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Viscosity reduction of heavy oil/bitumen using micro- and nano-metal particles during aqueous and non-aqueous thermal applications

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A B S T R A C T

The objective of this work is to clarify the mechanisms of additional viscosity reduction of heavy oil/bitumen using nano-size metal particles during steam injection techniques. For this purpose, three sets of experiments are designed. The objective of the first series of experiments was to study the effect of metal particles on the viscosity of the produced oil at low temperature. Viscometry experiments at temperatures below 100 °C were conducted for this purpose. Then, their effect was studied in the presence of aqueous phase at high temperature of 300 °C to simulate the steam stimulation processes. The third set of experiments was designed to study the effect of micro- and nano-sized metal particles on the enhancement of heat transfer within the oil phase.

The experiments showed that at low temperatures, the particles reduce the heavy oil viscosity after being mixed with the oil phase. The amount of the viscosity reduction is a function of the concentration of the particles and there exists an optimum concentration of particles yielding maximum amount of viscosity reduction. Also, the trend of viscosity versus concentration of the particles is a function of the type and size of the metal, and the temperature. The second series of experiments revealed that the same trend of viscosity versus concentration of particles is observed at steam injection conditions. However, much higher degree of reduction in viscosity was observed in this case compared to the low temperature experiments. The third series of experiments showed that metal particles used at their optimum concentration do not provide significant improvement of heat transfer.

The experiments provided a good understanding of the ongoing mechanisms that would lead to a viscosity reduction by the addition of metal particles. The concentration, type, and size of the particles were found to be highly critical on viscosity reduction. The optimal values of these parameters were identified. The results and observations are expected to be useful in further studies and applications as to the efficiency improvement of the thermal applications for heavy-oil/bitumen recovery.
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1. Introduction

Due to the growing world oil demand and scarcity of the conventional oil reserves, increasing attention is turning towards huge unconventional resources such as heavy-oil and oil sands deposits due to their enormous volume and worldwide distribution. Production from these reservoirs is challenging owing to the immobile nature of heavy oil and bitumen and reducing the in-situ viscosity of the oil is considered as the main objective of any recovery process.

Heavy-oil or bitumen recovery requires extensive reservoir heating using either conventional methods such as steam and air injection or unconventional ones that apply electrical or electromagnetic methods. Steam applications are costly due to infrastructure and operational cost, and environmental impacts, eventually yielding a high steam–oil ratio (SOR). Recently, considerable attention was devoted to find a suitable substitution for steam stimulation to be applied for uneconomic cases, or to improve steam injection technique in a way to reduce the SOR. Recently, electric/electromagnetic heating methods have been proposed and tested as an alternative, especially in thin bitumen reservoirs and oil shale deposits (Pizarro and Trevisan, 1990; Davidson, 1995; Sahni et al., 2000; Hascakir et al., 2008). Although they reported technically successful results, improvements are still required to have economically feasible projects.

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The main idea behind the efficiency improvement is to reduce the cost of energy used to heat the reservoir, either with steam or electric/electromagnetic heating. In other words, the reduction of heavy-oil or bitumen viscosity should be achieved in a quick and economic way. To improve the efficiency of steam applications, a better understanding of the reactions occurring between oil, water and sand which result in heavy oil/bitumen viscosity reduction is required.

In high temperature steam injection applications, steam is injected into a reservoir to provide the heat that is required for visbreaking of the heavy oil/bitumen (Omole et al., 1999). Earlier, Hyne (1986) showed that the reduction of heavy oil/bitumen viscosity is not only due to the high temperature effect but also a series of chemical reactions. These reactions known as aquathermolysis occurring among steam, sand and oil components lead to further change of the physical properties of heavy oil/bitumen (Hyne, 1986). The hydrolysis of aliphatic sulfur linkages is the main characteristics of these reactions. The main effects of aquathermolysis are the reduction of asphaltenes and resins, increasing saturates and aromatics, reducing the molecular weight, decreasing the sulfur content, increasing H/C ratio and the reduction of the viscosity of the produced oil (Clark et al., 1990a, 1990b; Fan et al., 2002, 2004; Guangshou et al., 2009). Yufeng et al. (2009) investigated the cracking of asphaltene and resins into lighter molecules during catalytic aquathermolysis. Nickel and iron based catalysts yielded significant conversion of asphaltene and resins into gas components, saturates, aromatics and resins. The gas mixture contained H_2, CO, CO_2, H_2S, and light hydrocarbons (Yufeng et al., 2009). Therefore, according to these references, the main effect of the aquathermolysis is break down of the complex asphaltene and resins structure.

One of the ways to achieve these reactions is to use metal species. It has been previously shown that micron-sized metal particles improve the efficiency of some ex-situ processes such as coal liquefaction and pyrolysis, heavy oil upgrading, oil shale recovery, and heavy oil viscosity reduction. It is believed that catalyzing the hydrogenation reactions and thermal conductivity enhancement are the important functions of transition metal species. Some of these effects result in in-situ oil upgrading. To our knowledge, the first application of the use of metals in bitumen upgrading during aquathermolysis was reported by Clark et al. (1990a). They noted that using aqueous metal salts instead of water in steam stimulation improves the properties of the recovered oil such as viscosity and asphaltene content. They explained that the observed improvements are due to the catalytic effect of the metals on the aforementioned aquathermolysis reactions. Later, Fan et al. (2002, 2004) studied the catalytic effects of minerals on aquathermolysis of heavy oils. They reported that, without the presence of water, minerals have no effect on oil properties (Fan et al., 2004). Also, Li et al. (2007) investigated the effect of nano-nickel catalyst in the viscosity reduction of heavy oil. They observed the same effect of the particles on the recovered oil properties as previous researchers. In an attempt to in-situ upgrading of heavy oil/bitumen, Hassanzadeh et al. (2009) and Loria et al. (2011) studied the effect of a mixture of metals nickel, tungsten and molybdenum on API gravity. However, their experiments were conducted at temperature range of 320–380 °C which is well above the steam stimulation temperature. Also in this study, hydrogen was also added to the mixture which is practically a challenging process. The same mixture of metal species, at the same experimental conditions, was applied by Hashemi et al. (2013) to enhance the recovery factor of steam flooding. In a different study, Chen et al. (2009) investigated catalysis of aquathermolysis, in a temperature range of 200–280 °C, using heteropoly acid catalyst containing molybdenum. Although this catalyst provides very good catalysis of aquathermolysis reactions, due to its high acidity, its application would require significant modifications in the production facilities. Furthermore, Hascakir et al. (2008) applied particles in a different way than the others. They investigated the effect of micron sized iron particles on heavy oil viscosity without steam treatment. Surprisingly, they reported a noticeable viscosity reduction by simply adding micron sized iron particles in absence of any water.

The objective of this study is to clarify some of the points raised by the studies listed above. The most critical point is the main cause of viscosity reduction when metal particles are added that eventually results in improved heavy-oil/bitumen recovery. A set of experiments, including viscosity change at different temperatures when the heavy-oil samples were mixed with aqueous and non-aqueous metal particles, were conducted. Also studied were the effects of the particle size on viscosity reduction and the improvement of heat transfer when different metal particles are used.

2. Statement of the problem

As stated above, the effect of metal particles on oil properties and recovery enhancement was studied over the last three decades from different points of view, i.e. in-situ and ex-situ oil recovery with and without thermal processes and heavy-oil/bitumen upgrading. Although there exists a limited number of works in this area, interestingly, different observations and interpretations were reported on the mechanics of viscosity reduction. On the basis of the above analysis, the following were raised as critical points to question and an attempt was made to answer them in the present study through a set of experimental work: (1) Although Clark et al. (1990a, 1990b) and others (Fan et al., 2002, 2004) observed improvements on the physical properties, especially the reduction in viscosity, of the recovered heavy oil/bitumen from steam stimulation by using metal catalysts, Hascakir (2008) achieved the same degree of enhancement by only mixing the oil with metal particles at much lower temperature. (2) A number of works (Clark et al., 1990a; Fan et al., 2004; Li et al., 2007) concluded that catalyzing the aquathermolysis reactions by metal particles is the main contribution of the metal particles in the viscosity reduction process. Since aquathermolysis corresponds to the breakage of C–S bonds of the asphaltene molecules, the effect of the asphaltene content needs to be investigated in the non-aquathermolysis (in the absence of heating) effects of the metal particles. The effect of metal particles on non-sulfuric oils has not been investigated. Use of metal particles instead of ionic solution for steam stimulation of heavy oil/bitumen and their viscosity reduction mechanisms have not been studied. Also, the non-catalytic effects of the metal particles in the viscosity reduction process, i.e., exothermic chemical reactions caused by particles, need to be explained. To clarify the effects of oil composition, especially the asphaltene content, on these, well designed viscometry experiments and their comparison with previous studies are needed. (3) Although the type and concentration of the particles are reported to be important factors affecting the degree of viscosity reduction (Clark et al., 1990b), the influence of the size of the particles has not been investigated. This should be clarified by testing nano- and micron-sized metals including iron, copper, nickel, and their oxides. (4) Enhancement of the thermophysical properties of fluids using metal particles were studied in a number of studies (Hamilton and Crosser, 1962; Masuda et al., 1993; Choi and Eastman, 1995). Heat transfer improvement can be considered as another important feature of the metal particles which can cause a faster recovery of heavy oil/bitumen. This is not well understood yet and the effect of micron-sized and nano-sized metal particles on heat transfer through heavy-oil and its possible

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