Development of the analytical theory of physicochemical flow in porous media, for pre-screening scenarios of enhanced oil recovery

Proposal of a Ph.D. study in France

Expected candidate

A candidate for this Ph.D. should have good skills in analytical techniques of solving one-dimensional non-stationary PDE used in various domains of mathematical physics and mechanics:

- asymptotic methods (perturbation theory) and singular asymptotic expansions (boundary layer techniques);
- methods of solving quasilinear hyperbolic systems of equations with discontinuous solutions (shock waves), similar to the gas dynamics;
- diffusion, or linear thermo-conductivity, convection-diffusion;
- integral transformations, Laplace, Fourier;
- approximate solutions to nonlinear PDE: various approximate techniques, variational and projectional (Galerkin, ...);
- be resourceful to find any possibilities to obtain an analytical solution by various linearizations, or by reduction to known models in physics already solved, etc.

The skills in numerical techniques are not necessary. The simplest skills is using MatLab would be welcome.

The level in English should be good: the candidate should read a lot of papers and to publish his own papers.

The brief description of the subject

I would like to obtain analytical or semi-analytical solutions of mathematical problems that describe multiphase flow in porous reservoirs applied to oil/gas recovery by various enhancing method (EOR = “enhanced oil recovery”). I will insert these simple analytical formulae in MatLab, which will give me a numerical code. Using this code I can perform very fast simulations to compare various EOR methods and take some primary technological decisions.

First of all, the doctorant will try to find the needed analytical solutions in the literature. If they do not exist, then the doctorant will have to obtain them himself. I hope that he is very resourceful in analytical methods of solving partial differential equations. “Analytical” means rather “simple” that really analytical. If it is graphical, or even numerical – why not ! The model problems to solve will be certainly maximally simplified, 1D, but while keeping the essential elements of the physics.

This code will be proposed to the company-sponsor to use in its practice.

The scientific results will consist of new analytical solutions the candidate will obtain, with my assistance, I hope. (Being an ancient pupil of the Russian scientific school, I should be good expert in analytical techniques).

According to my experience such kind of skills we are looking for is typical for physicists from theoretical physics.

Organization of the research

A Ph.D. student for 3 years.

Start: September - October 2014.

The research will be held in the university PARIS-6, in labo D'Alembert.

The research will be assisted by prof. Michel Panfilov, prof. Chistophe Josserand and prof. Stephan Zaleski.

Financing: the company Wintershall.

Long description of the research program

Experience shows that the traditional practice of screening EOR methods and scenarios for a given oil field would be more efficient if it was preceded by a special *pre-screening stage*. What does it means, a pre-screening stage?

The complexity of the problem of good selection of EOR methods is determined by two types of problems: (i) first of all, by the physical and chemical complexity of the corresponding processes; (ii) secondly, by the complex 3D geometry of the reservoir and the system of wells. More exactly, for a given reservoir of heavy oil, we should resolve two types of problems: (A) for a given viscosity ratio, pressure, temperature and heterogeneity degree of the medium, to determine what physics/chemistry is better among polymer flooding, chemical flooding, miscible gas injection, hot injection, bacterial methods, foams, and so on...; within each king of mentioned methods, we should determine the best choice of chemicals, the optimal heat temperature, the best mechanism of bacterial activity; (B) to take into account for the true geometry of the reservoir and the production/injection system. The *pre-screening techniques* have the objective to analyse deeply the physico-chemical features of the EOR methods, i.e. are focused on the problematic (A), while simplifying the true reservoir geometry (i.e. neglecting the problematic (B)). Grosso modo, we separate the physics/chemistry from the geometry. Note that the heterogeneity degree of the medium is considered as physical (hydrodynamic) parameter, but not geometrical, so it enters into the pre-screening methods.

Such a separation gives us the possibility to use analytical solutions of the model EOR problems as the theoretical basis for the pre-screening techniques. The advantage of analytical models is that they are visible and allow simple, meaningful and effective qualitative analysis of scenarios.

The typical pre-screening simulator will represent the following product:

(1) It will require the initial data on the properties of the reservoir fluids, the average hydrodynamic data (permeability, relative permeability, capillary pressure, wetting, heterogeneity degree), the average data on the system of exploitation (FDP) (well placing, injection/production rates, wellbore pressure, ...).

(2) Assuming that the miscible gas injection is applied, it will propose the set of the results of comparison between various versions of miscible injection depending on the composition of the injected gas and reservoir pressure. The analytical theory of these methods is based on the method of characteristics, which may be reduced to an effective graphical technique of qualitative analysis. This technique represents the compete behavior of the system along some pathways in various characteristic diagrams. Respectively, the result of simulations will be the following: the ternary of quaternary phase diagram for the reservoir fluid mixed with the injected fluid with the corresponding pathways ; the hydrodynamics diagram (fractional flow) with path-ways; the solution in terms of phase and total concentrations of various components in space for several times; the oil recovery in time, the water-cut and gas-cut in time.
Fig. 1 represents example of such a code whose home version for miscible EOR exist in LEMTA:

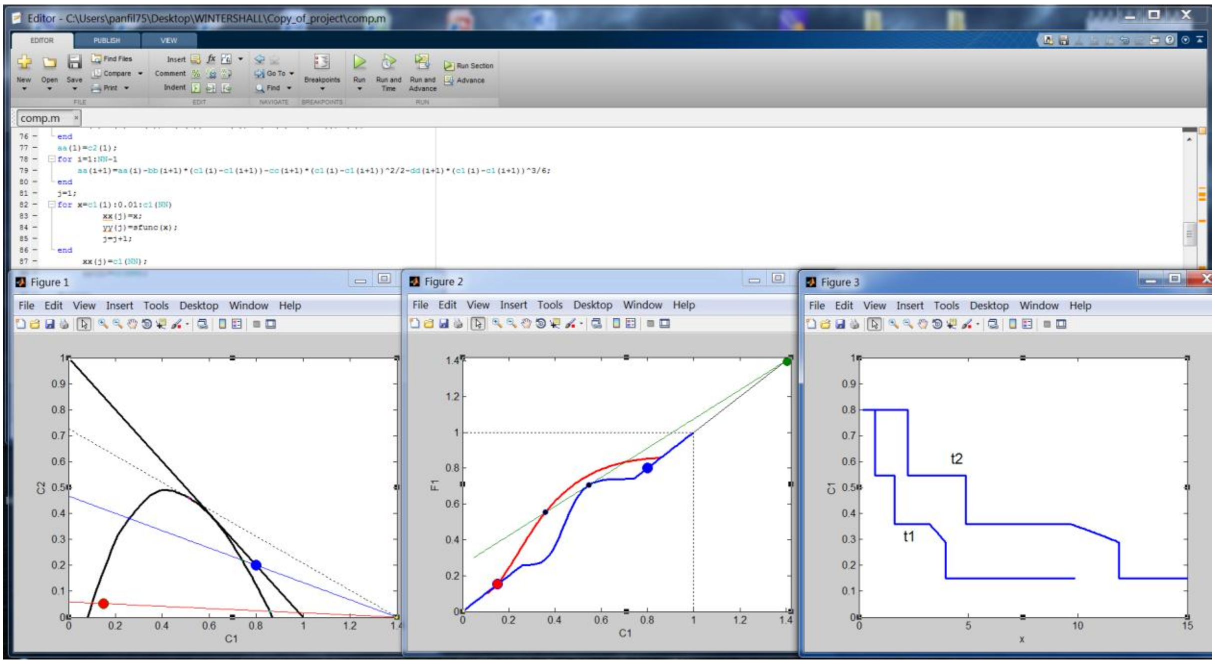

Fig. 1. Example of the pre-screening code for miscible EOR developed in LEMTA.
Programming in Matlab. The code constructs:

- *the ternary (or quaternary) phase diagram for given reservoir P,T and various compositions of the initial and injected fluid with all necessary tie lines (on the left);*
- *the hydrodynamic diagram (fractional flow for the light component), with respective graphical constructions and the pathway (the central plot);*
- *the plot of the total or/and phase concentration of any components in space for several times (on the right);*
- *the plot of the variation of the oil recovery in time (not presented)*

This code allows the analysis of the influence of the injected gas composition, the size of the injected slug (if a kind of WAG technique is modelled), the reservoir pressure and reservoir heterogeneity on the oil recovery.

(3) For chemical EOR techniques, the pre-screening code will propose the similar set of results of comparison between various versions of surfactant, or polymer injection, or combined techniques, including the injection of viscous-elastic surfactants (which prove non-Newtonean properties, but also can influence the residual oil saturation which becomes velocity-dependent). The analytical theory of these methods is also based on the method of characteristics but only in the first approximation. This first approximation uses the similar

effective graphical techniques for qualitative analysis. The respective results will be produced in the form close to that presented in Fig. 1. At the same time, several new physical effects like non-Newtonean reology of the polymer solutions or surfactants, the significant adsorption of chemicals, and other, can change significantly the physics of displacement, which becomes, in particular, much more dependent on the injection rate. Respectively, this also changes the mathematical models of these processes and the techniques of solution. Although the models of these processes exist, for the purpose of our research they should be simplified, in order to reduce them to analytical or *analyzable* solutions, while keeping the sufficient degree of adequacy to the true physics. Due to this a chapter of the project will be devoted to obtaining the corresponding theoretical results.

(4) For other techniques, the analytical theory is different being based on the equations of diffusion-reaction type (for thermal or microbiological EOR), or second-order hyperbolic type (electro-magnetic heating of oil). Respectively the model solutions represent the analytical or semi-analytical formulae. The pre-screening code will produce the numerical results of simulation for given initial data, but also the analytical relationships that are the solutions of the model problems, by using the symbolic tool of Matlab.

The presentation of the analytical tools, and not only the numerical results of simulation, is the key element of the suggested technique. The analytical tools, presented either in the form of the analytical formulae, or in the form of graphical diagrams and pathways, will be the main instrument of the user. These analytical tools will give much more information about the process than particular numerical solutions, while revealing the main complex parameters and the links between them that determine the process behaviour. This is on the basis of these analytical tools that the optimal engineering decision may be taken without any numerical simulations.

Consequently, the code will contain a significant “Help” in which all these analytical tools will be explained for engineers.

A particular moment concerns the question how the medium heterogeneity could be taken into account in a simulator based on analytical, i.e. mono-dimensional, solutions of the hydrodynamics problems? We will develop two alternative ways:

- First of all, by introducing the statistical dispersion of hydrodynamic parameters in mono-dimensional models, both for vertical layering and for horizontal heterogeneity;
- The second way consists of applying the streamline simulations for an element of the system of wells. As known, the solution along each streamline remains mono-dimensional, while the streamlines can be dresses by solving an approximate almost single-phase flow problem. LEMTA possesses its own streamline simulator. This kind of simulations will be performed specially to analyse the impact of the heterogeneity of oil recovery.

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