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Heavy oil polymer flooding from laboratory core floods to pilot tests and field applications: Half-century studies

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ABSTRACT

Reservoir development is increasingly moving towards the heavy oil resources due to the rapid decline in conventional oil reserves. With the production of conventional low gravity crude oil being surpassed by heavy oil production in Alberta, the vast fields of heavy oil have been considered an emerging source of energy to the growing demands for oil and gas. Although the applications of thermal methods have been successful in many enhanced oil recovery (EOR) projects, they are usually uneconomic or impractical in deep and thin pay zones reservoirs. Therefore, polymer flooding is a preferred EOR technique in such reservoirs.

An application of polymer flooding in heavy oil reservoirs dates back to more than half a century ago. However, it has long been considered a suitable method for reservoirs with viscosities up to 100 cP only. Recently, this EOR technique has attracted great attentions and become a promising method for oil recovery from heavy oil reservoirs with viscosities ranging from several hundreds to several thousands of centipoises. The main reasons for such a widespread application of the technique in heavy oil reservoirs during the last two decades have been rises in oil prices, extensive use of horizontal wells and advances in the polymer manufacturing technology. This paper aims to review the advances and technological trends of polymer flooding in heavy oil reservoirs since the 1960s. Upon the review, complete data sets of the laboratory works, pilot tests and field applications are established. The database provides qualitative description and quantitative statistics regarding both scientific research and practical applications. Then suitable ranges of some crucial affecting reservoir properties and polymer characteristics for successful field applications are examined. Finally, new screening criteria are developed specifically for heavy oil reservoirs based on an analysis of the data. The criteria are compared with the previously established ones. The outcome of this paper can be used as guidelines for screening, planning, design and eventually implementation of future projects.

1. Introduction

Supplying the world oil demand to sustain the growing economies requires increasing recoverable reserves, which can be done by exploration of huge new reservoirs or improving the recovery factors of the discovered ones. Geologists and petroleum engineers are very pessimistic about the possibility of bringing forth new significant petroleum resources, so upgrading the current reserves by applying enhanced oil recovery (EOR) methods is a more likely way to meet the demand. As conventional oils start to reach the peak production, heavy oil reservoirs become increasingly attractive. Heavy oil resources in the world are estimated to be about ten trillion barrels, almost three times the conventional oil-in-place (OOIP) (Salama and Kantzas, 2005; Lie et al., 2014). The vast heavy oil resources in the western Canada, particularly in Alberta, comprise the world's largest known petroleum basin; some heavy oil reservoirs are distributed in other parts of the world including the United States, Middle East, China, and Latin America.

Unfortunately, there is no agreement on the definition of heavy oil. Typically, it is defined as a crude oil with a viscosity of more than 100 or 1000 cp and gravity of less than 20 API (Dusseault, 2001). The term heavy oil in this paper refers to the oil with a

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Abbreviations: ASP, alkaline-surfactant-polymer; HPAM, hydrolyzed polyacrylamide; IE, injection efficiency; NR, not reported; PEF, polymer effectiveness factor; ppm, part per million; PV, pore volume; SP, surfactant-polymer.

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viscosity more than 100 cp. Veil et al. (2009) differentiated heavy oil from extra heavy oil, bitumen, and oilsands by defining the former to have sufficient mobility to flow towards the production wells under reservoir drive mechanisms, but the latters are too solid for natural flowing.

Thermal and miscible methods are successful and effective techniques for producing heavy oil. However, their applications to many reservoirs is restricted by technical, economical, and environmental issues. For example, a high recovery factor cannot be achieved by an application of thermal techniques in thin and deep formations and also in reservoirs with a bottom aquifer because of severe heat loss to the overburden and underburden layers. Additionally, heating up water requires significant fresh water and a natural gas source, which itself gives rise to an increase in the operating costs and emission of greenhouse gas to the atmosphere. Miscible solvent processes like VAPEX (vapor extraction) are not efficient in thin and low pressure formations because of unsuccessful gravity drainage in such situations. It is noted that many heavy oil reservoirs are as thin as a few meters. For example, the heavy oil containing third class reservoir of Daqing oilfield in China is as thin as 1 m (Pu et al., 2008). Thus implementation of thermal and miscible EOR techniques offer tremendous challenges in some reservoirs. Waterflooding, as the simplest improved oil recovery method which is widely used at the end of primary production, leaves a substantial volume of oil unswept due to severe viscous fingering through an oil zone resulting from an unfavorable (adverse) mobility ratio between the injected water and viscous oil (Table 1). However, several successful water flood projects have been reported with the recoveries ranging over a broad range of 1–2% to 20% of OOIP (Oefelein and Walker, 1964; Adams, 1982; Kasraie et al., 1993; Yang et al., 1998; Ko et al., 1995; Jameson, 1973; Miller, 2005; Energy Resources Conservation Board, 2012; Mashayekhizadeh et al., 2014). Miller (2005) attributed this wide range of the recoveries to different recovery mechanisms in the reservoirs. Generally speaking, incremental recoveries through waterflooding in heavy oil reservoirs are very low compared to conventional oils.

In light of these issues, concerns, and challenges, polymer flooding has become the most promising EOR technique for three potential ways that make the waterflooding process much more efficient. These reasons are a rightward shift of a fractional flow curve, a decrease in the water-to-oil mobility ratio, and diverting the injected water from the swept to unswept zones (Knight and Rhudy, 1977; Needham and Doe, 1987; Selby et al., 1989). Furthermore, an application of horizontal wells in heavy oil reservoirs has mitigated concerns about low injectivity of large slug viscous polymer solution and made it more technically feasible and economically profitable (Zaitoun et al., 1998; Wassmuth et al., 2007; Seright, 2010).

The main objective of this paper is to highlight the advances and technological trends of polymer flooding in heavy oil reservoirs. It presents learnt lessons and gained experiences from laboratory work, pilot tests, and field applications of the EOR technique. Accordingly, the paper is subdivided into four parts. The first part reviews the performed experimental work. Next, the pilot tests are presented. This is followed by a collection of field scale implementation of polymer injection projects. Finally, ranges of some crucial affecting parameters for successful field applications are examined based on the data analysis of the first three sections. It is noted that this work focuses on reported data available in the open literature.

2. Laboratory studies

Laboratory studies are the first steps for a proper selection of injected polymer parameters and planning and design optimization of a project (Weiss and Baldwin, 1985; Castagno et al., 1987; Pratap et al., 1997). In the 1950s, a number of researchers (Aronofsky, 1952; Dyes et al., 1954; Pye, 1964) initially found that adding water soluble polymers can lower the water–oil mobility ratio, which consequently improves corresponding waterflooding efficiency. Although a lot of laboratory tests were conducted to study polymer flooding, most of them have been concentrating on conventional oils. In spite of their importance, polymer flooding in heavy oil reservoirs has not attracted much experimental attention in the literature. Summaries of the coreflood parameters and recovery data of the experiments are given in Table 2. Data of this table are ordered by the time of evolution.

2.1. Experimental procedures

Coreflood experiments are performed to determine the potential of polymer flooding and evaluate its technical feasibility. Additionally, test results provide the data required for the coreflood and reservoir simulations. In most of the previous experimental studies, which are listed in Table 2, the following common procedure has been followed for conducting the displacement tests:

1. Prepare and characterize the core
   a. Trim, wash, and dry the core
   b. Measure the grain density, porosity, and absolute air permeability

2. Establish initial saturation
   a. Saturate the core with the formation brine and measure the liquid permeability prior to any flooding experiments.
   b. Flood the core with the heavy oil and displace the water down to irreducible water saturation (S_{wi})

Table 1
Water flooding projects in heavy oil reservoirs.

Field	Formation	Depth (ft)	Porosity (%)	Permeability (md)	Temperature (°F)	API Gravity	Viscosity at Tr (cp)	Incremental waterflood recovery (% OOIP)
Court Bakken	Middle Bakken	2854	29	2100	87.5	17	155	30
Taber South	Mannville B	3225	22	NR	92	19.1	146	10–15
Inglewood	Vickers East	1000	35	752	100	18.7	65	6.6–9.5
Lloydminster	Sparky/Waseca	1800	32	2000	72	13–17	400–1500	1–2
Battrum	Unit 4	2904	25	1300	99	16	112	6–9
Buffalo Coulee	Bakken	2690	24	767	77	13	350	4.1
Karamay	Conglomerate III	1640	20	200	68	28.94	21–214	25
Viking–Kinsella	Wainwright–Sparky	2129	29	300	79	21	103	27
Provost	Cummings	2503	28	385	86	24	39	15
Suffield	Upper Mannville N	3156	26	NR	89.6	14.23	1094	10