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PORE SCALE ASSESSMENT OF ENHANCED OIL RECOVERY IN DIGITAL ROCK WITH SCALABLE IT PLATFORM TECHNOLOGIES

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Abstract

We report progress in our research and development of information technology (IT) platforms for application in pore scale assessment of enhanced oil recovery (EOR) methods and materials. A data base implemented in a cloud computing platform contains a library of candidate oilfield chemicals and functional materials for enhancing oil production. The application of machine learning techniques within the data base provides a reservoir-specific ranking of suitable EOR cocktails that are pre-selected based on reservoir log data. For a quantitative evaluation of pre-selected EOR cocktails, a cloud-based simulator performs numerical flow simulations within reservoir rock representations at pore scale. The digital rock representations are derived from data obtained by applying computer tomography or scanning electron microscopy to representative core plug samples. The flow models deployed in the numerical simulations are calibrated at nanometer scale through molecular dynamics simulations and experimentally verified by means of a rock-on-chip test platform implemented with scalable semiconductor process technology. The chip based measurement method allows for extracting physical parameters that determine surface wetting and capillary flow properties at pore scale. The laboratory assessment of enhanced oil recovery materials based on the successive application of data-driven classification, numerical computer simulation and lab-on-chip experimentation will, ultimately, enable substantial cost and time reduction in pore-to-core scale permeability analysis for oil exploration and production.

Keywords: Exploration & Production. Reservoir Simulation. EOR. IOR. Oilfield Chemicals. Digital Rock. Wetting. Flow. Lab-on-Chip. Nanoscience. Nanotechnology. Cloud Computing.

1. Introduction

In the ongoing digitalization of the Oil & Gas industry, nanometer scale science and technology has the potential to transform oil exploration and production. Inclusion of

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chemical and physical processes that occur at molecular scale, into flow simulation models that predict at core scale, or even at reservoir scale, however, has been complicated by the lack of suitable feature propagation and model linkage techniques as discussed by Feger el al. (2014). Likewise, the experimental interrogation of the nanometer scale liquid-solid interactions that limit the efficiency of enhanced oil recovery methods, such as the wetting and flow behavior at the reservoir rock's pore scale, see discussion by Steiner et al. (2016), has been proven difficult to perform within the industry's standard laboratory framework.

In this paper, we discuss how we leverage nanoscience and nanotechnology through scalable cloud computing and chip technology for the assessment of enhanced oil recovery materials. We briefly review the research prototype components and how they are used to perform the EOR assessment at pore scale. The principal objective is the creation and implementation of a step-by-step process leveraging existing exploration and production data, in particular well logs and core analysis, for creating reservoir specific, high-accuracy computer simulations and experimental data to inform and support EOR decision making.

2. Scalable IT Platforms for Enhanced Oil Recovery Assessment at Pore Scale

As visualized in Figure 1, a sequence consisting of data-driven material screening, physics-based numerical simulations and chip-based laboratory experiments allows us to (I) create a short list of candidate EOR materials for a given reservoir condition, to (II) quantify the material's efficiency in a physical flow simulation and, finally, to (III) validate the results through lab testing with dedicated flow chips. In the following, we outline the technical approach and discuss the benefits of the application of this method within oil exploration and production.

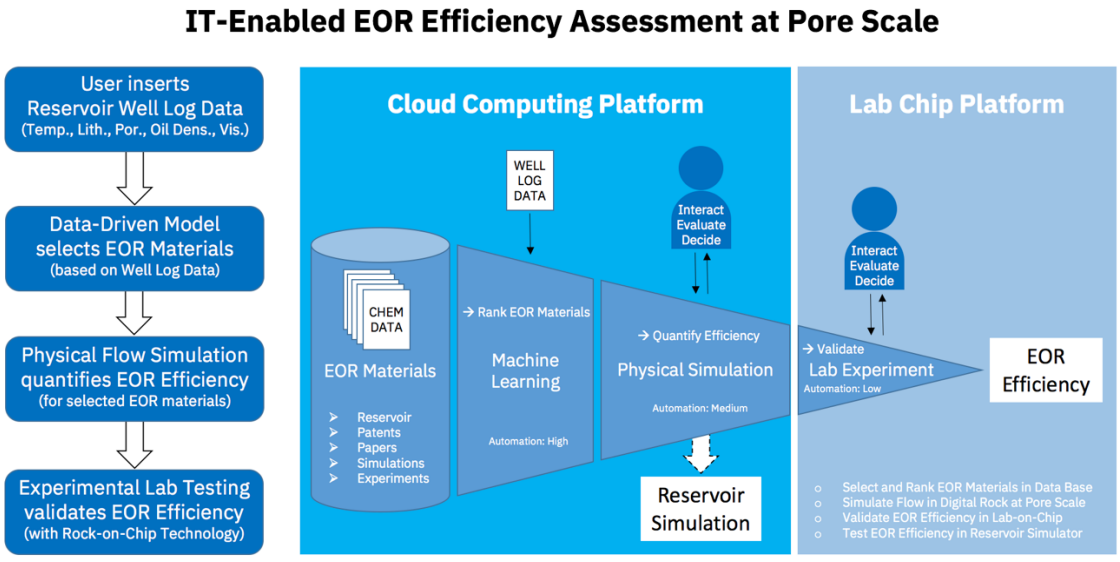

Figure 1. IT enabled EOR efficiency assessment at pore scale. The flow diagram (left hand side) visualizes the concept of EOR material selection step-by-step. Based on a reservoir-specific well log and machine learning algorithms, the user ranks candidate materials in a data base. Short listed materials are then further analyzed within a cloud-based physical flow simulator. The simulation results can be linked to a reservoir scale simulator and are validated by lab tests with flow chips that contain structural information of the reservoir's pore scale.

2.1. Cloud-Enabled Material Data Base and Artificial Intelligence Based EOR Screening

A major challenge for EOR applications is the identification of suitable chemicals for given reservoir conditions, considering the thousands of potential candidate materials ranging from research-grade nanoparticles available at lab scale to commercially available oilfield chemicals produced at industrial scale. In order to analyze the suitability for a particular EOR application, we have implemented a data base that contains a library of candidate materials separated into the following groups: generic materials, polymers, surfactants, nanoparticles and material mixtures. The chemical data has been extracted from various public sources such as catalogues, books, papers and patents and is currently being expanded by simulation and experimental data. Through a web interface, the data can be easily accessed and visualized; see Figure 2.

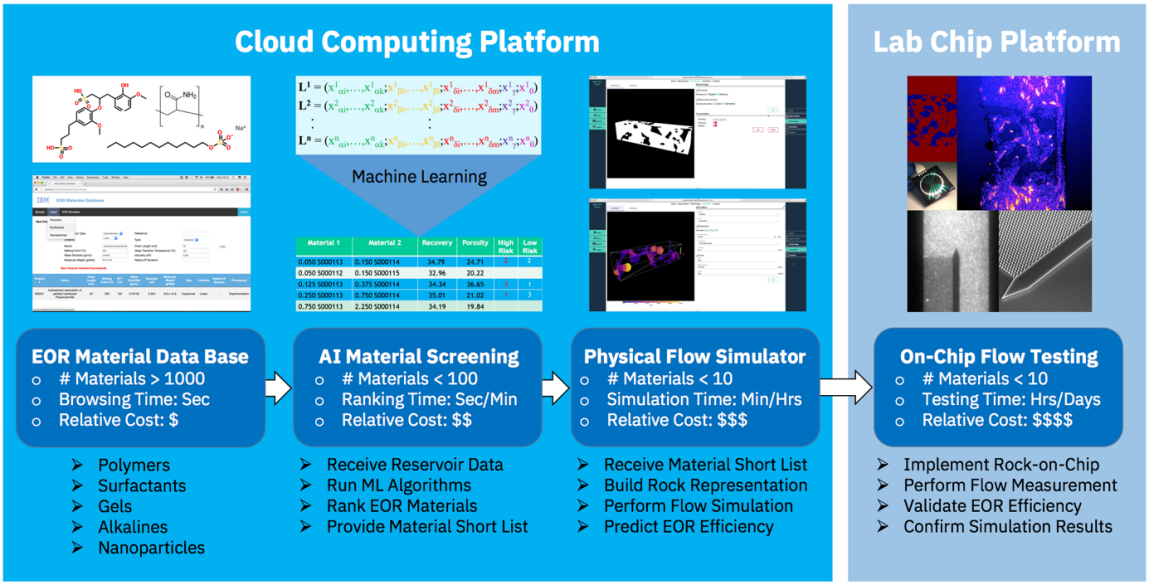

Figure 2. Cloud computing and lab chip platform, respectively, and their utilization in the pore scale assessment of EOR materials. A data base allows for inserting and managing a large number of candidate EOR materials (representative chemical species are visualized in the image) which are accessible through a user interface; see screen shot. Artificial Intelligence (AI) based machine learning techniques screen candidate materials against a set of reservoir conditions as indicated by the depicted vector definitions and screening table. For short listed materials, numerical flow simulations are performed based on reservoir specific, pore scale structural data taken from core analysis. Screen shots of the user interface show pore scale digital rock data processed with the cloud-based flow simulator prototype. The computed efficiencies obtained from the physical flow simulation for pre-selected candidate EOR materials is validated through experimental lab tests performed with a dedicated flow chip, see image set, which is customized to feature the same pore scale structure used in the flow simulation.

After initial data analysis, the application of machine learning algorithms in the data base allows for training a classification model that, once deployed, automatically short lists the most efficient EOR materials upon provision of a set of reservoir conditions; see Figure 2. Based on reservoir specific input data such as temperature, lithology, rock porosity, oil density and viscosity, which are typically available through reservoir well logs, the algorithm performs a ranking of the candidate materials with regards to their efficiency. The efficiency represents the increase of oil production due to the addition of a specific EOR material. This approach has the advantage that a large number of candidate chemicals can be screened in a short amount of time and at low computational cost while representing expert knowledge and production experience already available through the literature and industry data. In order to

further analyze and quantify their efficiency, the preselected EOR materials, which are characterized by a set of physical and chemical parameters, are then used as input data for numerical flow simulation at pore scale. In the following, we briefly describe the physical simulation environment which we have implemented in a cloud computing platform.

2.2. Cloud-Enabled Digital Rock and Flow Simulator for EOR Efficiency Assessment

In order to provide a pore scale test environment for physical flow assessment of preselected EOR materials, a numerical flow simulator performs a computational analysis of reservoir rock based on data provided by microscale computer tomography or scanning electron microscopy performed on core plug samples as discussed by Neumann et al. (2016, 2018). Such physical data is typically taken in lab experiments as a part of the geological assessment in core analysis. In a first step, image processing algorithms transform structural data into a three-dimensional capillary network representing the reservoir rock at pore scale, see Figure 2. In a second step, a morphological analysis is performed to extract geometrical and statistical parameters, such as the surface-to-volume ratio, that characterize the pore network. In a third step, based on the computational representation of the connected pore space, single-phase and multi-phase fluid flow simulations are performed to assess oil displacement properties induced by a certain EOR material. The fluid flow simulations are calibrated by all-atom and coarse grain molecular dynamics simulations that reveal critical parameters such as adsorption energy; details are discussed by Giro et al. (2014, 2015, 2017). In addition, fluid-fluid interface dynamics are modeled at the molecular level and then up-scaled thermodynamically via molecular kinetics theory, to capture the effects of nanoscale phenomena on the capillary pressure that controls the multi-phase flow through porous media as outlined by Giro et al. (2018). This procedure is certainly more resource intensive then the initial, data-driven ranking of EOR materials. However, it allows for explaining and quantifying the physical and chemical effects caused by the injection of a certain EOR cocktail in the pore scale capillary network of reservoir rock. This approach may also serve as the basis for pore scale parametrization of flow properties for linking and upscaling to macroscale reservoir simulations. Importantly, the pore scale flow simulation results can be directly tested and validated at the relevant physical length scale in lab-on-chip experiments.

2.3. Integrated Flow Chip Platform for EOR Lab Testing

The numerical flow simulations are validated by a lab-on-chip approach based on semiconductor process technology. As compared with artificial intelligence based materials screening and numerical flow simulation, experimental testing with flow chips requires significantly more time and resources. However, laboratory testing is the ultimate method for validating the computational model predictions prior to field application and could, therefore, be a necessary step to limit operational risk. The silicon based chip technology is highly scalable which allows manufacturing flow chips at wafer scale and in large quantities while representing within the flow channels reservoir specific, nanoscale to microscale, pore throat distributions as discussed by Engel et al. (2017a,b). Digital rock analysis allows to extract and transfer geometrical or statistical pore scale features for customizing flow chips to reservoir conditions; see Figure 2. The flow properties are then measured on chip and compared with

the results of numerical flow simulations obtained by using the same geometric boundary conditions. In addition to geometrical feature representation, the flow channels surfaces are customizable through chemical and physical processes in view of their wetting properties.

Surface wetting properties at pore scale, on the other hand, can be measured and validated directly on nanometer to micrometer scale liquid droplets. To do so, the droplets are deposited at a customized test surface of a dedicated, integrated optoelectronic device that allows for simultaneous determination of surface contact area and droplet topography through application of optical micro-spectroscopy and atomic force microscopy as reported by Steiner et al. (2015) and Engel et al. (2017c). As discussed by Giro et al. (2017), the application of this measurement method to individual oil droplets allows to extract the scaling relationship of adsorption energy which is a measure for nanometer scale liquid-solid interactions that limit fluid flow at pore scale.

3. Summary & Conclusion

In summary, by using as input a structural data set typically used in digital rock analysis and a reservoir-specific data set that contains information such as temperature and chemical composition of oil and brine, we are able to shortlist a subset of candidate EOR materials drawn from a dedicated data base. For the identified materials, we perform multi-scale flow simulations at pore scale to quantify the efficiency of EOR materials and their impact on oil displacement. The computational simulation results are then experimentally verified in dedicated lab-on-chip experiments in order to validate optimum EOR efficiencies. Alternatively, the same workflow can be used in order to determine the nanoscale rheological properties of oilfield chemicals or EOR materials that are used in the production process.

In conclusion, scalable platform technologies such as cloud computing for multi-scale flow simulations and integrated silicon chips for laboratory testing open a route to introduce nanoscale science and technology into exploration and production processes with potential to save time and cost in wellbore assessment and to improve accuracy of reservoir predictions. The platform technologies can be used in order to perform pore scale flow assessment and recovery experiments in a stand-alone mode, for research and development purposes, or they can be connected to reservoir scale simulators in order to capture nanometer scale effects not included in today's predictive production models. Operated as exploration and production tools with reservoir-specific input, these technologies have the potential to substantially reduce production risks and costs while optimizing recovery efficiency.

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