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A comprehensive review of formation damage during enhanced oil recovery

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ABSTRACT

Injection of chemicals and thermal fluids in discovered petroleum reservoirs are becoming more commonplace to achieve improved recovery and sustainability of oil/gas resources. A lack of understanding on the induced damage in subsurface reservoirs is likely to bring downside risks associated with the projects of enhanced oil recovery and negative economic consequences. As a synthesis and extension of our recent work (Yuan and Wood, 2018), this paper aims to raise more awareness and promote more discussion on the mechanically, chemically, biologically and thermally induced damage issues associated with enhanced oil recovery processes, by integrating the state-of-the-art modelling, laboratory experiments and field applications. Potential formation damage issues are considered in the context of each specific enhanced oil and gas recovery project to answer why, where and when formation damage issues occur, their extents and impacts, and how to control, prevent and take advantages of such issues in various reservoir systems. Moreover, an integrated risk & opportunity assessment and management framework is proposed to improve outcomes of diverse enhanced oil recovery projects in practice. By providing an integrated understanding of formation damage from multi-disciplinary perspectives, it is possible to better understand and manage petroleum extraction using enhanced oil recovery techniques.

1. Introduction

The consumption of crude oil is expected to contribute 26% of the world's energy until 2040 (I. E. A, 2014). Although the average recovery for major oil reservoirs is only between 20% and 40% of the resource present in mature reservoirs, and about half of the unrecoverable oil (~200 billion barrels) in the United States is at reasonable depths where enhanced oil recovery (EOR) techniques could be applied. Such techniques improve the amount of oil extracted and offset production declines from mature reservoirs, and by doing so help to meet the growing demands and constraints on energy resources. They also overcome some of the difficulties associated with discovering and developing new oilfields. As the production of existing oil fields continues to decline, EOR has the potential to offset this decline (Fig. 1). The IEA forecasts that the global oil produced from EOR will expand to about 4 Mb/d in 2040 (I. E. A, 2015). However, history shows that it is only the cost-effective EOR techniques that tend to be commercially applied during periods when oil prices have been sufficiently high to render these techniques economically attractive (Lake et al., 2014; Koottungal, 2014).

Chemical and thermal EOR projects made a decreasing contribution to the world oil production from 1986 to 2004 (Fig. 2). However, as reported by Alvarado and Manrique (2010) (Alvarado and Manrique, 2010), interest in chemical flooding projects in US and Canada grew from 200 to 2010 (Fig. 2), especially in heavy oil and offshore oilfields. Gas injection EOR projects also grew from 2000 to 2010 driven in part by a greater uptake of CO_2-injection projects. The numbers of EOR projects (including thermal, chemical and gas injection recovery) are highly sensitive to production costs and crude oil prices. Despite some delay in investors reacting to shifts in crude oil prices (almost 3–4 years' time lag), the initiation and persistence of EOR projects numbers shows a strong positive correlation with crude oil prices, reflecting the willingness and confidence, or otherwise, of investors regarding EOR projects. Hence, the profit-motivated oil companies are constantly seeking more advanced and cost-effective EOR technologies that can sustain profitability in volatile-oil-price markets (Muggeridge et al., 2014). During periods of low oil prices there is increased competition for available sources of finance and only the most profitable projects tend to be sanctioned. In such circumstances, it is particularly desirable to improve the efficiency of enhanced oil recovery by minimizing its potential risks and costs, and by providing sustainable production improvements.

Enhanced oil recovery (EOR) is the implementation of various techniques for increasing the efficiency of crude oil recovery from an oil field. It includes enhanced oil recovery (thermal recovery, gas injection and chemical flooding), secondary recovery (water and gas injection),

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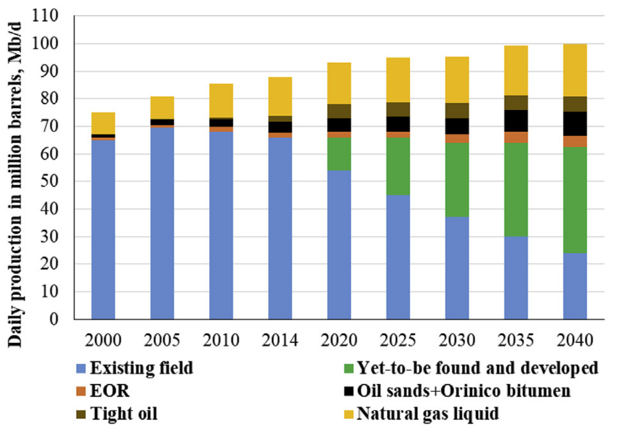

Fig. 1. Global production of oil and gas in World Energy Outlook (2015) by IEA (I. E. A, 2015).

hydraulic fracturing and the drilling of horizontal and multi-lateral wells (Walsh and Larry, 2003). Traditionally, the oil and gas industry has not linked improved oil recovery techniques with formation damage in high-oil-price environments, although formation damage is frequently a consequence of the implementation of EOR. Civan (2015) summarized the relevant causes of formation damage and its consequences, and various approaches and techniques for formation assessment, control and remediation (Civan, 2015). Formation damage refers to the impairment of physical, chemical or mechanical properties of petroleum-bearing formation, which primarily involves permeability damage during various processes of oil and gas recovery. The changes of chemical-physical-thermodynamic conditions associated with EOR techniques can result in various types of formation damage, such as, water and gas bubble blockage, fines/sands migration, fluids-rock incompatibility, organic and inorganic precipitation and deposit, alterations of pore surface properties, pore structures and mechanic characteristics. In some cases, formation damage may itself lead to some benefits that enhance oil recovery, for instance, improving sweep efficiency thorough selected blockage of high-permeability regions caused by fines migration (Yuan and Moghaloo, 2017; Bedrikovetsky et al., 2011a); however, more usually, it reduces the efficiency of secondary and tertiary recovery from the reservoir and impairs well injectivity and/or productivity dramatically (Bedrikovetsky, 1993). Hence, in this work, formation damage will not simply be addressed as a “problem”, but rather as an “issue”, reflecting its potentially positive and negative effects on well productivity and economic performance.

Porter (1989) stated that it is better to avoid formation damage in advance than to make tremendous efforts to remediate it after it has occurred (Porter, 1989). However, different types of formation damage may be realized by different EOR methods, meaning that studies of a formation's susceptibility to specific type of damage have limited practical value if conducted without consideration of the associated engineering activities which may, or may not, lead to that specific type of damage. It is beneficial for oil operators to understand formation damage specific to various EOR approaches, because it enables them to maximize oil recovery both technically and economically by optimizing EOR techniques in different types of reservoir paying due consideration to relevant formation damage issues. As an extension and short summary of our previous work (Yuan and Wood, 2018), the intention here

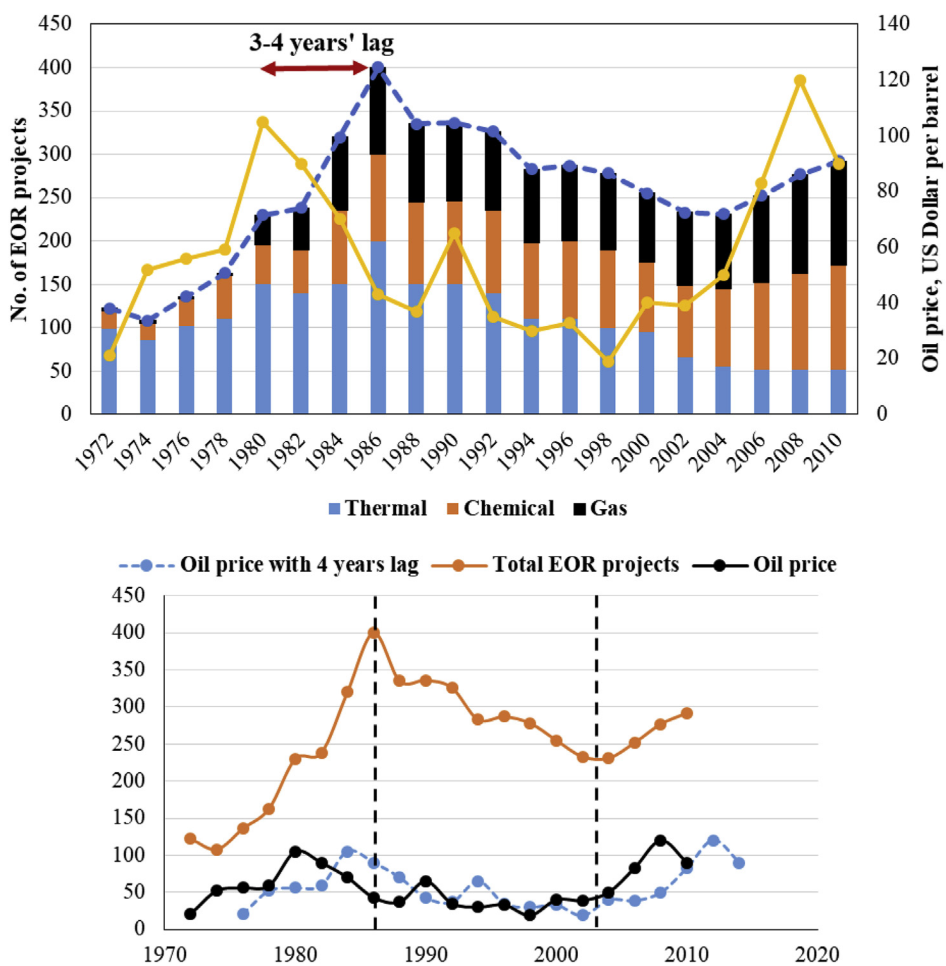

Fig. 2. The evolution of EOR projects with changes of oil price (US$/barrel) in the United States from 1970 to 2010.