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Introduction

In 2013, a cooperation between the Petroleum Institute Abu Dhabi and the Institute of Petroleum Engineering Clausthal was established. The cooperation targets the exchange of ideas, concepts and the creation and transmission of knowledge in the framework of an international research partnership. As part of this cooperation, a comprehensive experimental and numerical study on low-salinity effects in limestone samples was developed. The vast majority of the research project was completed during a three and a half years long research stay at the Petroleum Institute Abu Dhabi.

The study fundamentally benefited from the unique research opportunities at the Petroleum Institute Abu Dhabi. Particularly, the newly established ADNOC Research and Innovation Center provides an exceptional Enhanced oil recovery specialized collection of state-of-the-art research equipment. Furthermore, the study profited from the short link to the Enhanced oil recovery division of the Abu Dhabi National Oil Company. The experimental findings were presented to an international audience at the 2018 Society of Core Analysis Symposium in Trondheim, Norway [34].

The capabilities of the Institute of Petroleum Engineering Clausthal contributed to the numerical analysis of the experimental data. Based on several years of experience on the open-source C++ simulator DuMu^x, the Institute assisted in the development of an independent numerical centrifuge and coreflooding model. A description of the implemented mathematical and numerical model approach is (going to be) published in the Journal of Petroleum Science and Engineering [35].

1.1 Motivation

The 2019 United Nations World Population Prospects forecasts a world population of more than 9.7 billion people in the year 2050 [102]. Related to this significant population growth, the World Energy Council [40] predicts a total primary energy supply increase of 27 to 61 %. Although the development and expenditures on renewable energy systems significantly change the energy production mix, the dependency on the fossil fuels coal, oil and gas remains high. It is expected that approximately one-quarter of the primary energy consumption in 2050 will still be supplied by the combustion of hydrocarbons. Besides the development of alternative concepts, especially the transport sector will predominantly depend on combustion engines, which emphasizes the continuous importance of the Oil & Gas energy sector.

Since it is generally believed that the majority of the existing oil reservoirs are discovered, the oil industry increasingly focuses on enhancing field recovery factors to meet the unabated oil demand. By currently holding 7 % of the worldwide oil reservoirs, Abu Dhabi plays a major role in maintaining the required oil supply [84]. While the current worldwide average recovery factor amounts approximately 35 %, the Abu Dhabi National Oil Company targets ambitious and challenging recovery factors of up to 70 % [100].

The huge hydrocarbon reservoirs of the Middle East are typically located inside carbonate formations. Albeit carbonate reservoirs are believed to contain 60 % of the world's oil reserves, several factors such as complex rock micro-structures, heterogeneous porosity and permeability distributions and unfavorable wettability conditions cause an inefficient oil production [95]. In order to achieve significantly higher recovery rates, it is therefore inevitable to invest in improved oil production concepts and technologies.

1.2 Production stages

The production of an oil field is typically divided into three recovery stages. During the primary recovery, the oil production benefits from the naturally existing reservoir drive. Typical examples are an aquifer, solution-gas, gas cap and/or rock and fluid expansion drive. Depending on the primary recovery drive and reservoir properties, 5 to 15 % oil can be recovered without the application of external energy [92].

Once the primary recovery decreases, oil production is typically maintained by the introduction of external energy. The secondary recovery stage focuses on the reservoir pressure maintenance and volumetric sweep efficiency increase due to the injection of immiscible fluids. Most secondary oil production stages are represented by conventional waterfloodings.

Tertiary recovery refers to the last production stage of an oil field, in which the oil recovery is stimulated by the injection of a fluid, which usually does not occur inside the reservoir. Examples are the injection of miscible and immiscible gases, chemical floodings, thermal application and other methods. Tertiary recovery technologies often conflict with economic interests, as tertiary oil production methods cause incremental production costs.

1.3 Geology

The vast majority of Abu Dhabi's oil reservoirs are located inside the Thamama Group (Lower Cretaceous) and the Arab Formation (Upper Jurassic). The porosity typically ranges between 20 to 30 %, while the permeability locally exceeds 100 md [48, 81].

As a result of carbonate reservoir genesis, the spatial porosity and permeability distribution within carbonates formation are strongly fluctuating. During the deposition, grain size, packing and sorting determine the fundamental rock structure. Typical carbonate depositional environment range from tidal flats to deep-water basins. The subsequent diagenesis includes several geological processes that affect the rock set-up. Compaction and cementation reduce the original porosity, while in contrast, chemical dissolution increases the void space. Thereby the dissolution of calcite can lead to the creation of new pores, which are typically not connected to original void space [3]. Besides primary and secondary porosity, fractured porosity is known as a third possible porosity type in carbonates. Caused by high mechanical stress, the arising joints (fractures) lead into a locally unrestricted flow. Typical consequences are matrix bypassing, early water breakthrough and/or gas coning [95].

1.4 Wettability

Besides the strong permeability and porosity heterogeneity of carbonates, the typically intermediate to oil-wet rock surface complicates an efficient oil production. In general, the concept of wettability describes the tendency of a fluid to adsorb on or detach from a surface under the presence of at least a second immiscible fluid [93]. After the hydrocarbon accumulation inside the reservoir formation, a chemical and physical equilibrium between the initial reservoir fluid, hydrocarbons, impurities and rock arises over a time period of millions of years [93]. Depending on the fluid properties and mineralogy of the reservoir, either water, oil or a mixture of both fluids tends to wet the rock surface. While the majority of sandstone reservoirs are assumed to be water-wet, carbonate reservoirs are characterized by an intermediate/oil-wet wettability. As a result, injected water typically bypasses the surface adsorbed oil, which hence causes an inefficient oil recovery.

As one of the primary purposes of tertiary oil recovery, Enhanced oil recovery (EOR) applications are conducted in the hope of altering the reservoir wettability. By shifting the initially intermediate or oil-wet wettability to more water-wet conditions, it is assumed that initially adsorbed oil can be re-mobilized [95].

1.5 Low-salinity waterflooding

Besides the complicated geology and unfavorable wettability conditions, the Middle East carbonate reservoirs are furthermore characterized by a high saline and high temperature environment. In regard to the typically light crude oil containing formations, the application of several Enhanced oil recovery methods is reasonable. As an alternative to the more expensive chemical EOR methods such as polymer, surfactant and/or alkaline floodings, this thesis evaluates the potential of low-salinity waterflooding to increase oil recovery.

The work of Jadhunandan [55, 94] (1991) was one of the first publications, in which a correlation between brine composition and oil recovery was described. In general, the concept of low-salinity water injection targets the reservoir wettability alteration towards stronger intermediate or water-wet conditions by the injection of a desalinated and/or modified injection brines.

Although low-salinity is generally linked to wettability alteration, the involved physical and chemical mechanisms are still controversial. Starting from five published low-salinity publications in 2007, the amount of proposed low-salinity mechanisms increased to already seventeen in 2014 [94]. Besides brine and oil properties, particularly the reservoir type significantly impacts the physics of low-salinity effects. Consequently, the proposed low-salinity mechanisms fundamentally differ for sandstone, chalk, limestone and dolomite samples.

The current research findings on low-salinity effects in limestones are summarized in Chapter 3. The literature review points out that the impact of low-salinity waterflooding on oil recovery is still not well understood. This thesis therefore develops, conducts and analyzes a comprehensive low-salinity study on limestone samples to evaluate the impact of low-salinity waterflooding on oil recovery.

1.6 Outline

The thesis is divided into ten chapters. In line with the current status of low-salinity research on limestone, Chapter 2 develops and formulates the scope, objectives and methodology of the conducted study.

Chapter 3 initially introduces the concept of low-salinity waterflooding at the example of the Buckley-Leverett solution. A comprehensive literature review summarizes the reported spontaneous imbibition and corefloodings experiments on limestone samples. Furthermore, the proposed low-salinity mechanisms on carbonates are introduced.

The subsequent chapters are divided into an experimental and numerical part. In the first place, Chapter 4 describes the experimental preparation of the study. The chapter emphasizes that a careful experimental preparation is crucial to obtain high-quality research data. Besides the core and fluid treatment, the section pictures the establishment of the initial sample conditions.

Chapter 5 describes the theory, experimental conduction, results and conclusions of the spontaneous imbibition section. The spontaneous imbibition experiments include fourteen test samples to evaluate the impact of connate and imbibing water composition impact on spontaneous oil recovery. Additionally, zeta potential measurements are conducted in order to evaluate the involved low-salinity mechanisms.

The principle of the centrifuge method is initially explained at the example of primary drainage (Chapter 6). The imbibition experiments are analytically corrected by the combination of Forbes First solution and a hyperbolic fit of the acquired forced imbibition data.

The three conducted unsteady state corefloodings are described in Chapter 7. Besides a description of the experimental conduction and results, Chapter 7 includes a general introduction of the unsteady state coreflooding technique.

The numerical part of this thesis includes the development of a centrifuge and coreflooding simulation within the C++ open-source software DuMu^{x}. Chapter 8 derives a two-phase numerical centrifuge model. The development of the numerical model includes the implementation and evaluation of suitable boundary conditions, centrifugal force and hydraulic property adaption. Furthermore, the chapter validates the developed centrifuge model against the commercial Cydar software.

Chapter 9 completes the numerical work by the development of a two-phase-three-component coreflooding simulation. Due to the introduction of a salt tracer component, the proposed coreflooding model allows the simulation of viscosity changes and low-salinity effects. In accordance with the centrifuge model, the presented coreflooding model is validated against Cydar.

Finally, the main findings of the study are summarized in Chapter 10. The spontaneous imbibition, centrifuge method and displacement results are attached in Appendix A. An impression of the numerical work is provided in Appendix B, where excerpts of the source code illustrate the C++ implementation of the proposed mathematical centrifuge and coreflooding model.

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Scope & objectives

The implemented low-salinity study combined spontaneous imbibition, centrifuge method and USS corefloodings to investigate the impact of brine composition on oil recovery. Each method is suitable to cover a specific aspect of the complex reservoir oil recovery processes [72]. Furthermore, zeta potential measurements were conducted to gain a better understanding of low-salinity mechanisms in limestones. The study is completed by the development of a numerical centrifuge and a coreflooding model to validate and history match the experimental data.

2.1 Experimental methodology

2.1.1 Spontaneous imbibition

Spontaneous imbibition experiments are a simple and widely used method to screen the potential of imbibing fluids to recover oil spontaneously. In regard to carbonate reservoirs, in which highly permeable and conductive fractures surround low permeable matrix systems, spontaneous imbibition is believed to be an important recovery mechanism [74]. Although spontaneous imbibition tests are a frequently reported experimental procedure, it remains questionable if the experiments are suitable to evaluate the potential of improved oil recovery applications [69].

The conducted spontaneous imbibition test sequence included eight different connate water and imbibing brine combinations. In line with the literature, the study initially evaluated the capability of a medium saline (Sea-water) and a low saline (Diluted-sea-water) brine to spontaneously recover oil from a system at higher salinity. To improve the understanding of spontaneous imbibition physics, the study additionally examined the connate water composition impact on oil recovery. Therefore, a sequence of spontaneous imbibition tests was conducted, in which the connate water and imbibing water had an identical composition. Moreover, low saline connate water was combined with a high saline imbibing water. All tested connate water and imbibing combinations are summarized in Figure 2.1.

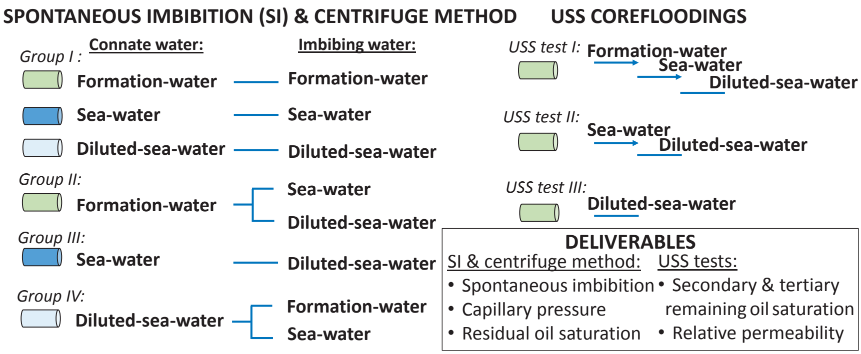

Figure 2.1: Experimental overview - The overview summarizes the spontaneous imbibition, centrifuge method and unsteady state corefloodings experiments.

As part of the spontaneous imbibition chapter, zeta potential measurements were conducted to investigate the involved mechanisms of the spontaneous oil recovery. A comprehensive overview of the proposed low-salinity mechanisms is provided in Chapter 3. The scope and objectives of the spontaneous imbibition tests can be summarized as follows