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Use of nano-metal particles as catalyst under electromagnetic heating for in-situ heavy oil recovery

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A B S T R A C T

In order for heavy oil and bitumen recovery to be efficient, all components present within the oil must be produced. To achieve a highly efficient production process it is essential that we are able to produce asphaltenic components and limit their precipitation. Solvent and conventional thermal techniques are largely limited in their ability to crack asphaltenic components; thus, new techniques and catalysts are needed to more efficiently recover heavy oil.

When nano-size metal particles are present they catalyze the breaking of carbon–sulfur bonds within asphaltenic components. The result of this process is an increase in saturates and aromatics, while simultaneously reducing the asphaltene content. This process dramatically lowers the viscosity of heavy oil and bitumen by significantly reducing the average molecular weight. This effect can be dramatically increased by having a strong hydrogen donor present and can be completely inhibited by the removal of all hydrogen donors. When conducting these types of reactions in-situ, it is very difficult and expensive to introduce strong hydrogen donors. Therefore, it is imperative that hydrogen donors be created within the oil rather than be introduced from an external source.

In this paper, we investigated the effects of microwave radiation, using a 2.45 GHz emitter, on the recovery of heavy oil from a sand pack. Experiments were conducted with and without nano-size nickel catalyst being present. Heavy oil samples were heated at differing power levels until recovery of heavy oil leveled out. In all cases, the nano-nickel catalysts performed better than their microwave-only counterparts due to the increased cracking and vaporization demonstrated by Greff and Babadagli (2011) to take place in the presence of nano-size metal catalysts and microwaves.

1. Introduction

Due to the worldwide depletion of easily accessible light crude reservoirs, other more difficult and economically prohibitive reservoirs are gaining greater interest. Since light crude production is peaking at the same time as global demand for oil is increasing, this is making medium, heavy, and extra heavy oil reservoirs more crucial than ever to the sustained availability of cheap oil. Heavy oil and bitumen comprise nearly 70% of remaining oil reserves (Liu, 2005), which makes it the most prominent alternative oil source to light oil reservoirs. However, the high viscosity of these oil sources makes them technically challenging and economically prohibitive to produce. The high average molecular weight of these substances and the interesting interaction of aspaltenic components give these oils a very high viscosity and density. These two properties cause problems not only for production, but also for transportation. Currently these properties are primarily negated through the use of thermal heating due to the reduction of viscosity which accompanies the increase in temperature.

Steam is the most commonly used heat carrier for thermal methods. Steam induced heating relies upon the temporary reduction of oil viscosity in order to increase the flow rate of the oil through the reservoir and likewise increase the production of oil. Cyclic Steam Stimulation and Steam Assisted Gravity Drainage are the two most commonly utilized methods by operators. These two methods rely on the large heat capacity of steam and the availability of a sufficient water supply. However, sufficient water supplies are not available globally and likewise these methods are not universally suitable. In addition, due to the high steam–oil ratios that are required for these methods, there are additional capital expenditures that are needed to not only create the steam but also to treat the waste water byproduct. These two issues represent major liabilities in the form of lost profitability.

Additionally, beneficial chemical reactions also take place during steam stimulation techniques lowering the viscosity of

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oil. Hyne et al. (1982) used the term "aqua-thermolysis" in order to describe the chemical reaction that occurs at high pressure and high temperature between steam and certain components of heavy oil/bitumen. The dominating hypothesis used to explain this phenomenon is that high pressure and temperature steam is capable of breaking the carbon–sulfur bonds present within the asphaltenic components of heavy oil/bitumen (Clark et al., 1990; Liu et al., 2002). This effect permanently lowers the viscosity of the heavy oil/bitumen by reducing the average molecular weight of the oil.

The "aqua-thermolysis" reaction can be more efficiently performed by the addition of catalytic aqueous metal species (Clark and Hyne, 1990; Clark et al., 1990). When the steam–oil reaction is enhanced by the addition of these metal species, the viscosity reduction of the heavy oil/bitumen is increased significantly. This catalytic property has been found to be associated with all of the first row transition metal species, which makes all of these metals capable of increasing the efficiency of the "aqua-thermolysis" reaction. Additionally, more recent experiments performed by Zhao et al. (2002) have demonstrated that these catalytic properties are maintained in-situ. Typically, in the "aqua-thermolysis," water acts as both the hydrogen and heat donor. However, stronger hydrogen donors such as Tetralin have been shown to be more effective in combination with a catalyst at reducing the viscosity of heavy oil compared to a weak hydrogen donor such as water (Zhong et al., 2003). However, strong hydrogen donors such as Tetralin are very expensive and would therefore be very cost prohibitive for field scale implementation.

On the hand, there are many circumstances that steam injection may not be feasible such as deep, and highly heterogeneous and shaly formations. Electromagnetic heating could be an alternative to steam injection for this type of reservoirs. Microwaves are very photoreactive and therefore it may be possible to use them in order to produce extremely reactive hydrogen-radicals in-situ. These hydrogen radicals would in turn act as an ideal hydrogen donor, both increasing the rate of the "aqua-thermolysis" reaction while spontaneously being replenished in-situ. In addition, by having catalytic nano-metal catalysts present, it may be possible to catalyze the breaking of the carbon–sulfur bonds. This would enable us to not only temporarily lower the viscosity of heavy oil/bitumen through thermal mechanisms, but also to induce a permanent upgrading of the oil through photochemical alteration. This permanent change in the oil's properties would enable us to increase our overall recovery while producing the oil at lower temperatures. Therefore, we would effectively be able to produce highly upgraded crude more efficiently, without the potential environmental liabilities.

2. Basic microwave theory

Microwaves have an extremely high frequency with a range between 300 MHz and 300 GHz. Microwaves are very effective stimulators of dielectric reactions and are able to cause atomic polarization, interfacial polarization, and dipolar turning to polarization. When we polarize dielectric materials it causes an inner power dissipation which results in an increase in temperature of the material. Microwave heating does not rely solely on convection or conduction and can likewise heat objects internally regardless of whether or not physical contact is achieved between the microwave source and the sample. This enables us to remotely heat samples very quickly and efficiently, provided that the substance absorbs the particular frequency of radiation that is being applied (Li et al., 2003). In addition to the heating properties of microwaves, there are many specific documented and undocumented photochemical reactions that they participate in.

3. Experimental set-up and materials

3.1. Microwave generator

The microwave set-up used for these experiments consisted of a microwave generator with a set frequency of 2450 MHz. This microwave generator's available power range was 100–1000 W. Power settings were adjustable in 100 W increments. The microwave generator and reactor were equipped with an output power readout as well as ports to collect produced gases/condensates and liquids, which enabled us to collect gases/condensates and liquids on a continual basis for analysis. A diagram of the experimental setup can be found in Fig. 1.

3.2. Crude oil and viscosity measurements

We used a crude oil sample obtained from a heavy oil reservoir in Northern Alberta, Canada. The stock tank crude oil viscosity curve is shown in Fig. 2a. We also measured the viscosity of the produced liquids and condensates using a Brookfield DV-II+Pro viscometer, which enabled us to measure the viscosities of the produced substances at varying temperatures to establish viscosity curves. A detailed analysis of the effects of the nano- and micro-particle catalyst on the viscosity of heavy-oil was provided in our earlier study (Greff and Babadagli, 2011). An example of these analyses is given in Fig. 2b and c. After treating the oil sample under the microwave at 300 W for 5 h, with and without nano-metal particles, the viscosity of the oil samples was measured (this is called the control case). For comparison, the original oil sample viscosity was also measured at different temperatures but without exposing to any microwave heating. Obviously, the control case (heated in microwave without any metal particles) viscosity in Fig. 2b and c (solid lines) is higher than the original oil (Fig. 2a) due to the removal of lighter ends under microwave heating.

In both metal particle addition cases (iron and iron (III) oxide), increasing particle concentration yielded an increase in viscosity. However, below a certain concentration, the catalyst yielded a lower viscosity than the control case (sample without catalyst) indicating the existence of an optimal value of concentration. This value was observed to be around (or less than) 0.1% as can be inferred from Fig. 2b and c. A similar trend was also observed by Hamedi and Babadagli (2010, 2011) reporting the optimal

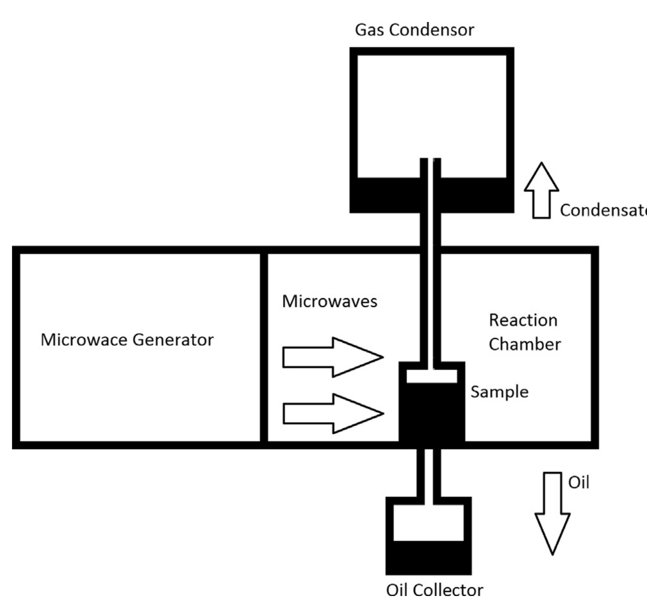

Fig. 1. Microwave design and experimental setup.