitation of well test analysis with a composite model is that it is only capable of describing the near-wellbore region at the time of the test. Because the composite model does not incorporate the physics of gas condensate behaviour, it cannot be used to predict this behaviour as a function of time. This requires a compositional simulator. We are therefore developing a line source solution for a two-phase compositional flow model in which the thermodynamic properties of the phases are modelled by a cubic equation of state with zero binary interaction coefficients. The usual simplifying assumptions are used, namely gravity and capillary pressures are neglected, the formation is assumed to be homogenous and laterally unbounded, and the production rate is constant over time. The absence of fixed time or length scales allows a similarity transformation under which the governing equations reduce to a system of coupled ordinary differential equations in the similarity (Boltzmann) variable with two fixed and three free boundary conditions[16].

We have also shown that rock permeability, gas relative permeabilities at the end points and critical oil saturation are the most important parameters for forecasting gas-condensate well productivity. We have developed a new technique for estimating these parameters, the base capillary number (i.e., the minimum value required to see capillary number effects) and the critical oil saturation from build-up pressure transient data using single and two-phase pseudo-pressures simultaneously. The calculated parameters can be used for generating the gas relative permeability data.

Having established the results described above, we have extended our investigations to include horizontal wells[15] and fractured vertical wells.

Horizontal wells and fracturing are implemented to minimize pressure drop in gas condensate wells in order to reduce liquid drop-out and productivity problems. We have investigated fractured vertical wells from both the North Sea and Algeria in the context of MSc projects and work is continuing.

Horizontal wells are the subject of a current PhD project. Although horizontal wells have been used in gas condensate reservoirs for the last ten years, there is a lack of published knowledge on their flow behaviour below the dew point pressure. The limited studies in this area[25-27] focused on well performance rather than on well test behaviour. Consequently, we focused on the near-wellbore well test behaviour in horizontal wells in gas condensate reservoirs, and especially on the existence of different mobility zones due to condensate dropout. We used a 3D fully compositional model to develop derivative shapes to be expected from horizontal well test data in gas condensate reservoirs below the dew point under various conditions. We then analyzed actual well test data that exhibit such derivative characteristics. Finally, we used a compositional model to verify the results obtained from conventional well test analysis[17]. It was found that condensate deposit near the wellbore yields a well test composite behaviour, similar to what is found in vertical wells, but superimposed on a horizontal well behaviour, which makes it much more complex (Fig. 5):

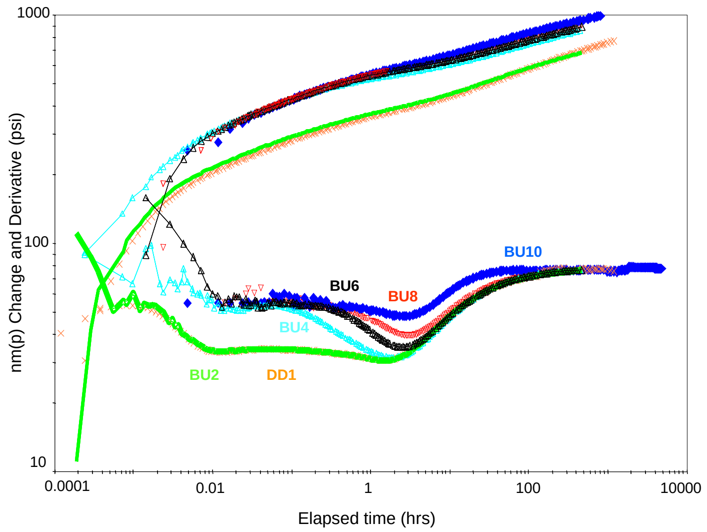

Figure 5: Horizontal well test behaviour below the dew point pressure

Such a behaviour was confirmed with actual well test data on three horizontal wells from a gas condensate reservoir in the North Sea (Fig. 6):

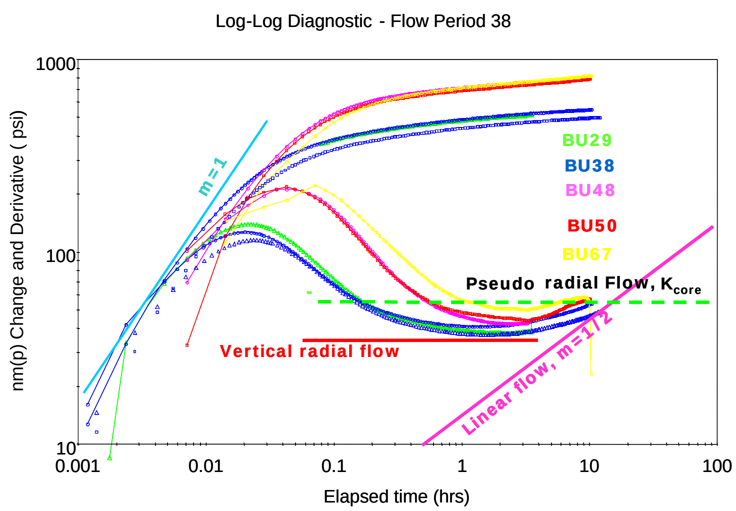

Figure 6: Example of condensate horizontal well test behaviour in the North Sea

Analysis of these well tests by conventional interpretation techniques and by compositional simulation leads to the following conclusions:

1) Actual well test behaviours were consistent with the behaviours predicted from compositional simulations.

2) Only the derivative stabilisations corresponding to the reduced mobility zones due to condensate deposit could be identified on the log-log diagnostic plots at early times. A derivative stabilisation due to capillary number effects could not be identified on the data because of dominating wellbore storage effects.

3) Capillary number effects did exist, as a plot of skin versus flow rate did not show the increasing trend due to non-Darcy flow expected in gas wells. This was probably due to non-Darcy effects being compensated by capillary number effects[13].

4) Analyses of build-ups in production tests yield larger skins than in the DSTs. This was due to the condensate bank increasing over the test duration as the production tests were performed at pressures significantly below the dew point pressure.

5) Due to the complex PVT behaviour in gas-condensate systems, a combination of analytical well test analysis and compositional simulation is required to analyze well tests in horizontal wells.

Finally, we have started a study of volatile oil well test behaviour below the bubble point. This study, which is continuing, includes the analysis of actual well test data (from Algeria and Russia) and computer simulations for a range of reservoir, rock/fluids, and vertical well conditions accounting for the effects of relative permeability (capillary number dependency) and non-Darcy flow. This work is continuing.

We have also started investigating gas condensate well tests in carbonate reservoirs. Preliminary studies indicate that well tests in such systems are more complex than in sandstone reservoirs, because core permeability no longer represents the reservoir effective permeability and therefore cannot be used to estimate the final derivative stabilisation if the test is too short. Furthermore, well tests in carbonate reservoirs often exhibit double-porosity behaviours, and condensate deposit affects the storativity ratios and interporosity flow coefficients in ways that make interpretation difficult. This work is also continuing.

RESEARCH AREA

Although a large body of knowledge has been acquired through our research in the last seven years, significant challenges remain in the analysis of well tests in gas condensate reservoirs below the dew point pressure, and of well tests in volatile oil reservoirs below the bubble point pressure.

The proposed research aims at:

1. Completing the work initiated during Phase 2 and described in the previous chapter,

namely:

- Well test analysis of fractured gas condensate wells
- Well test analysis in naturally fractured gas condensate reservoirs
- Well test analysis in volatile oil reservoirs
- Development of a horizontal well composite model
- Completion of the line source compositional model
- Experimental and theoretical work on phase redistribution
- Use of two-phase pseudo-pressures to predict dry gas effective permeability from production tests (at the moment we are using core data)
- Further assessment of capillary number effects to compensate non-Darcy flow effects.

2. Applying deconvolution to the analysis of gas condensate and volatile oil well test data:

A new **deconvolution** algorithm developed at the Centre of Petroleum Studies at Imperial College[28,29] makes the use of deconvolution possible for well test analysis. Contrary to deconvolution algorithms previously published in the literature, our algorithm provides stable results. Extensive usage at Imperial and, independently, at BP, has confirmed its huge potential for well test analysis of permanent pressure gauges: deconvolution provides information over a radius of investigation that corresponds to the total duration of the production period, which can be orders of magnitude greater than that available from individual flow periods used for conventional well test analysis. Alternatively, deconvolution can reduce considerably the required duration of an extended well test, by revealing boundaries not visible in individual flow periods. The use of deconvolution in combination with single-phase or two-phase pseudo-pressures should help solve the interpretation problems created by the flow periods being too short to show the final derivative stabilisation in production tests.

3. Developing methods for predicting and improving well productivity and evaluating the effectiveness of different remediation solutions.

The techniques to be investigated will include:

- drilling horizontal wells instead of vertical wells,
- hydraulically fracturing vertical wells before or after the development of the condensate bank
- acidising after the condensate bank has formed.
- using multilateral wells
- Lean gas recycling to remediate liquid drop out in gas condensate reservoirs and its effect on well test behaviour.

BRIEF RESUME OF PRINCIPAL RESEARCHERS

Prof. Alain C. Gringarten - Professor of Petroleum Engineering

Prof. Gringarten will be the principal investigator for this project. He holds the Chair of Petroleum Engineering at Imperial College in London and is also director of the Centre for Petroleum Studies, Department of Earth Science and Engineering, which covers all petroleum activities at Imperial. Before joining Imperial College in March 1997, Dr. Gringarten spent 25 years with service companies, first with Schlumberger where he was Director of Engineering and created their well test interpretation service; then with Scientific Software-Intercomp, where he held several senior technical, marketing and management positions including Executive Vice President for E&P Consulting and Products. Prof. Gringarten is a recognised expert in well test analysis and has published numerous articles on that subject. He received the Society of Petroleum Engineers (SPE) Formation Evaluation award for 2001, the 2003 SPE John Franklin Carll award, and was a SPE Distinguished Lecturer for 2003-2004. Prof. Gringarten holds an engineering degree from Ecole Centrale, Paris, France, and obtained an MSc and a Ph.D. in Petroleum Engineering from Stanford University.

Dr. Thomas von Schroeter – Research Associate

Dr von Schroeter has been a Research Associate in the Centre for Petroleum Studies, Department of Earth Science and Engineering, Imperial College London since 1998. He obtained a Diplom in Physics from the University of Göttingen, Germany, and a D. Phil. from the University of Oxford. His research interests include Fluid Mechanics, Numerical Analysis, and Signal Processing.

Professor Martin J. Blunt – Professor of Petroleum Engineering

Professor Martin J. Blunt is professor of Petroleum Engineering in the Centre for Petroleum Studies at Imperial since June 1999. He was previously an Associate Professor of Petroleum Engineering in the Department of Petroleum Engineering at Stanford University and worked for four years at BP’s research centre in Sunbury-on-Thames. Professor Blunt's research interests are in multiphase flow in porous media with applications to oil and gas recovery, and contaminant transport and clean-up in polluted aquifers. He performs experimental, theoretical and numerical research into many aspects of flow and transport in porous systems, including pore-scale modelling of displacement processes, and large-scale simulation using streamline-based methods. He is on the editorial board of SPE Journal and Advances in Water Resources. He has over 70 scientific publications. He holds B.A., M.A. and Ph.D. degrees in Physics from Cambridge University.

Prof. G. F. Hewitt - Professor of Chemical Engineering

Prof. Hewitt and his team are involved in the study of a wide variety of multiphase flow systems, including both two-phase (liquid-liquid) and three-phase (liquid-liquid-gas) flows in horizontal, inclined and vertical tubes. In recent years, there have been great improvements in the understanding of the development of flow patterns in vertical pipes (as will be relevant to the present project) and Prof. Hewitt and his team have published widely in this area.

Centre for Petroleum Studies (CPS) at Imperial College

The Centre for Petroleum Studies is a focus for research, postgraduate teaching and professional development within the framework of Petroleum Sciences and Engineering at Imperial College. Its main objectives are to facilitate multi-disciplinary research between geologists, geophysicists, petroleum engineers and members of other key disciplines in order to advance the state of the art in exploration, appraisal/development and reservoir management, and to plan and implement related postgraduate teaching programmes which reflect current best practice within the petroleum industry. The Centre has one of the largest concentrations of petroleum scientists and engineers in a UK academic institution, with almost 50 members of staff providing research expertise across the complete Exploration-Production spectrum.

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Appendix: Imperial College reports on Gas Condensates

1	Saifon DAUNGKAEW	Well-Test Analysis using a Triple Radial Composite Model and its Application to Gas Condensate Reservoirs	MSc 1997/98
2	William BEVERIDGE	Britannia Gas Condensate Well Deliverability Predictions	
3	Edward CHAMBERS	An Investigation and Simulation to Determine Development Sensitivities of a North Sea Gas-Condensate Field	
4	Nicolas FETTA	Flow to a Well in a Gas Condensate Reservoir	
5	Djamel OUZZANE	Experimental Study of Wettability Alteration to Gas-Wetness in Porous Media	
6	Lamia GOUAL	Modelling of Wax Precipitation in Gas Condensate Systems	

7	Ali AL-LAMKI	The effects of rate-dependent relative permeabilities on the interpretation of gas condensate well tests.	MSc 1998/99

8	Gregor COLVILLE	Effect of condensate dropout on productivity and recovery from a lean gas condensate field.	MSc1999/00
9	Hashem MONFARED	Well test analysis in multi-layer gas condensate reservoir: effect of individual layer skins.	

10	Jirades TANAPATCHAIPONG	Well test analysis in a gas condensate reservoir in the Gulf of Thailand	MSc 2000/01
11	Binayak AGARWAL	Wireline formation test interpretation in a gas condensate reservoir	
12	George MYKONIATIS	Composite behaviour in multilayer reservoirs	
13	Akepeki AKEMU	Wellbore Dynamics in Gas Condensate Wells	
14	Daniel MAROKANE	The Applicability Of Timely Gas Injection In Gas Condensate Fields To Improve Well Productivity	
15	Manijeh BOZORGZADEH	Evaluation of the potential of well 30/7A-P1 in the Judy field	
16	Abdolnabi HASHEMI	High Pressure High Temperature Well Test Interpretation: Jade Field, UKCNS	

17	Abdimurat AYAPBERGENOV	Prediction of the Production Performance of Highly Volatile Oil Reservoirs Below the Bubble Point Pressure	MSc 2001/02
18	Clare HOWAT	A Feasibility Study of Horizontal Wells in the Development of a Carbonate Reservoir Oil Rim – Comparative Sensitivities Using a Sector Model	

19	Alekan ALUKO	Well Test Analysis on a Condensate Gas Field in the North Sea	MSc 2002/03
20	Mirza Tariq BAIG	Productivity enhancement of gas condensate wells by fracturing	
21	Thierry LAUPRETRE	Determine the level of grid refinement required around Jade wells to ensure the most correct prediction of wellbore productivity below the dew point.	
22	Arsyad SIREGAR	Well test analysis in a volatile oil reservoir in Algeria	
23	Piyatad TABMANEE	Well test analysis in the Hassi R'Mel field, Algeria	

24	Bandar AL-MALKI	Well Test Analysis In Condensate Gas Reservoirs In Carbonate Formations In Saudi Arabia	MSc 2003/04
25	Ahmed ALI	Experimental investigation of phase redistribution effect on pressure transient data	
26	Moshood SANNI	Simulation of well tests in volatile oil reservoirs	

1	Saifon DAUNGKAEW	Well test analysis in gas condensate wells	PhD	1998-2001
2	Djamel OUZZANE	Phase behaviour in gas condensate reservoirs	PhD	1999-2004
3	Manijeh BOZORGZADEH	Well Test Analysis in Gas Condensate and Volatile Oil Reservoirs	PhD	2002-2005
4	Abdolnabi HASHEMI	Horizontal Well Test Analysis in Gas Condensate Oil Reservoirs	PhD	2003-2006
5	Gioia FALCONE	Modelling of flows in vertical pipes and its application to multiphase flow metering at high gas content and to the prediction of well performance	Part-time PhD	2000-2005
6	Alekan ALUKO	Well Test Analysis of Fractured Wells in Gas Condensate Reservoirs	Part-time PhD	2004-2007