Minutes of foamy heavy crude project meeting (Intevep, September 18, 1997)

☒ Arjan Kamp
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Project 5137

reviewed by:
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persons present:

Marlene Huerta, Paul Hammond, Arjan Kamp, Vladimir Alvarado, Brigida Meza, Douglas Escalante, Bare Wadou, Youssef Espidel, Carlos Heny, Carlos Otero, Mariela Araujo, Adolfo Rodriguez, some students in training in the reservoir group

1. Opening

Marlene Huerta opens the meeting, introducing Paul Hammond and Arjan Kamp. She announces as well that Paul Hammond's six month stay in Intevep will end on October 17.

Arjan Kamp does an introductory talk, explaining the objectives of, and the idea behind, the foamy heavy crude (FHC) project. The large time goal is the development of a descriptionthat could be used in a reservoir simulator; something in which client Carlos Otero might be interested. The short time goal is the understanding of the physics that govern the flow of foamy heavy crudes, and application of that physics to small scale experiments. The characteristics of FHC are recalled: a low produced GOR, which means that little gas leaves the reservoir, a high primary recovery due to the work performed by gas coming out of solution and a high critical gas saturation. The latter means that gas does not easily get connected. The rate of pressure draw down appears to be an important parameter.

At the basis of the modelling are the transport equations for liquid, free gas in bubbles, connected free gas and dissolved gas. The latter does not appear in the model of Dan Joseph (Univ. Minnesota). Connected free gas is probably less important below the critical gas saturation. These transport equations need closure terms for mobility, nucleation, bubble growth and recombination (coalescence and break-up). The number of closure term that have to be modelled depends on the type modelling.

Gradual goals are set in the project, starting with the write-up of transport equations and proposals for closure terms. The resulting model will then be applied to simulate laboratory experiments, for which due to stationary or homogeneity hypotheses, the description reduces to a system of ordinary differential equations. The obtained results are compared to experimental data and the result of the comparison is feed back to the closure terms modelling. Parallel to this, a code will be developed for solving the partial differential equations so that problems can be simulated which depend on time and space co-ordinates. The model can eventually be applied to model the production from one well and might lead to the development of a reservoir simulator. Paul Hammond will present the transport equations and three different levels of transference closure term modelling in a presentation entitled "Modelling FHC flow in core flood tests". Arjan Kamp will then present the results of the linear kinetic closure (type 1) applied to some simple cases. Adolfo Rodriguez will present some preliminary results on numerical solutions of the PDE equations.

2. Presentation Paul Hammond

Paul Hammond sketches the physical configuration of a semi-infinite core, at one end de-pressurised below the bubble point and above the bubble point at infinity. Bubbles are then created and the bubble front propagates into the core. Due to this creation of bubbles, oil is expelled out of the core.

Mass conservation equations are presented for liquid, free gas in bubbles, connected free gas and liquid, coupled by transfer terms. An additional equation is given for bubble number density.

The closure terms are the following:

- velocities and pressure gradients are coupled by a mobility matrix;
- gas phase (connected or bubble) and liquid phase pressure are coupled by capillary pressures;
- transfer from dissolved gas to free gas in bubbles is governed by nucleation and diffusive mass transfer;
- transfer from dissolved gas to free connected gas is governed by diffusive mass transfer;
- transfer from bubbles to connected gas has to be modelled by a coalescence term;
- constitutive equations couple densities of gas and liquid phase to pressure and dissolved gas concentration;
- the convection velocity of bubble number density is coupled to the convective velocity of the gas phase by the mean bubble volume. This mean bubble volume equals the saturation of the gas phase in the form of bubbles, divided by the bubble number density.

Until now, the modelling effort has mainly been focusing on modelling the transfer terms which govern the transfer of gas between a dissolved state and a free state.

Bubbles can be trapped or be moving with the liquid. Both situations have been observed experimentally. Carlos Otero says that he has experimental evidence that a great part of the bubbles are trapped until the critical gas saturation is reached and the gas starts to flow as one phase. This information is obtained by interpreting GOR measurements at the outlet of the well.

Carlos Otero asks whether Paul Hammond knows which equations are solved in the STARS code. He mentions that the STARS simulator solves transport equations and that it has capabilities to model non-equilibrium reactions. It would be worth to compare the numerical solutions of Paul Hammond's model with numerical solutions of the STARS code. Paul Hammond replies that he does not know what is done in the STARS code. He thinks that first order kinetics might have been implemented for the transfer term, but he doubts whether nucleation modelling has been included. The STARS code has some basic chemical reaction capabilities and it might be possible to treat the dissolved gas as a separate component. He confirms that it might be worth finding out.

Paul Hammond identifies 3 levels in the modelling that has been attempted until now:

- level 1: mass fraction of dissolved gas is always near equilibrium;
- level 2: off-equilibrium with simple relaxation mechanism;
- level 3: microstructure models for mass transfer.

2.1. Mass fraction of dissolved gas is always near equilibrium

This approach assumes that the gradient of mass fraction of dissolved gas with respect to pressure equals the equilibrium solubility. Arjan Kamp mentions that it is not necessary to suppose that the mass fraction of dissolved gas equals its equilibrium value, as is mentioned on PH's overhead sheets. It is possible that an super saturation exists, but this has to be a constant supersaturation.

Paul Hammond presents the results for the case of an incompressible liquid and gas, no connected gas and bubbles trapped in the pores. The result is a differential equation in pressure with a diffusive term, a time derivative and a square of a space derivative. Arjan Kamp mentions that the same system is obtained for the flow of a compressible gas in a porous medium. The analogy comes from the fact that the solubility of the gas is proportional to the pressure, so that when pressure is increased, the volume of free gas decreases with pressure, just as it would when pure gas is compressed.

At $t = 0$ in a constant expansion rate PVT cell simulation the void fraction, pressure and pressure gradient shows a discrete jump. This is due to the fact that a finite amount of gas has to come out of solution to continue the de-pressurisation process and a direct consequence of the hypothesis that the liquid is incompressible.

2.2. Off-equilibrium with simple relaxation mechanism

The level 1 mechanisms are mechanisms which recognise that super-saturation might exist, but that it will eventually disappear by a relaxation of the relevant parameters (void fraction or dissolved gas fraction) to their equilibrium values. Several possibilities exist to model this relaxation, but it is always done without modelling the actual microscale process of nucleation. Three different models of this type are presented:

- Dan Joseph's model. A conservation equation is written for the equilibrium situation where pressure and void fraction are linearly related. A time derivative in pressure is then added for off-equilibrium behaviour. In the case for incompressible gas and liquid, immobile gas bubbles and no connected gas, the result is one differential

equation in pressure, a so-called telegraphers equation, in which appear a first and second derivative of pressure with respect to time and a diffusive term with a second derivative of pressure with respect to space. The same equation can be obtained after dropping some higher order space derivative terms if it is assumed that the bubbles move with the liquid, instead of being trapped. That's the way Dan Joseph has written down the problem. Arjan Kamp remarks that assuming trapped bubbles (what Paul Hammond does), conflicts with the equilibrium relation between void fraction and pressure. He thinks that if bubbles stay trapped, that when the crude is moving, some fluid might exist which is at a pressure lower than the saturation pressure, without having bubbles in it (because they stayed behind). Dan Joseph thinks, according to a recent e-mail, that bubbles *can* move at a different velocity as the liquid in his model.

- A variation of this model is obtained by adding a first derivative of void fraction with respect to time to the equilibrium equation in void fraction and pressure. Again for the case for incompressible gas and liquid, immobile gas bubbles and no connected gas, a single differential equation results, now in void fraction. The terms which appear are: a diffusion term with a double space derivative, a single time derivative and a double space-single time derivative.
- A third version of the level one model is the formulation which has up to now been proposed by Paul Hammond. It can not be turned into one equation (without linearization), and a system of three coupled differential equations has to be solved, describing transport of liquid, free gas and dissolved gas. The transfer rate of mass is written proportional to the difference in mass concentration of dissolved gas and the equilibrium mass concentration, which is proportional to pressure.

2.3. Microstructure models for mass transfer

Paul Hammond has established a new model for mass transfer by modelling the microscale nucleation and diffusion process. The rate of mass transfer is proportional to the sum of a nucleation and a diffusion term. The nucleation term is the product of the bubble number density generation rate and the volume of the created bubbles. The former is proportional to a negative exponential probability which involves one over the square of supersaturation. The second is the critical nucleus volume which is given by thermodynamic stability analysis and which is proportional to one over the cube of supersaturation. The diffusion term is proportional to the product of supersaturation and an average bubble radius. This average bubble radius is simply proportional to the cubic root of division of gas fraction of mass by the bubble number density. The total result is a transfer term which is zero for small supersaturations and then rises sharply for higher supersaturations, finally fading away because of the fact that the formed nuclei become very small.

2.4. Anticipated behaviour of solutions

Paul Hammond presents his ideas about the form of spatial distributions of pressure and void fraction. Three regions are anticipated:

- Close to the point where pressure is drawn down the mixture is in approximate equilibrium;

- Moving away from this equilibrium point further into the formation or the core, pressure rises approximately linearly until arriving in a region where active nucleation and non-equilibrium growth take place. This region contains a sub-region where non-equilibrium bubble growth dominates and a sub-region where nucleation is predominant;
- Very far in to the core the pressure is higher than the pseudo bubble pressure and a weakly compressible single phase exists.

2.5. Some solutions

Paul Hammond shows some solutions of the previous presented models for the PVT problem: a PVT cell, where the piston is pulled out at constant rate (dV/dt constant) or at a rate which insures that dp/dt is constant. The partial differential equations can in these cases be simplified by volume averaging so that a system of Ordinary Differential Equations remains which does no longer depend on the space co-ordinate.

The results for the level 1 models are (assuming incompressible fluids):

1. Dan Joseph model: pressure initially decrease quadraticly with time, finally the decay becomes exponential;
2. Dan Joseph model, but with void fraction derivative instead of pressure derivative: pressure jumps down at t=0, then decays by an algebraic relation
3. Paul Hammond's formulation with first order kinetics in mass fraction of dissolved gas: pressure step at t=0 and then an algebraic decay of pressure.

The pressure decay at t=0 is a direct consequence of the fact that the liquid is incompressible. To increase in this case the cell volume at a moment where no gas is present, some gas has to be nucleated infinitely fast.

Paul Hammond has performed simulations for the second level approach (nucleation and diffusive growth modelling), again for the PVT cell problem, solving the Ordinary Differential Equations, now at constant pressure decline rate. The results are too complex and extensive to resume in this minute. The main characteristic is that the created bubble number density increases more than linearly with the pressure decline rate. The amount of gas created does not depend strongly on the pressure decline rate, so that for high decline rates (many bubbles) the bubbles must be smaller. The supersaturations increase with the pressure decline rate, so that the model shows that smaller bubbles are formed when the supersaturation if higher.

Paul Hammond has observed overshoot phenomena in the pressure-void fraction relations which he calculated, similar to those observed in the experiments of Firoozabadi (1992). The question is whether reservoir simulations need to predict this phenomena in order to yield sufficiently precise predictions.

2.6. Conclusions

Paul Hammond states his conclusion rather carefully since the nucleation and growth model have not yet been carefully verified.

- If the bubble number density increases with the rate of pressure decline, and thus the bubble size decreases with increasing pressure decline, then this might partially explain why (and how) critical gas saturation depends on pressure decline. The hypothesis made in this reasoning is that small bubbles coalesce less easy than large bubbles and that it thus is

more difficult to create connected gas with small bubbles. The critical gas saturation is the phase fraction of gas at which the gas gets connected and starts to flow;

- The different constitutive equations (level 0 model, the three submodels of level 1 and the level 2 model) give different results for the PVT cell experiments.
  - ⇒ It might be possible to decide which models might be correct and which not;
  - ⇒ None of the simple models reproduces the non-monotone pressure behaviour (overshoot) as observed in the experiments of Firoozabadi (1992);
  - ⇒ The nucleation model *does* reproduce this.
- It is worth continuing the comparison with PVT experiments to decide which type of transfer models are needed and whether the jump condition for the level 0 model is sometimes observed.
- Paul Hammond and Dan Joseph did not have the same objectives concerning the foamy heavy crude modelling. Paul Hammond wanted to predict what the critical gas saturation is and how this depends on the pressure draw down. The critical gas saturation is related to the primary recovery of a reservoir. Dan Joseph is more interested in predicting how flow rate and pressure decline are related when the gas fraction is below the critical gas saturation. It might be possible that these different objectives permit models of different degrees of complexity. For production predictions (Dan Joseph) it might not be essential to know the bubbles size. For prediction of critical gas saturation (Paul Hammond) it might be important to know the bubble size since the coalescence probability between bubbles depends on their size. In one case (Dan Joseph's model) the result of the model (one equation) is much simpler than in the other case (Paul's nucleation model).
- Paul Hammond suggests to look for the following phenomena in experiments data:
  - ⇒ Rate of advance of a sharp bubble front into a core or a micro model;
  - ⇒ Detailed dynamic PVT relations;
  - ⇒ Rate dependence of bubble size and number and volume fraction, during PVT cell experiments or micro models.
- The big advantage of the nucleation and growth model is that it might be possible to relate the model constants to the properties of the system. If one of the properties changes then it might be possible to predict how production of the well or reservoir changes.
- The big disadvantages of the nucleation and growth model is that it contains more parameters than the simple models and that these parameters are hard to evaluate, experimentally or theoretically.

3. Presentation of Adolfo Rodriguez

Adolfo Rodriguez works in the group of Mariela Araujo. They are involved in the present project on the micro model part and the development of a numerical simulator.

3.1. Micro model

Adolfo Rodriguez gives a few details concerning qualitative results of the micro model experiments which were performed during his stay at the Petroleum Recovery Institute in Canada .

The micro model should be ready soon (next month ?), depending on the availability of the services of the mechanical workshop.

3.2. Numerical simulation of PH's model

Adolfo Rodriguez has developed a numerical solution of the partial differential equations of Paul Hammond's model (1997) in a one dimensional situation. He solves the equation in the form presented in the document Hammond (1997), section: *Solution of model problems*, subsection *Rearrangement of governing equations*. These consist of

- liquid phase mass conservation equation, divided by liquid density added to the gas phase mass conservation equation, divided by the gas density;
- gas phase mass conservation equation;
- dissolved gas phase mass conservation equation.

The equations are closed by an equation of state each two density.

An explicit method is used, which appears to be stable enough. The problem of a core flood is simulated, where the pressure on two sides is kept constant. On one side below the saturation pressure, at the other side a little bit above the saturation pressure. The void fraction and the dissolved mass fraction are zero on the latter side. The transfer term is supposed proportional to the difference between dissolved mass fraction of gas and an equilibrium dissolved mass fraction. The latter does not depend on the pressure, as is supposed to be given by Henry's law. Paul Hammond remarks that it might be worth to change this and to write that the equilibrium mass fraction of dissolved gas is proportional to the pressure.

Preliminary results are presented for the pressure as a function of the distance in the core at different times. One of the most striking observations is that the bubble front linearly propagates into the core, but that this linear relation flattens out and that finally the propagation of the bubble front stops. Adolfo Rodriguez and Vladimir Alvarado think that this halt of propagation is caused by the fact that pressure at one side is constant and a little above the bubble point pressure.

The short-time perspectives of this work are:

1. Comparing the numerical solutions with analytical solutions of the linearised equations. These can be obtained for low time constants in the transfer rate and result in similarity solutions for the variable $x/t^{1/2}$.
2. Comparison with solutions of Dan Joseph's model
3. Comparing with the long time behaviour in the core flow with constant pressure boundaries. Arjan Kamp is obtaining numerical results for this system by solving the Ordinary Differential Equations that governs this system. Experimental results are available as well, presented by Maini & Sarma (1994).
4. Variation of the time scale as a function of pressure and void fraction (or supersaturation). Paul Hammond wonders whether it is possible to reproduce the behaviour of the microscopic nucleation model by writing down a functional behaviour of the time scale on local system variables.
5. Implantation of the nucleation model. This signifies however that an extra transport equation (the transport of bubble number density) has to be solved. The problem with the complete nucleation and growth model is that is possesses some strong non-linearities and it is not clear whether the current numerical method can handle these.

4. Presentation of Arjan Kamp

Arjan Kamp presents some results of the level 1 description (transport equations of free gas, liquid and dissolved gas and a linear transfer term in mass fraction of dissolved gas, compressible gas and liquid). These equations result in a set of Ordinary Differential Equations depending on time (PVT experiments, Brigida Meza's experiment, the Firoozabadi et al., 1992 experiment) when volume averaging is applied and depending on space for the steady state core flood experiment of Maini & Sarma (1994).

Several experiments are chosen to investigate different physics:

	experiment	**porous medium**	**mobility**	**mass transfer**	**nucleation**	**deviation from equilibrium**
d/dx=0	dynamic de-pressurisation PVT cell	no	no	yes	wall	small
d/dx=0	dynamic de-pressurisation of a core	yes	no	yes	pores	small
d/dx=0	sudden super-saturation (Brigida's experiment)	no	no	yes	wall	large
d/dt=0	steady state core flow	yes	yes	yes	pores	small

4.1. Dynamic de-pressurisation of a PVT experiment

No data have been found in the literature about the dynamic de-pressurisation of a PVT cell but this experiment is planned in Intevep. Some results will be available in due course, possible before Paul Hammond leaves Intevep. The experiments is performed in a classical PVT cell, with the difference that it is a dynamic experiment intended to measure the time dependence of the transfer function, and therefore the experiment does not yield the equilibrium behaviour. Instead, the piston is pulled out at a known speed and the pressure is recorded. Comparison of the thus obtained pressure-volume curves with equilibrium data show whether the transfer function can keep-up with the volume expansion and thus yields information about a typical transfer time. Numerical solutions have been performed which show that the problem depends on one characteristic parameter which involves the product of rate of volume expansion and the characteristic time scale. A fast and a slow de-pressurisation experiment are simulated, at constant volume expansion rate. Although volume fraction and dissolved mass fraction for the two experiments are not very different when plotted as a function of the product of time and the characteristic parameter, the pressure is much lower in the fast experiment. This is caused by the fact that transfer is more difficult, and thus to keep up with the same volume expansion, the pressure has to be much lower.

4.2. De-pressurisation of core at constant flow rate

Data for this experiment are reported by Firoozabadi et al. (1992). It consists of the de-pressurisation of a core, containing a mixture of Decane and Methane. The flow rate of oil flowing out of the core is kept constant. The experiment provides interesting data on the influence of

- flow rate,
- core material,

- mixture composition;

The main result of the simulation is that a transfer term based on first order kinetics as in the level 1 model, cannot simulate super saturation behaviour. Decreasing the characteristic time scale for transfer, indeed increases the super saturation, but the experiments show that the nucleation rate is increasing faster for high super saturation than is predicted by a linear transfer term. This is supported by the nucleation model proposed by Paul Hammond, where indeed the transfer term is not a linear function of supersaturation, but a function which is zero for low supersaturations and which increases fast for higher supersaturations.

4.3. Sudden supersaturation

Brigida Meza has been performing experiments in Intevep, initially intended for the measurement of stability of oleic foams, where the pressure in a live crude oil is suddenly changed. This is done by evacuating inert gas which is present above the oil in the cell After the evacuation of inert gas, the cell is closed again, and the pressure increases in time, due to nucleation of bubbles, is measured. This experiment differs from the preceding experiments by the fact that the supersaturation is established very rapidly, and then decreases in time.

An analytical solution can be found for this experiment. Comparison with the data show however that, although the calculated shape of the pressure-time behaviour is qualitatively correct, the calculated final pressure is more than twice the measured final pressure. At this moment it is investigated where this difference comes from. Possible reasons are:

- the experiment is leaking;
- gas stays “trapped” in the oil at low supersaturations;
- the used solubility values in the calculations are not correct.

4.4. Flow out of a core with constant pressure gradient

In this experiment a constant pressure gradient is maintained on a core. The volume flow rate out of the nucleus is measured. This experiment has been performed by Maini and Sharma (1994). In contrast to the preceding experiments, this is a steady state experiment. The transport equations can be simplified in this case as well, by dropping the time derivatives. Solutions for this problem have not yet been obtained, but will soon be available.

It can be noted that this experiment provides the long-time behaviour for the calculations performed by Adolfo Rodriguez, where also a fixed pressure gradient is applied to a core, but where also the transient behaviour is calculated.

4.5. Conclusions and remarks

The conclusions of the comparison between experiments and the level 1 theory show that the level 1 models cannot correctly calculate supersaturations, and it is thus questionable whether the level 1 models will yield more useful information than the level 0 models. Level 1 models *can* calculate super saturation, but its time dependence is not correctly predicted with a linear kinetics mechanism.

Furthermore, these models do not yield information about bubbles size, probably necessary for the estimation of critical supersaturations. It is as well difficult to link the characteristic time scale which these models involve, with the properties of the crude-rock system.

Some additional remarks are:

- The hypothesis of an incompressible gas phase (made by Dan Joseph) seems to be reasonable one. This is however not due to capillary effects. If pressure is reduced, the volume of a gas bubbles increases by decompression and by gas coming out of solution. The ratio between the two depends on a dimensionless number which is of order one for typical heavy crude systems and on the void fraction of the gas, which is in most cases much lower then one. If this is the case, the gas can be considered as incompressible.

- The critical gas saturation probably not only depends on bubble size, but as well on the viscosity of the oil. The coalescence rate between two bubbles can be written as the product of a collision rate and a coalescence probability. The latter can be modelled as an negative exponential probability of the ratio of contact time between two bubbles and drainage time of the liquid film between two bubbles. The drainage time is for viscous dominated coalescence proportional to the viscosity. This explains why light oils have a much lower critical supersaturation than heavy oil, which have a much higher viscosity.

5. Closure

Vladimir Alvarado asks whether impurities might play an important role in behaviour of heavy crude oils. This might explain why sometimes a recombined heavy oil does not display the same behaviour as a heavy oil sample taken at the bottom of the well. If for example the contents of suspended sand particles change, then the nucleation behaviour might change as well so that different super saturation and different bubbles sizes are obtained. No one has a good answer to this question, other than that it might be an important effect.

Arjan Kamp asks Paul Hammond whether he can defend the reason of setting up a model including detailed micro mechanic nucleation modelling.

Paul Hammond answers that his model shows that the created bubble sizes depend on the super saturation history. He suspects that the critical supersaturation depends on the bubbles sizes as well (coalescence between many small bubbles is more difficult than the coalescence between few large bubbles), which implies that a correct estimation of bubble sizes is important to estimate critical supersaturations.

If however production-pressure decline has to be simulated, it might not be necessary to estimate correctly the super saturation history. This has to be further investigated.

6. Literature references

Firoozabadi A., Ottesen B., Mikkelsen M., 1992, "Measurements of supersaturation and critical gas saturation", SPE Formation Evaluation, Dec. 1992: 337-344.

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