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Review article

Literature review of low salinity waterflooding from a length and time scale perspective

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ABSTRACT

In recent years, research activity on the recovery technique known as low salinity waterflooding has sharply increased. The main motivation for field application of low salinity waterflooding is the improvement of oil recovery by acceleration of production ('oil faster') compared to conventional high salinity brine injection. Up to now, most research has focused on the core scale by conducting coreflooding and spontaneous imbibition experiments. These tests serve as the main proof that low salinity waterflooding can lead to additional oil recovery. Usually, it is argued that if the flooding experiments show a positive shift in relative permeability curves, field application is justified provided the economic considerations are also favorable. In addition, together with field pilots, these tests resulted in several suggested trends and underlying mechanisms related to low salinity water injections that potentially explain the additional recovery.

While for field application one can rely on the core scale laboratory tests which can provide the brine composition dependent saturation functions such as relative permeability, they are costly, time consuming and challenging. It is desirable to develop predictive capability such that new candidates can be screened effectively or prioritized. This has not been yet achieved and would require under-pinning the underlying mechanism(s) of the low salinity response.

Recently, research has intensified on smaller length scales i.e. the sub-pore scale. This coincides with a shift in thinking. In field and core scale tests the main goal was to correlate bulk properties of rock and fluids to the amount of oil recovered. Yet in the tests on the sub-pore scale the focus is on ruling out irrelevant mechanisms and understanding the physics of the processes leading to a response to low salinity water. Ultimately this should lead to predictive capability that allows to pre-select potential field candidates based on easily obtained properties, without the need of running time and cost intensive tests.

However, low salinity waterflooding is a cooperative process in which multiple mechanisms acting on different length and time scales aid the detachment, coalescence, transport, banking, and eventual recovery of oil. This means investigating only one particular length scale is insufficient. If the physics behind individual mechanisms and their interplay does not transmit through the length scales, or does not explain the observed fast and slow phenomena, no additional oil may be recovered at core or field scale.

Therefore, the mechanisms are not discussed in detail in this review, but placed in a framework on a higher level of abstraction which is 'consistency across the scales'. In doing so, the likelihood and contribution of an individual mechanism to the additional recovery of oil can be assessed. This framework shows that the main uncertainty lies in how results from sub-pore scale experiments connect to core scale results, which happens on the length scale in between: the pore-network scale.

On the pore-network scale two different types low salinity responses can be found: responses of the liquid-liquid or the solid-liquid interfaces. The categorization is supported by the time scale differences of the (optimal) response between liquid-liquid and solid-liquid interfaces. Differences in time scale are also observed between flow regimes in water-wet and mixed-wet systems. These findings point to the direction of what physics should be carried from sub-pore to core scale, which may aid in gaining predictive capability and screening tool development. Alternatively, a more holistic approach of the problems in low salinity waterflooding is suggested.

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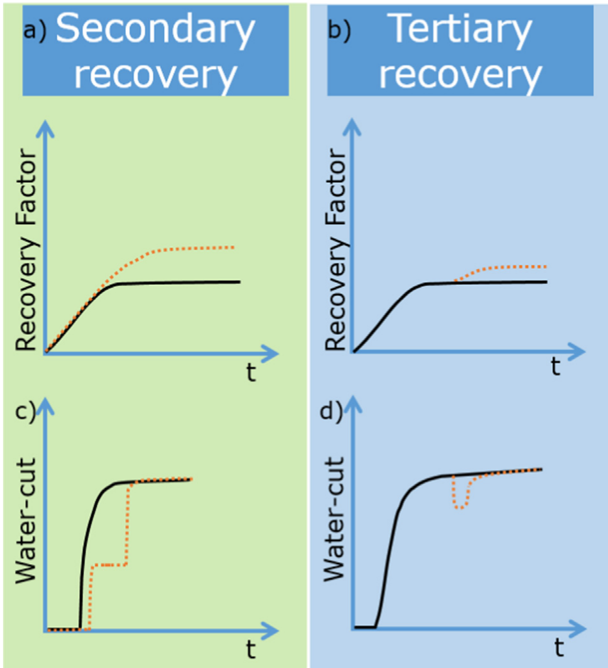

Fig. 1. Cartoon of secondary and tertiary low salinity waterflooding. The low salinity schemes are shown as orange dashed lines. The increase in recovery factor in a) and b), the dual-step water-cut in c), and the decrease in water-cut in d) are all manifestations of a response to low salinity waterflooding.

1. Low salinity waterflooding and predictive capability

1.1. Definition and motivation of low salinity waterflooding

Recovery techniques commonly described as low salinity waterflooding aim at improving recovery by reducing and/or modifying the ionic content of injected brines [1–9]. The same group of recovery techniques have been described by other terms such as Smart waterflooding [10–13], LoSal [14,15], Advanced Ion Management [16,17], or Ion Tuning [18,19]. A cartoon of a successful application of this technique is shown in Fig. 1, in which the effect of low salinity water injection is indicated as a dashed orange line.

Throughout this paper, the terms microscopic displacement efficiency, microscopic sweep efficiency, and macroscopic sweep efficiency are used. Microscopic displacement efficiency and microscopic sweep efficiency are used interchangeably. Both refer to the fraction of oil that has been recovered from (a) pore(s) that has/have been swept. Macroscopic sweep efficiency is standard reservoir engineering terminology and related to areal and volumetric sweep, which therefore is related to the overall result of the oil recovery process (including the effect of e.g. well patterns, thief zones etc.). These definitions follow the Schlumberger Oilfield Glossary [20].

Therefore we formulate the main motivation for field application of low salinity waterflooding as the acceleration of oil recovery, i.e. getting oil out by injecting less volumes of water due to improvement in microscopic sweep efficiency. From a commercial perspective reducing the residual oil saturation is of secondary importance [21,22]. The acceleration and/or residual oil reduction can be achieved by injecting low salinity water directly after primary depletion (secondary mode) or after a secondary high salinity brine waterflood (tertiary mode). Both scenarios are depicted in Fig. 1.

1.2. Development of low salinity waterflooding research

Over the past fifty years, particularly since 1990, the activity around this group of techniques has increased, which is reflected in the number of publications related to the topic displayed in Fig. 2. Prediction of the future trend is difficult, and can be influenced significantly by the uptake and actual field deployment of the technology by the industry.

The first studies on intentional use of low salinity water to improve recovery were published by Reiter [24] and Bernard [25], although studies related to the role of salinity in clay swelling, and consequently on recovery efficiency in waterflooding, have been around longer [26,27]. In parallel to the development of literature revolving around low salinity waterflooding, the literature on wettability and wettability alteration in a more general context has evolved, but a detailed review thereof is beyond the scope of this work. The reader is referred to Anderson [28–34].

Despite the significant interest in the topic of low salinity waterflooding and the progress made over the past decades, it cannot be predicted reliably which crude oil, brine, rock (COBR) system is responsive to low salinity waterflooding, what the amount of additional

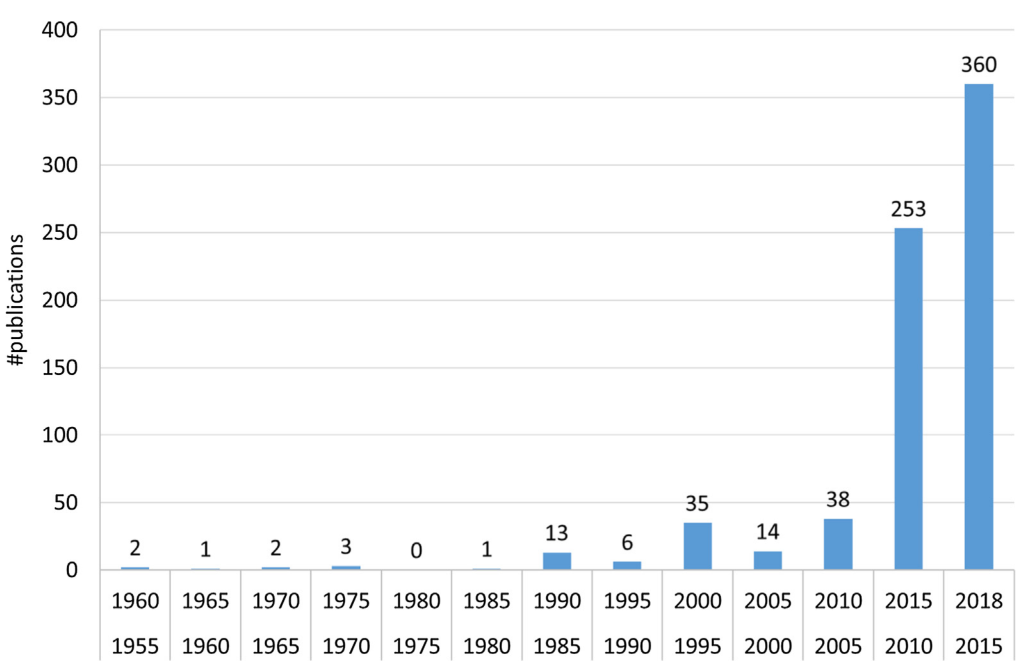

Fig. 2. The increase in number of publications since the mid 50's. The graph was created combining query data from Publish or Perish [23], Query: low salinity oil brine ion water flood NOT surfactant polymer coast plant bio, with the references in this paper, and a manual search on low salinity waterflooding. Each bin represents papers published in the interval including the lower boundary up to the upper boundary (e.g. 1955 ⩽publication year < 1960).