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Hot Solvent Injection for Heavy-Oil and Bitumen Recovery

by

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ABSTRACT

This research was undertaken to study the performance of paraffinic solvents at higher temperatures for heavy oil/bitumen recovery. Heavy oil or bitumen saturated glass bead packs, Berea sandstone and carbonate cores were used in the experiments to represent different types of pore structures, porosity and permeability.

Final recovery and the quantity of asphaltene precipitated in each experiment were reported. It was observed that recovery decreased with increasing temperature and pressure of the system and that the best results were obtained when the experimental temperature is slightly higher than the solvent saturation temperature. It was also noticed that butane diluted the oil more than propane.

Furthermore, numerical simulation was conducted using a commercial simulator including asphaltene precipitation option. Visualization experiments were also carried out using 2-D Hele-Shaw models to observe the effect of asphaltene precipitation on the dynamics of the process.

Using this analysis, the mechanics of the hot solvent process was clarified and the impact of temperature, pressure, asphaltene deposition, permeability and solvent type on recovery were quantified.

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1. INTRODUCTION

1.1 Literature Review

Thermal and miscible methods are commonly used for in-situ recovery of heavy oil and bitumen. Both techniques have their own limitations and associated shortcomings, often times yielding an inefficient process. The most common thermal method is steam injection, which is highly energy intensive. Steam generation costs and water production affect the economics of the thermal technique adversely. On the other hand, miscible methods are energy effective but their economics is highly dependent on solvent retrieval. Various combinations of these two techniques such as co- or alternate injection of steam and solvent have been proposed as a solution, but no optimal solution has yet been developed.

1.1.1 **Introduction to SAGD and VAPEX**

Steam Assisted Gravity Drainage (SAGD) is the most frequently used steam injection technique for the recovery of heavy oil and bitumen, and has been implemented successfully in many heavy oil projects across Alberta. This technique was modified to incorporate injection of solvents instead of steam and the new technique was named as Vapour Extraction (VAPEX), originally proposed by Butler and Mokrys (1991). In both of these techniques, recovery agents, i.e., steam and solvent vapors for SAGD and VAPEX respectively, are introduced into the reservoir through a horizontal injection well, and displaced oil is produced from a horizontal production well located below the injector. In SAGD, recovery is enhanced due to the heat transfer from steam to the heavy oil

The contents of this chapter were published in various papers during this research. These papers are enlisted in section 1.4.

whereas in the VAPEX process, solvent vapours dissolve at the interface between solvent and heavy oil and diffuses through the oil. In both these processes, the less viscous produced oil flows down by gravity to the producer well.

However, there are several shortcomings associated with both of these processes. SAGD is not economic in cases where reservoirs are thin, because heat losses to confining strata become excessive compared to the resource. Another problem in SAGD is the cost involved for treating effluent water and the high energy requirements in order to have a continuous production of steam. Energy losses incurred in SAGD operations are much higher than in VAPEX (Upreti et al. 2007). Singhal et al. (1996) presented guidelines for making a decision between SAGD and VAPEX for heavy oil reservoirs. They stated that the VAPEX process is highly energy efficient as compared to SAGD. Moreover, condensation of fresh water from steam poses problems to the formation by clay swelling and reduction in oil relative permeability. VAPEX does not pose such problems. Lastly, solvents used in VAPEX are either insoluble or sparingly soluble in water; hence, there is no concern of solvent loss to water (Das and Butler 1996). In the case of SAGD, however, steam may be lost to water. Thus, the use of hydrocarbon solvents seems more promising than using steam alone. Using gaseous solvent is better than liquid ones because it reduces the amount of solvent needed, results in higher rate of diffusion, and provides a high density contrast for the gravity drainage (Friedrich 2005).

At first, it seems that VAPEX is a much more efficient method and should be preferred over SAGD for heavy oil recovery. However, this is not completely true. There are some serious problems associated with VAPEX too. The main problem in VAPEX is low initial recovery because of the slow nature of diffusion process. When gases like propane and butane are used for VAPEX process, they may condense because of the high pressure in reservoir slowing down the diffusion even further. Another problem appears to be high asphaltene precipitation resulting in reduced permeability. This also implies lower recovery of bitumen, although of slightly upgraded quality. Thus, selecting the type of solvent and application conditions becomes a critical issue. Because of the problems associated with VAPEX, it was never used widely in the industry and is still not considered economically viable.

1.1.2 Introduction to Hot Solvent Process

The hot solvent technique for the recovery of heavy oil has been under consideration for several years now. This technique combines the heating effect of steam and the dilution effect of a solvent. This is not a new concept; it was introduced almost three decades ago. The idea of using solvent in the presence of steam for heavy-oil recovery dates back the 1980s (Redford and McKay 1980; Shu and Hartman 1988). The method of recovering very viscous oil using superheated solvents was patented by Allen et al. (1984). They showed the effectiveness of superheated pentane in tar sand recovery. They introduced heat in the system by drilling the core used from the center and placing a heating rod in this inner bore. A numerical study was conducted by Tam et al. (1984) which evaluated the performance of injecting CO_2 with hot water and they found that the results were not promising. Palmgren and Edmunds (1995) tested the effects of

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injecting high temperature naptha instead of steam and found that recovery was improved by using naptha. However, this technique has not yet been fully tested in a field and efforts are underway to understand the physics involved in the process and to make it economically viable.

Several other researchers studied the performance of the steam injection process if some solvent is added in small proportions (Shu and Hartman 1988; Goite, Mamora and Ferguson 2001 etc.). To assess such heat-solvent hybrid processes, Frauenfeld, Jossy and Wang (2007) conducted experiments on sandpack models with various solvents and different well configurations and different ways of heating the system. They found that the amount of solvent needed in a thermal VAPEX process was much less than that needed in a normal VAPEX process for the same amount of oil recovery. Zhao et al. (2005) conducted lab experiments and numerical simulations for a variant of this technique: the Steam Alternating Solvent (SAS) process. They found that the energy requirements were reduced by 47% when a solvent was used alternatively with steam, whereas the recovery increased. Asphaltene precipitation was also observed in the experiment. A history match was done for temperature profiles and production rates using a thermal reservoir simulator. Further, Rezaei and Chatzis (2007) conducted warm VAPEX experiments using a rectangular packed model saturated with cold lake bitumen. Superheated pentane vapours were injected and the recovery was found to be promising. It was also found that the produced live oil contained as much as 62% of solvent by weight. Currently, several commercial field scale projects are underway to investigate the performance of SAGD in presence of solvents

(Edmunds et al. 2009). Thus it was established that this technique has a great potential in terms of combining the heat and mass transfer effect to yield a more efficient process as compared to SAGD or VAPEX alone. Further investigations have been done to identify optimum conditions and governing phenomenon for such processes, but so far, the findings have been very limited. Some researchers have indicated that it is preferable that the solvent be in a gaseous phase because it reduces the amount of solvent needed, gives a higher rate of diffusion and a higher density contrast for gravity drainage (Friedrich 2005). Frauenfeld et al. (2007) conducted experiments and numerical simulations for hybrid solvent process and found that there is an optimum solvent concentration for such a process, and determined the optimum concentration of propane and butane when used with steam. Rezaei et al. (2010) noted that the best results for heavy oil recovery are seen when solvent temperature during the experiment is slightly higher than the solvent saturation temperature. As the temperature increases further, the recovery decreases. Govind et al. (2008) also conducted a numerical simulation work on Expanding Solvent – SAGD (ES-SAGD) and concluded that the addition of solvent accelerates production significantly and reduces the Steam-Oil Ratio (SOR) and thus, improves the energy efficiency of the process. They also said that at higher operating pressure, butane seems like an optimum solvent because of a high vapour pressure value. Dehghan et al. (2010) conducted cold solvent experiments in micromodels and concluded that asphaltene precipitation appears to increase the recovery of heavy oil.

Numerical simulation of this process can give valuable insights about the associated physics and can help in predicting the overall impact of various parameters on oil recovery. However, it is very complicated because of the composition changes happening along with heat transfer, and it is made even more complex because of asphaltene precipitation and its effect on the overall dynamics of the process. Several conceptual models are available in the literature for asphaltene precipitation and deposition modeling. Wang et al. (1999) developed a 1-D model for deposition of paraffin and asphaltene in porous media and matched the model with experimental data. Later, this model was incorporated into commercial simulators and has been used by researchers to characterize asphaltene precipitation in the case of compositional reservoirs under various production strategies (Figuera et al. 2010). But in the absence of accurate compositional and asphaltene deposition related data, these strategies are not used extensively. Whether asphaltene precipitation is good for recovery is also uncertain (Haghighat and Maini 2008). Recently, Peterson et al (2010) presented a numerical simulation based attempt to optimize solvent addition to a SAGD process in a highly porous and permeable sandstone. They stated that the problem has many variables and is non-linear in nature, making it hard to find an optimum steam-solvent process. Al-Murayri et al. (2011) also performed a simulation study to see the impact of using non-condensable gases on SAGD performance and found that methane co-injection with steam was actually not beneficial.

1.1.3 Popular Variants of Hot Solvent Process

Variations of this technique were studied by various researchers. One such variant was named Expanding Solvent-SAGD (ES-SAGD). In this technique, a solvent is injected in low quantities along with steam and solvent was chosen such that it would evaporate and condense at the same conditions as water under the prevailing reservoir pressure and temperature (Nasr et al. 2003). A low pressure ES-SAGD process was also tested experimentally and numerically in which the pressure of the system was maintained at 1500 kPa (Ivory et al. 2008). Another variant named N-Solv was introduced and patented by Nenniger and Nenniger (2005). In this technique, heated solvent vapours are injected into the bitumen zone where solvent condenses and enhances oil recovery by transferring latent heat to the oil and by diffusing into the oil. Apart from these two popular variants, other researchers have come up with slight variations too and have discussed the applicability of their techniques for specific cases. For example, Al Bahlani and Babadagli (2009) introduced Steam-Over-Solvent Injection in Fractured Reservoirs (SOS-FR). From their experiments and simulations, they concluded that this technique is promising for naturally fractured heavy oil and bitumen reservoirs. In this technique, first steam is injected to heat and produce oil by thermal expansion, then solvent is injected to produce oil by viscosity reduction, and finally steam is injected again to retrieve solvent and additional oil.

1.1.4 Recent Field Applications

Hot solvent injection is finally being tried in the field through pilot projects. At least two such examples have been published recently for Albertan fields. In one of these, a non-condensable gas was co-injected with steam to aid the heavy oil recovery in Hangingstone project of Japan Canada Oil Sands Limited (JACOS 2009; Wang 2011). The other example is from a proposed pilot project of Laricina Energy in Grosmont carbonates in Alberta (Solanki et al. 2011). In this project, solvent injection will be done after steam has already been injected in the reservoir. Once the steam chamber is fully developed, a heavy solvent will be injected followed by propane. The pilot has already been constructed and will become operational in coming months. Recently, Jiang et al. (2010) also conducted one warm solvent soak experiment with butane for a Grosmont carbonate core, and achieved a 50% recovery while keeping the experimental conditions at 50°C temperature and 400 kPa pressure. These conditions mean that butane was in vapour phase (vapour pressure of butane at 50°C is about 500 kPa).

However, the physics associated with the process is still not understood very well.

1.2 Statement of the problem

As discussed above, SAGD is the most common in-situ recovery technique for heavy oil and bitumen in Alberta. It is a highly energy intensive process and requires huge amount of steam generation. In fact, many experts consider using Steam-to-Oil Ratio (SOR) as the indicator of the efficiency of a SAGD process. The SOR is defined as the volume of water needed to be converted to steam for producing a unit volume of oil. For most SAGD operations, SOR is in the range of 2 to 5. In fact a SOR of 2.5 is considered extremely good as per current industry standards. For other steam injection techniques, the SOR is even higher.

For example, a typical SOR for Cyclic Steam Stimulation (CSS) lies in the range of 5 to 8.

To produce such massive amounts of steam, fresh water is used in most cases and natural gas provides the energy required for converting water to steam. In the Jackfish project, Devon Energy uses saline water produced from sub-surface reservoirs for their SAGD operations and re-cycles this water resulting in minimal fresh water consumption (Devon ARL Corporation 2009). But such examples are few. Apart from continuous fresh water requirements, steam generation also involves significant amount of CO_2 production. Thus, the effect of SAGD operations on the environment is significant. Moreover, SAGD performance is not optimal in certain cases such as in thin formations and fractured reservoirs. By adding solvent to the recovery process, it is possible to reduce dependence on steam, and a lesser requirement of steam can have a favourable impact on the environment.

Apart from being more environmentally friendly, hot solvent technique is also promising from the perspective of oil recovery. Previous researches have shown that this technique can result in higher recoveries in certain cases as compared to the use of steam alone. Moreover, the solvent changes the composition of oil and precipitates the asphaltene particles. This causes an in-situ upgrading of heavy oil or bitumen. These reasons create the need for introducing solvents and develop a heat-solvent hybrid process which can operate more efficiently with a reduced environmental impact and higher oil recovery.

The lack of detailed analysis and research on hot solvent process was the main motivation behind this thesis and research. Although previous researchers have shown that recovery tends to improve with the incorporation of solvents in thermal recovery processes, the fundamental reasons for this improvement have not been studied in detail. Effect of temperature and pressure on the recovery has not been completely understood. Moreover very few experiments were done on original preserved cores. Unless this technique is tested extensively on real cores, it is hard to conclude that it is advantageous for field applications.

Hot solvent technique needs to be developed and mechanisms which dominate the effectiveness of the process need to be identified. Understanding the impact of factors like temperature, pressure, asphaltene precipitation and deposition will be critical if hot solvent technique is implemented in the field. For such a detailed analysis, experiments (both on ideal pore geometries and real cores), visualization (both 2- and 3-dimensional) and compositional simulations are required. A big challenge in experimentation is to be able to simulate sub-surface reservoir conditions in terms of temperature and pressure. Thus, means for pressure and temperature control are needed. Another challenge for both core experiments and visualization is to saturate the models with very heavy oil, and to deal with the problems posed by heavy oil during experimentation.

Numerical simulation is also a difficult task because it involves modeling heavy oil and its change in composition due to exposure to solvents. Furthermore, numerical simulations need to incorporate asphaltene precipitation and deposition modeling to be able to predict the effect of asphaltene on dynamics of the process.

In addition, data from all such analyses needs to be analyzed to develop a qualitative and quantitative understanding of the process. This would provide the ability to optimize the process by maximizing recovery and using less energy input (both by using less steam and less solvent).

1.3 Objectives of the Study

The objective of the current work was to simulate the history of an element of rock that is exposed to solvent front, without having to construct and operate a full-up 3D physical model. Key to this is controlling the amount of solvent that can condense on or in the core, by thermodynamic means.

Thus, this project aimed to assess the performance of heated hydrocarbon solvent vapours for recovery of heavy oil under a fixed pressure (typical reservoir pressure for shallow Albertan fields) and quantify the expected amount of asphaltene precipitation for each experiment. The solvents used were propane and butane for gaseous solvent experiments. Liquid solvents (pentane, heptane, decane) were used in the visualization experiments. The heavy oil used was from the Lloydminster area and the bitumen used was from an Albertan field. The recovery factor (or ultimate recovery) was analyzed for the cases where a pure solvent is in contact with heavy oil/bitumen in a heated rock. In other words, all experiments were conducted with pure solvents (selection of propane and butane) and no steam, with the heating of the samples done by a mechanical convection oven. The samples were kept soaked in the solvent (and not in a regular injection-production scheme). The samples were of three kinds – glass beads saturated with heavy oil or bitumen, sandstone cores saturated with heavy oil and original carbonate cores saturated with bitumen. It should be noted that there is only one example in literature where an original carbonate core was tested for recovery using hot solvents (Jiang et al. 2010). In fact, at the initiation of this research, there were no examples of the use of hot solvent technique for recovering bitumen from carbonate cores. The main purpose in these experiments was to observe the sensitivity of the process to pressure and temperature, which critically influences the phase behaviour of the solvent and consequently, asphaltene precipitation and ultimate recovery.

Subsequently, mechanics of the hot solvent process was understood in much more detail than before and the effect of parameters such as permeability, capillary pressure, gravity and asphaltene precipitation on the overall recovery was investigated in addition to the effect of temperature and pressure. Visual experiments and numerical simulation helped to understand asphaltene flocculation and deposition and their effect on recovery in more detail. Another achievement was to come up with an optimum operating temperature of the system during a hot solvent process.

1.4 Structure of the thesis

This is a mixed format thesis, and its chapters are parts of various papers which are either published, under review or to be submitted soon. During the course of this study, several papers were published in both conferences and journals and also presented in conference proceedings:

The contents of this chapter were published in various papers during this research. These papers are enlisted in section 1.4.

1. Pathak, V., Babadagli, T. and Edmunds, N.R. 2010. Hot Solvent Injection for Heavy Oil/Bitumen Recovery: An Experimental Investigation. Paper SPE 137440 presented at 2010 SPE Canadian Unconventional Resources and International Petroleum Conference, Calgary, AB, Canada, 19-21 October.
2. Pathak, V., Babadagli, T. and Edmunds, N.R. 2011a. Heavy oil and bitumen recovery by hot solvent injection. *Journal of Petroleum Science and Engineering*. DOI: 10.1016/j.petrol.2011.08.002
   (This paper is in press)
3. Pathak, V., Babadagli, T. and Edmunds, N.R. 2011b. Mechanics of Heavy Oil and Bitumen Recovery by Hot Solvent Injection. Paper SPE 144546 presented at the SPE Western North American Regional Meeting, Anchorage, AK, USA, 7-11 May.

   (A version of this paper has been submitted to a peer reviewed journal and is currently under review)

4. Pathak, V. 2011. Heavy Oil and Bitumen Recovery by Hot Solvent Injection: An Experimental and Computational Investigation. (Presentation only) SPE Canada Regional Student Paper Contest, Regina, SK, 15 June. (The presentation won the first prize in Masters' division and was thus selected for the international competition (SPE International Student Paper Contest to be held at 2011 SPE Annual Technical Conference and Exhibition, Denver, 30 October – 2 November)

5. Pathak, V. 2011. Heavy Oil and Bitumen Recovery by Hot Solvent Injection: An Experimental and Computational Investigation. Selected for presentation at the SPE International Student Paper Contest at the SPE Annual Technical Conference and Exhibition, Denver, CO, USA, 30 October -2 November.
6. Pathak, V., Babadagli, T. and Edmunds, N.R. 2011. Bitumen Extraction Using Hot-Solvent Soaking in Grosmont Carbonates.

(This paper highlights the last part of this study and will be submitted to a peer reviewed journal in next few weeks)

Chapter 2 comprises of parts of the second and the third papers published during this research (Pathak et al. 2011a; 2011b). It discusses the experimental setup design and procedures for recording data. It also discusses the initial observations from the nineteen glass beads experiments done with heavy oil and two glass beads experiments done with bitumen, and an analysis of results.

Chapter 3 contains parts of the data published in the second and the third papers (Pathak et al. 2011a; 2011b). It discusses the four experiments done using sandstone cores and the observations.

Chapter 4 contains parts of the data published in the third paper during this study (Pathak et al. 2011b). It discusses visualization experiments conducted to further support the conclusions from the previous chapters. 2-D visualization was done using plexiglass made Hele-Shaw models of different sizes.

Chapter 5 is a section of the third paper published during this research (Pathak et al. 2011b). It describes the computations performed to study the hot solvent process. Compositional simulation was performed on 2-D reservoir models using a commercial simulator, ECLIPSE 300.

Chapter 6 discusses 3 hot-solvent experiments conducted for original carbonate cores from an Alberta formation. It will be published in near future as the sixth paper during this research once confidentiality clearance is obtained from sponsors.

Chapter 7 contains the overall conclusions from this study, contributions and recommendations for future research in this field.

2. HEAVY OIL AND BITUMEN RECOVERY BY HOT SOLVENT INJECTION: GLASS BEADS EXPERIMENTS

2.1 Overview

The hot solvent process is a variant of the VAPEX process with the difference being the incorporation of temperature. Hence, it is a complex process involving both heat transfer (transfer of sensible heat to the oil) and mass transfer (of lighter components into the oil phase). As an example, when light solvents are added to steam in SAGD, the more-volatile solvent forms a vapour zone between the steam front and the solvent condensation zone (**Figure 2-1**). Oil is substantially drained by the time (if ever) the steam reaches a given point. Before the solvent front reaches a given point, the rock will have been pre-warmed by thermal conduction. It is believed that the amount of solvent which condenses on the sample can be controlled, and thus the degree of viscosity reduction and 'upgrading' of the original oil can also be controlled. This chapter discusses the initial efforts to determine which parameters affect the degree of solvent based upgrading.

At the onset of this research, it was decided to start the work with glass beads experiments and based on the observations, move towards core experiments. The reason behind this was that glass beads are much cheaper and till the time a certain workflow is established, it is better to try the cheaper option. Moreover, glass beads packed model can represent porous media reasonably well, giving credence to this method. This chapter describes the experimental setup for the glass beads experiments and the considerations that went behind the design of

The contents of this chapter have been published in two papers: Pathak, V., Babadagli, T. and Edmunds, N.R. 2011. Heavy oil and bitumen recovery by hot solvent injection. Journal of Petroleum Science and Engineering (in press), and, Pathak, V., Babadagli, T. and Edmunds, N.R. 2011. Mechanics of Heavy Oil and Bitumen Recovery by Hot Solvent Injection. Paper SPE 144546 presented at the SPE Western North American Regional Meeting, Anchorage, AK, U.S.A.

setup. All the experiments were solvent soak experiments, i.e. glass beads samples were prepared by saturating glass beads with heavy oil or bitumen and were kept soaked to solvent vapours for an extended duration of time. During this time, the system was left in equilibrium at constant pressure and temperature and all valves were kept closed. So there was no continuous injection and production. At the end of the soaking time, production valve was opened and production was taken out into an oil collection system. The collected oil was analyzed and the results were presented. In this chapter, the effect of pressure and temperature on the recovery is shown and an empirical correlation was generated. The amount of asphaltene left in the sample was also quantified for each case.

2.2 Experimental Details

The details of the experiments for this work were as follows:

2.2.1 Setup

The special considerations for this study were:

- As a constant temperature was required for the experiment (higher than the boiling temperature of the solvent), two heating options were tried. The first check was done with a hot water bath with core holder sitting in it. The thermocouple readings from the hot water bath showed fluctuations and so water bath was not used. A mechanical convection oven was also tested as the medium for experiments. The oven was found to keep the entire system at a constant temperature, and thus, it was chosen for the experiments.

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- The sample was to remain exposed to solvent vapours for a sufficiently long time for diffusion and the products were to be drained into a sample collection system at the end. As the pressure was to be maintained by injecting the gas at a constant pressure, a cylindrical pressure vessel was designed. The vessel was capable of handling samples up to 30 cm in height to have a meaningful gravity effect. The gas was to be drained only from the production end along with the diluted oil at the end. Therefore, the gas would be at the same temperature as the oven.

The experimental setup is shown in **Figure 2-2**. The set-up consisted of a cylinder to house the saturated core or the glass beads sample. The largest sample which the cylinder could fit was 5cm in diameter and 30cm in length. This gave us a chance to explore the effect of gravity by changing the height of the sample. The cylinder was placed inside an oven and a thermocouple and a pressure transducer were installed at the center of the cylinder. Hydrocarbon gases were injected using high pressure gas cylinders and the produced oil was collected in a sealed sample collection system. The hydrocarbon gases were not recovered and vented out through fumehood at the end of each experiment. **Figures 2-3** to **2-6** show the different components of the experimental setup: the oven, the cylinder, sample collection system and gas cylinder.

Experiments were conducted on glass beads (500 micron diameter or 2400 micron diameter) samples mixed with heavy oil obtained from the Lloydminster area. Porosities, i.e. the original oil in-place in pores, were typically in the range of 30-

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40% of the total volume. The glass beads were selected to represent the porous media as it is easier to control the capillary diameter with uniform sized glass. It also allowed us to understand the effect of gravity alone without worrying about capillary pressure changes due to changes in the capillary diameter. A wire mesh basket was designed for holding the glass beads-heavy oil mixture. The mesh selected was finer than the glass beads. The length of the basket was 30cm and this gave the option of testing various lengths of the sample.

2.2.2 Procedure

In all the experiments, a metal funnel was placed in the cylinder to direct the flow of the diluted oil towards the exit. Once the setup was tested for leakages, the oven was started and the system was left to equilibrate overnight. This was done to ensure steady state condition with a constant temperature. The temperature and pressure were constantly monitored using a thermocouple and a pressure transducer mounted at the center of the cylinder. The data was logged using an acquisition system.

After a constant temperature was ensured, the solvent gas was injected in a quantity required to have a pressure around 1500 kPa inside the cylinder. The exit valve was kept closed so that the gas would heat up and the sample was left exposed to the gas for a long time (in the order of several hours, depending on sample size and type), which is termed as soaking time. For glass beads samples, it was decided to have a soaking time from 4-12 hours depending upon the volume of oil being used in the experiment. Later, the initial experiments showed

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that this estimate of soaking time for glass beads experiments was quite reasonable. After that, the exit valve was opened and the diluted oil was collected in the sample collection system. The gas was vented to fumehood and the oil was taken for analysis. Care was taken to drain the produced oil completely from all the piping. The produced oil was analyzed for asphaltene content, refractive index, viscosity, and in some cases, for composition.

2.2.3 Heavy Oil and Bitumen Properties

The oil used in most of the experiments was a heavy oil from the Lloydminster area in Alberta with no light components (C6 and lighter). Its properties are given in **Table 2-1**. **Figure 2-7** illustrates the phase plot for this oil showing that it is dead oil, which is also obvious from the composition. The oil had no components lighter than C7, and the fingerprint plot in **Figure 2-8** implies that it contains mostly the components of C30 or higher. These plots are generated based on several assumptions and should be used only to get an idea of the nature of fluid. The viscosity of the oil was measured to be around 9,000 cP at 25°C and the specific gravity was calculated as 0.96. The asphaltene content, as measured by excess solvent-filter paper method, was about 14.6% by weight.

Two experiments were also conducted with an Alberta bitumen sample. Its properties are listed in **Table 2-2**. The bitumen was very viscous and was produced during a field scale cold solvent injection process (Edmunds et al., 2009) and had no components lighter than C9.

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2.3 Results

Results for all the glass beads experiments conducted with heavy oil are presented in **Table 2-3** and results for the two experiments conducted with bitumen are presented in **Table 2-4**. In general, the recovery was observed to decrease with increasing pressure keeping all other parameters constant as can be seen from experiments 3, 4 and 5 in **Table 2-3**. Experiments 9 and 10 also showed the same behaviour. Temperature was also observed to adversely affect the recovery. Asphaltene content of produced oil is directly related to the weight percentage of original oil left over as asphaltene precipitates in the porous media. In general, asphaltene content and viscosity of oil produced with butane as a solvent was observed to be lesser than those of the oil produced with propane as a solvent. Recovery was also higher when butane was used as solvent as can be seen from experiments 1 and 2 in **Table 2-4** for bitumen. Detailed analysis of the results is provided in the next section.

2.4 Analysis of Results

2.4.1 Effect of Temperature and Pressure on Recovery

Various glass-beads experiments showed recovery varying from 48% to 95% (Table 2-3). Only the overall recovery factors were recorded and not the production rates. The experiments did not involve continuous injection-production so there was no continuous recording of production rates. The recovery was found to be highly dependent on the temperature. The recovery was less when the temperature was much higher than the saturation temperature. This is in

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accordance with the Raoult's law of partial pressures. Raoult's law states that if the components of a solution are in equilibrium, then the total vapour pressure (P_{total}) is given by:

$$P_{total} = x_A P^*_A + x_B P^*_B \tag{1}$$

Where x_A and x_B are the mole fractions of components 'A' and 'B' in liquid phase, and P^*_A and P^*_B are the vapour pressures of pure component A (propane or butane in these experiments) and pure component B (tested heavy oil). The tested heavy oil had no light components, hence its vapour pressure can be assumed to be negligible. This means that equation (1) changes to,

$$P_{total} = x_A P^*_A \tag{2}$$

As (P_{total}) is constant, the quantity of solvent gas in liquid is inversely proportional to its saturation pressure at that temperature. Saturation pressure increases with temperature, making the value of x_A smaller. Thus, the solution will have very little quantity of solvent and the dilution effect of the solvent will be minimal. As a result of this, recovery will be less. Therefore, after testing higher temperatures, it was decided to test temperatures in the range of the saturation temperature of the solvent gases. However, it was also seen that recovery was lower for the cases when the experimental temperature was lower than the saturation temperature. The best results were seen when the experimental temperature and pressure were very close to the solvent phase envelope, inside the vapour region, as shown in **Figure 2-9** through **Figure 2-12**. A sample calculation has been shown in section 2.5. It should also be noted that the

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experiments where the solvent is in liquid phase (all experiments to the left of the phase envelope) may give a good recovery, but at the expense of using a larger quantity of solvent and a slower diffusion process. The analysis here considers only those experiments in which solvents were present in vapour phase.

The recovery was also observed to be affected by pressure. For example, with an increase in pressure in experiments, 3, 4, and 5 at the same temperature, the recovery reduced. This can be attributed to the condensation of solvent in the system, which results in slower diffusion of the solvent into the heavy oil (note that the saturation pressure at 98^oC is about 1,500 kPa for butane). Contrary to our expectations, height of the sample did not seem to have a significant effect on recovery. This was later explained during numerical simulation study. It was found that the recovery decreased with the increase in the product of height of the sample, pressure of the system and the difference of the experimental temperature and saturation temperature. Figure 2-13 shows an increasing trend of recovery with a decrease in the product of pressure of the system and the difference of the experimental temperature and saturation temperature (sample height was not considered in this figure because the effect of height on recovery was small).

A curve fit was also attempted for recovery, assuming that the recovery is a function of sample height, operating temperature, operating pressure, and other factors which need to be explored further. Many functions were tested and the following two were observed to yield a best fit (based on the best coefficient of determination, R^2):

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$$Recovery = 0.244\,h - 11.903\,ln\,(T\text{-}T_{sat}) - 0.086\,P + 217.619 \quad (3)$$

and,

$$Recovery = 2.885(h/t) - 13.727\,ln\,(T\text{-}T_{sat}) - 0.0999\,P + 237.502 \quad (4)$$

Here,

Recovery = Oil recovery in % of original oil in place

h = Sample height in cm

T = Experimental temperature in °C

T_{sat} = Saturation temperature for the selected solvent at experimental pressure in °C

P = Experimental pressure in kPa

t = Soaking time in hours

The coefficients in equations (3) and (4) indicate that temperature and pressure have an adverse effect on recovery, while sample height effects positively. This is in accordance with above discussion. The last coefficient shows that there may be other factors dominant in the process too. The fit to the experimental data was shown in **Figure 2-14**. The experiments chosen to achieve the fit are only the ones where the solvent is present in vapor phase. Looking at the **Figure 2-14** and matching experiments in **Table 2-3**, experiments 6, 10, 11, 13 and 14 appear to be away from the general trend. These are also the experiments in which the

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produced oil contained a higher percentage of asphaltene. In other words, asphaltene precipitation in the porous media was lower than the other experiments. This infers that the role of asphaltene precipitation on recovery is critical and needs more attention as it directly impacts the drainage rate and phase entrapments (i.e, recovery). The constants in equations (3) and (4) imply that there could be other parameters affecting the recovery. A further investigation on other dominant mechanisms is presented in later chapters.

2.4.2 Effect of Gravity

Samples of different heights were chosen and sensitivity of recovery to the sample height was monitored. It was seen that the sample height affected the recovery very slightly, as can also be seen from equations (3) and (4). During all the experiments, prior to introducing solvent gas into the system, the system was checked for leaks by injecting air and then vacuuming the system. No oil was produced during this period, suggesting that gravity itself may not be a dominant factor for producing such heavy oil. Gravity will play a role when the heavy oil has been diluted by other factors like heat or mass transfer. Increasing the sample height just increases the volume of oil, and thus a longer period of time is needed to achieve the same amount of mass transfer as for a shorter sample. If the experiment is aborted without taking this factor into consideration, recovery may be smaller. The effect of gravity has been discussed in detail in chapter-5.

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2.4.3 Asphaltene Content of Produced Oil and Asphaltene Precipitation / Deposition

Asphaltene are defined as the n-heptane insoluble, toluene soluble components of heavy oil, bitumen or coal (Sirota 2005). These are the components which increase the viscosity of oil and are also undesirable because they deposit inside tubulars. During conventional VAPEX processes if paraffines are used as solvent, after a certain solvent concentration, asphaltene start to drop out as precipitates (at a constant pressure and temperature).

Asphaltene precipitation is a very important issue in heavy oil recovery by miscible methods and is still not fully explored. A general perception is that asphaltene precipitation is favourable for recovery as it reduces the oil viscosity and "upgrades" the oil. However, as the asphaltene get deposited on the pore throats, they adversely affect the permeability. Haghighat and Maini (2008) conducted experiments to investigate the effect of asphaltene precipitation on overall recovery. They found that when operating pressure was less than the vapor pressure of solvent, no asphaltene precipitation occurred because oil was not upgraded. For pressures higher than the vapour pressure of the solvent, the benefits and disadvantages of asphaltene precipitation almost negated each other. Johnson et al. (1975) tested the effectiveness of 25 solvents based on heavy oil viscosity reduction and amount of asphaltene precipitation. They indicated that solvents with higher aromatic content are likely to give low asphaltene precipitation. Beyond all these, asphaltene is a commercial product and is part of the oil. The ultimate target is to produce it rather than deposited in the reservoir.

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To measure the asphaltene content of produced oil and precipitation, a small quantity of the produced oil sample (4-5 gm) was mixed with a large quantity of n-heptane (40-50 times by weight), and left to stand for 2-3 days. Next, the mixture was filtered using an 11µ filter paper, and a vacuum pump was used to assist in increasing filtration rate. The system was covered with aluminum foil to minimize the evaporation losses during filtration. The schematic for the setup is shown in **Figure 2-15**. Then, the filter paper was removed carefully with all filtered asphaltene contained in it, and placed in an oven overnight to evaporate all the heptane. Weight of the dried filter paper with asphaltene gave the asphaltene content of the produced oil. The asphaltene contents of produced oils in various propane and butane experiments are shown in **Figure 2-16**. It shows that experiments with propane yielded diluted oil with asphaltene content higher than the oil obtained from butane experiments. This directly relates to the amount of asphaltene that was deposited from the original oil on the pores (**Figure 2-17**). The asphaltene content of the produced oil are given in **Table 2-3**.

A Dean Stark analysis was also done on the sample from experiment-9 and the value of asphaltene precipitation (in the sample after the experiment) was found to be comparable to the value measured using filter paper-excess solvent method (about 6%). The extraction for Dean Stark process was done in 2 stages, first with n-heptane and then with toluene. While the Dean Stark analysis is a more time consuming process (takes upto 10 days to have a reliable result), the filter paper-excess solvent method is a more practical approach to measure asphaltene content.

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2.4.4 Composition

It was expected that the solvent would diffuse into the heavy oil in experimental conditions and would "upgrade" the oil. This essentially involves a degree of change in composition and viscosity. However, all analyses were made after finishing the experiments and letting the system equilibrate to standard conditions. Under the standard conditions, all the solvent was expected to leave the liquid phase as the boiling temperatures of both propane and butane are very low under atmospheric pressure. To conform this, a Gas Chromatography-Mass Spectroscopy (GC-MS) measurement of oil produced was performed on two samples, (for propane and butane based experiments). No light fractions were seen in the oil after conducting the GC-MS analysis. Thus, the produced oil is not likely to contain any light hydrocarbons after leaving the system to atmospheric conditions. However, it must be kept in mind that GC-MS is not the most suitable technique for analyzing heavy oil samples as the amount of sample introduced into the instrument is very small (and is dissolved in toluene prior to injection) and thereby introduces a problem of detection of trace quantities of the light hydrocarbons. A headspace-GC technique involves an additional instrument which allows a much larger sample size to be heated. The hot headspace gases above the sample can be collected and then injected into GC. This kind of analysis will be done in future to confirm the findings of GC-MS.

2.4.5 Viscosity

The viscosity was found to reduce, as per expectations. It was observed that the reduction in viscosity of produced oil was more in case of butane, which

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corresponds with the lower asphaltene content of the oil produced with butane as solvent. To give an average value, propane reduced the viscosity by 2 to 3 times, whereas the viscosity reduction by butane was 6 to 7 times. This can be explained by evaluating the mass transfer involved with propane and butane. For example, in experiment-3, the temperature used was 98°C. At this pressure the saturation pressure of butane is about 1470 kPa. From equation (2), it corresponds to a butane mole fraction of 0.95 at equilibrium conditions. On the other hand, in experiment-11, the temperature used was 52°C. At this pressure the saturation pressure of propane is 1790 kPa. From equation (2), it corresponds to a propane mole fraction of 0.84 at equilibrium conditions. Thus, the mole fraction of butane in the oil is higher under experimental conditions. Moreover, the molecular mass of butane is about 1.25 times higher than that of propane. This means that the mass of butane dissolved in the heavy oil is further greater than mass of propane dissolved in heavy oil. This effect is likely to contribute towards the higher viscosity reduction caused by butane. Moreover, butane experiments are done at a higher temperature as compared to propane experiments, so as to maintain butane in vapour phase. This also contributes towards the higher viscosity reduction. Results for three samples tested for viscosity of oil produced at increasing temperatures are shown in **Figure 2-18**. For experiments with bitumen, butane reduced the viscosity from 22,000 cP to 8,000 cP whereas propane reduced the viscosity to only 16700 cP (all values at 60°C). The viscosity measurements were performed using a Brookfield viscometer along with a water bath (**Figure 2-19**)

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2.4.6 Refractive Index (RI)

The refractive index is a good indicator of the solvent concentration in oil and has been used in the past to predict the onset of asphaltene precipitation on addition of solvent to heavy oil (Buckley et al 1998). In our analysis, the refractive indices were measured for all samples using a digital refractometer at a constant temperature of 25°C. The refractive index of the sample and asphaltene content were found to be related and refractive index increased with asphaltene content (**Figure 2-20**). This relates well with the other data and is a direct indicator of the fact that a medium with higher asphaltene content will be a denser medium, and refractive index can be used, at least qualitatively, to compare between different oil samples for asphaltene content.

2.4.7 Flow Dynamics of the Process

Three possible factors affecting the recovery of heavy-oil or bitumen from sands were studied: pressure, temperature, and sample height. Their effects were clarified in this paper qualitatively and quantitatively (equations (3) and (4)). One critical issue is indirect effects of these three parameters. Pressure, temperature and solvent type used have direct influence on asphaltene precipitation. The blockage of pores by asphaltene particles, however, is indirectly controlled by sample height. As the process is dominated by gravity drainage, the thickness of the asphaltene deposition zone has to do with the sample height (or travel time of the particles through the sample). In almost all the experiments, asphaltene deposits were observed in the lower half of the sample after the experiments were finished. During the fluid flow, this deposit would have formed a lower

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permeability zone hindering the downwards flow of diluted oil. Note that this is a capillary holdup phenomenon; the height of which stays the same as the reservoir thickness increases. The results given in **Figures 2-9** through **2-12** show no specific trend even if only pressure and temperature are used (**Figures 2-9** and **2-10**) or sample height is included (**Figures 2-11** and **2-12**). This no-trend behaviour can be attributed to other factors indirectly impacting the recovery factor, and asphaltene precipitation is the more critical one. This effect needs further clarifications also supported by numerical and visual investigations. In succeeding chapters, this effect has been investigated in detail.

2.4.8 Extraction Rates

Understanding the factors affecting the extraction rate in a hot solvent injection is critical for upscaling such a technique to field scale. Several researchers studied this topic in detail and proposed correlations for predicting parameters like mass flux of solvent (Nenniger and Dunn 2008). Such an analysis was beyond the scope of this research, mainly because the experiments conducted were not continuous injection-production type experiments. However, it is believed that the parameters affecting the overall recovery (temperature, pressure, sample height, and asphaltene deposition – as discussed above) will also affect the production rate. Another parameter, which is crucial in predicting production rates, is the sample permeability. In fact, it was observed in the experiments that soaking time of a few hours was enough to drain significant amount of original oil from glass beads samples (permeability of the order of Darcies), whereas for Berea sandstone cores (permeability of the order of milliDarcies), much less oil was recovered

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even after a soaking time of up to 2 days. This will be shown in the next chapter. Moreover, lower permeability implies smaller pore throats and thereby higher capillary pressure, which can increase the possibility of blockage if there is some asphaltene deposition on the rock grain surface. This has also been discussed in the next chapters.

2.4.9 Effect of Permeability and Pore Size

Permeability directly affects the recovery according to Darcy’s law. However, an interesting observation was made during the glass beads experiments. When using a larger sized glass bead (which implies higher permeability) in experiments 18 and 19, the recovery was observed to decrease. This indicates that capillary forces play a dominant role in recovery. When glass beads are larger (and thus the pore radius is also larger), the capillary force gets smaller. When the analysis is done for extremely high permeability media, decrease in capillary pressure becomes a more significant factor than increase in permeability. A higher capillary pressure means higher rise of solvent in the medium due to capillary action and better recovery. This phenomenon has been discussed with the aid of numerical simulation in chapter 5.

2.4.10 Effect of Solvent Type

Solvent type did not seem to affect the recovery a lot, as long as the conditions were kept close to the saturation conditions of the used solvent, making sure that the solvent exists in gas phase. This means that if the hot solvent technique is used in the field, solvent choice should be based upon reservoir pressure and temperature. However, solvents differ in asphaltene flocculation properties. Asphaltene precipitation is higher in the case of lighter solvents. Additionally, the properties of asphaltene flocs in the case of different solvents can be significantly different. Two examples are shown in **Figure 2-21** and **2-22**. These flocs can have different adsorption and deposition properties. Furthermore, asphaltene deposition occurs at the interface of solvent and heavy oil as shown chapters 4 and 5. The thickness of this deposit depends on the type of solvent and the experimental conditions. In moderate and low permeability systems, this precipitation zone can be a hindrance to flow. This makes the process of asphaltene precipitation very complex.

2.5 Sample Calculation

Sample calculations for Experiments 10 and 11: Propane at 1500 psia pressure and different temperatures

Experiment 10:

$$P^*_{\mathrm{Pr}opane}(at\ \ 67°C) = 2438.09\ \ kPa$$

Vapour mole fraction of solvent,
ypropane = 1.00 (considering oil / bitumen to be completely non-volatile)

Liquid phase mole fraction of solvent,

$$x_{\mathrm{Pr}opane} = y_{propane}\frac{P_{total}}{P^*_{propane}} = 1*\frac{1500}{2438.09} = 0.615$$

Experiment 11:

$$P^*_{\mathrm{Pr}opane}(at\ \ 52°C) = 1789.67\ \ kPa$$

Vapour mole fraction of solvent,
ypropane = 1.00 (considering oil / bitumen to be completely non-volatile)

Liquid phase mole fraction of solvent,

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$$x_{\Pr opane} = y_{propane}\frac{P_{total}}{P^{*}_{propane}} = 1 * \frac{1500}{1789.67} = 0.838$$

Thus, because of a higher solvent concentration in experiment-11, a higher recovery can be expected.

Table 2-1: Properties of tested heavy oil (obtained from the Lloydminster area)

Property	Value
Density (at 25°C)	0.96 g/cc
Degree API	15
Viscosity (at 25°C)	9231 cP
C6+ Molecular weight	395 g/mol
Refractive Index	1.550
Asphaltene (% by weight)	14.6

Table 2-2: Properties of tested Alberta bitumen

Property	Value
Density (at 25°C)	1.033 g/cc
Degree API	7
Viscosity (at 60°C)	22030 cP
Refractive Index	1.592
Asphaltene (% by weight)	15

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Table 2-3: Summary of all glass beads experiments conducted with heavy oil

		Porous Media Details						Results		
Exp. No.	Solvent used	Type	Height (cm)	Diameter (cm)	Porosity (%)	Temp (°C)	Pressure (kPa)	Recovery (%)	Asphaltene content (weight %)	Approx Soaking Time (hrs)
1	Butane	Glass beads 500 µ	29	5	40	70	1030	55.6	5.7	4
2	Butane	Glass beads 500 µ	29	5	40	80	1030	52.6	6.5	4
3	Butane	Glass beads 500 µ	18	5	30	98	1400	94.5	6.7	6
4	Butane	Glass beads 500 µ	26	5	30	98	1500	72.1	11.3	12
5	Butane	Glass beads 500 µ	10	5	30	98	1600	62.3	Not measured	8
6	Butane	Glass beads 500 µ	17	5	30	112	1500	45	11.3	7
7	Butane	Glass beads 500 µ	17	5	30	108	1600	64.5	13.8	8
8	Propane	Glass beads 500 µ	29	5	40	90	1500	55.3	13.7	4
9	Propane	Glass beads 500 µ	15	5	40	85	1500	53.7	11.4	4
10	Propane	Glass beads 500 µ	17	5	40	67	1500	47.8	12.5	4
11	Propane	Glass beads 500 µ	17	5	30	52	1500	83.8	10.1	4
12	Propane	Glass beads 500 µ	17	5	30	54	1830	64.2	10.6	4
13	Propane	Glass beads 500 µ	23	5	30	53	1500	75.5	12.3	10
14	Propane	Glass beads 500 µ	27	5	30	53	1500	60.3	13.6	10
15	Propane	Glass beads 500 µ	20	5	30	52	1500	65.5	Not measured	6
16	Propane	Glass beads 500 µ	17	5	30	54	1650	43.3	10.8	8
17	Propane	Glass beads 500 µ	18	5	30	53	1450	74.6	12.7	8
18	Propane	Glass beads 2400 µ	19	5	30	52	1450	56.9	Not measured	8
19	Propane	Glass beads 2400 µ	15	5	30	54	1650	40.4	Not measured	7

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Table 2-4: Summary of glass beads experiments conducted with bitumen

		Porous Media Details						Results		
Exp. No.	**Solvent used**	**Type**	**Height (cm)**	**Diameter (cm)**	**Porosity (%)**	**Temp (°C)**	**Pressure (kPa)**	**Recovery (%)**	**Asphaltene content (weight %)**	**Approx Soaking Time (hrs)**
1	Butane	Glass beads 500 µ	15	5	30	98	1500	48.0	8.2	12
2	Propane	Glass beads 500 µ	13	5	30	56	1500	40.5	Not measured	12

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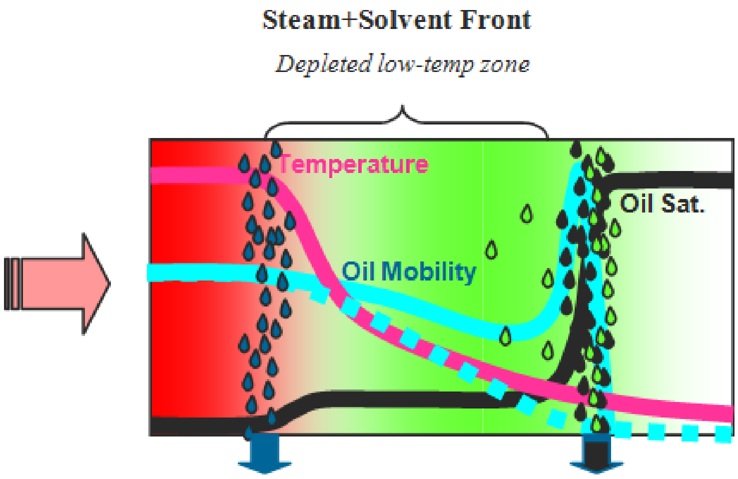

Figure 2-1: Schematic representation of heating and condensation zone during hot solvent injection

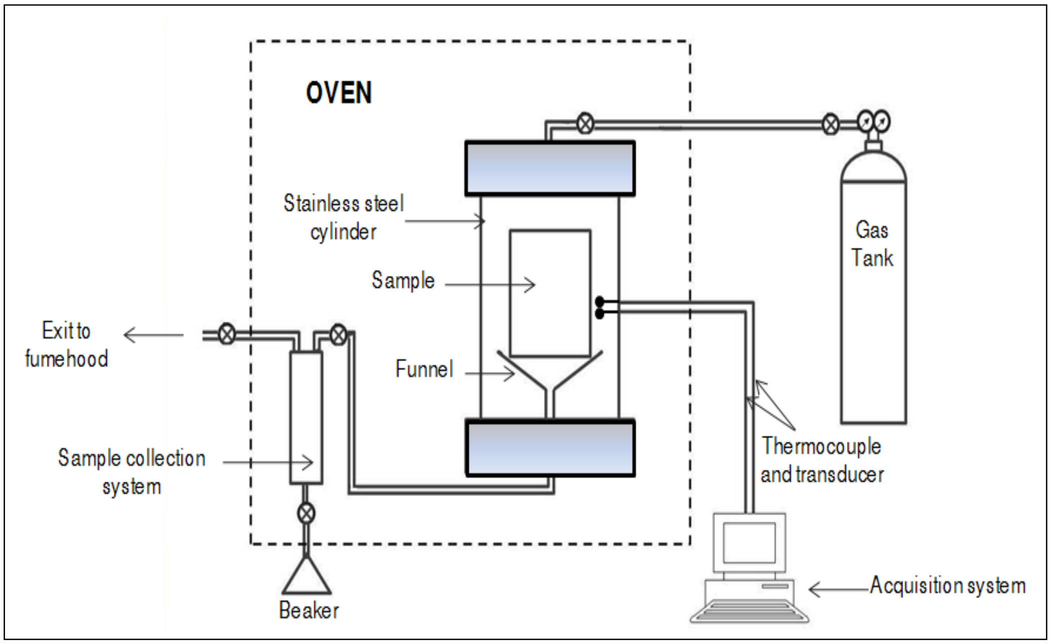

Figure 2-2: Schematic representation of the experimental set-up

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Figure 2-3: Oven used for experiments

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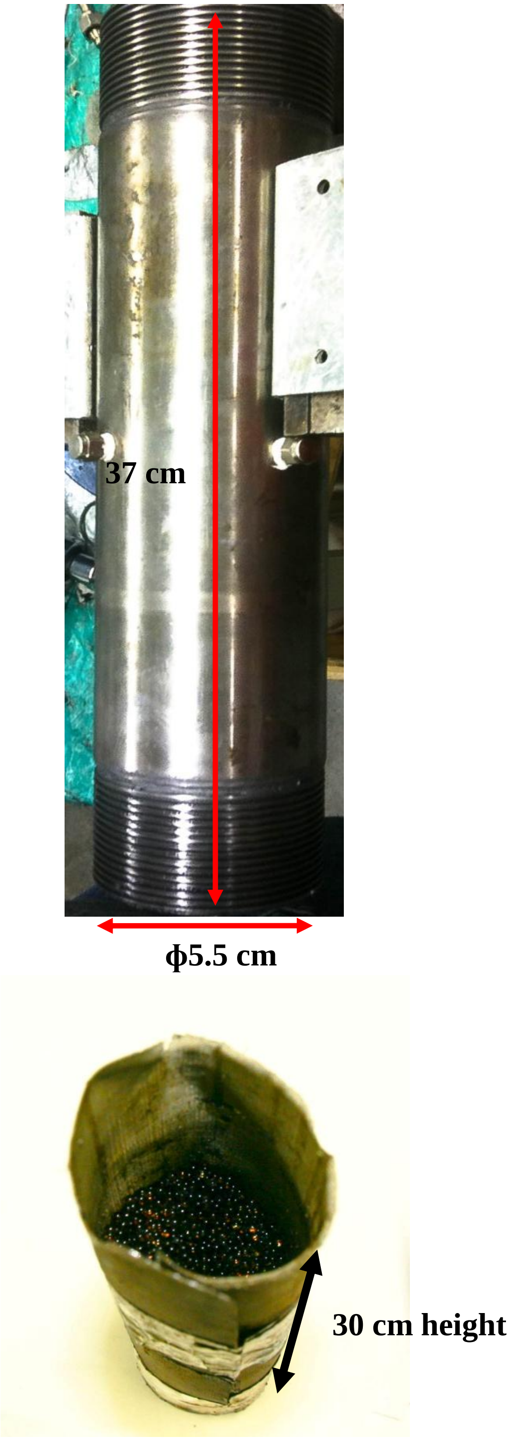

Figure 2-4: Cylinder (above) and mesh basket with saturated glass beads inside (below) used for glass beads experiments

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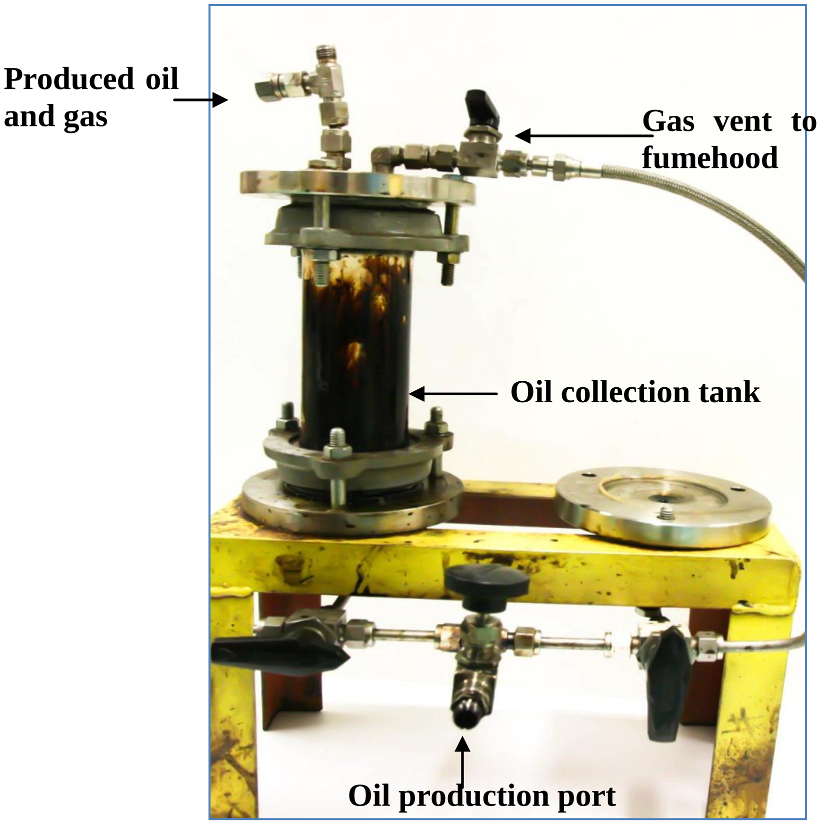

Figure 2-5: Oil collection system with chamber for holding oil

Figure 2-6: Hydrocarbon gas cylinder

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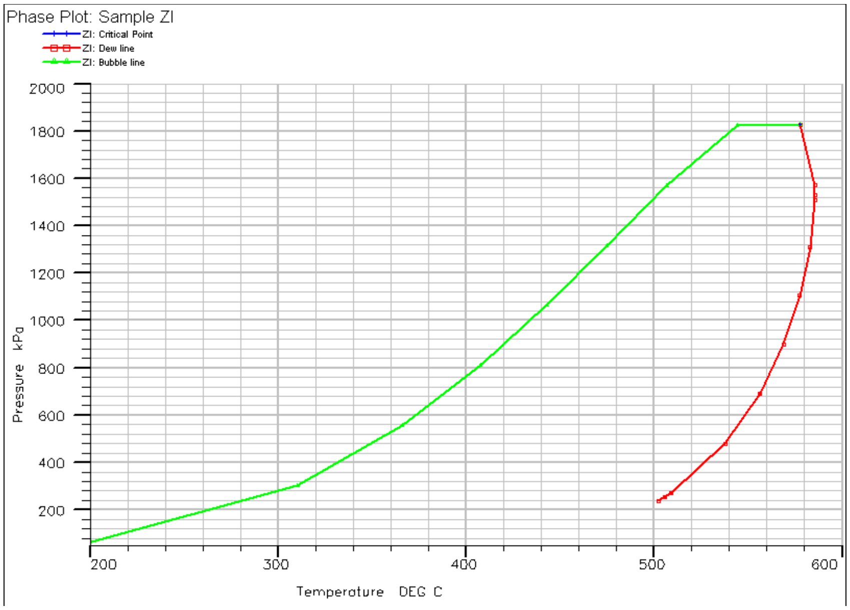

Figure 2-7: Phase plot of the dead oil used

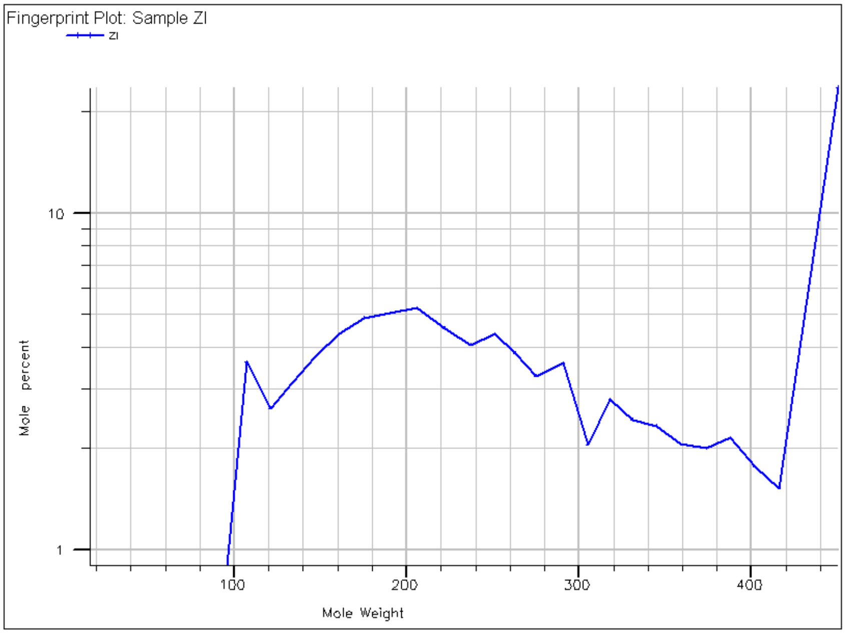

Figure 2-8: Fingerprint plot for the dead oil used

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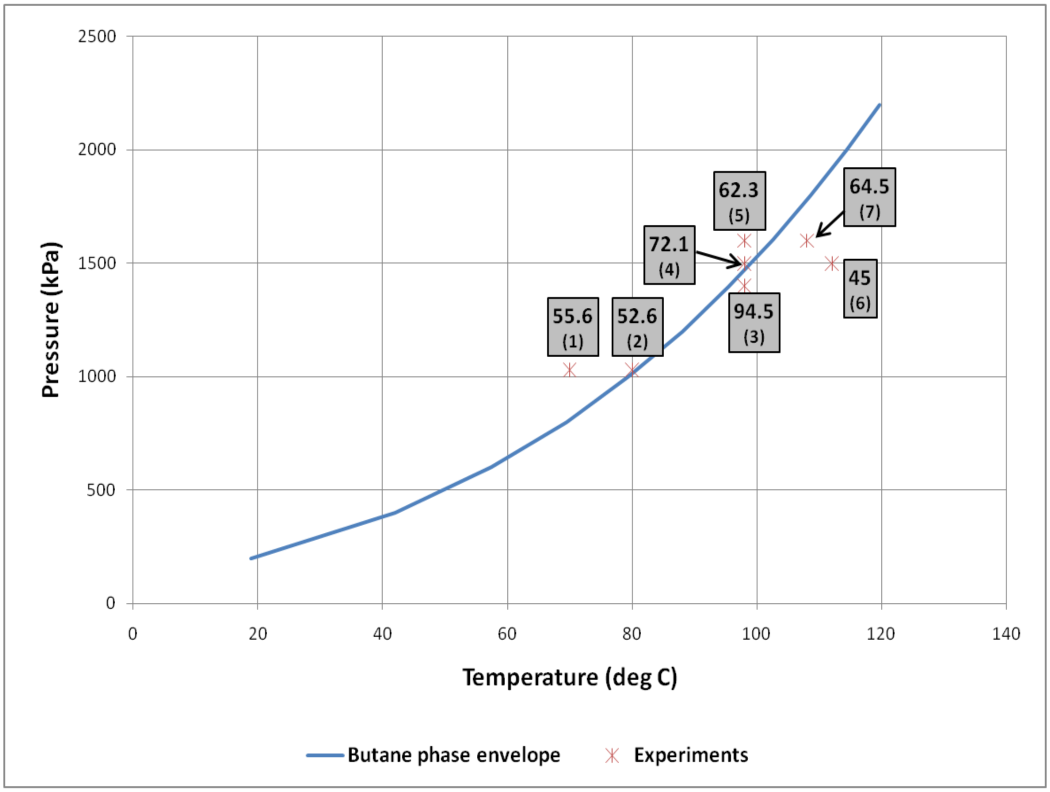

Figure 2-9: Results for butane experiments – Recovery

Phase envelope for butane with experimental pressure and temperature indicated by the red points. The numbers indicate the recovery for the corresponding experiment and the numbers in bracket indicate the experiment number, showing that recovery is higher if the experimental conditions are very slightly on the right of the phase envelope.

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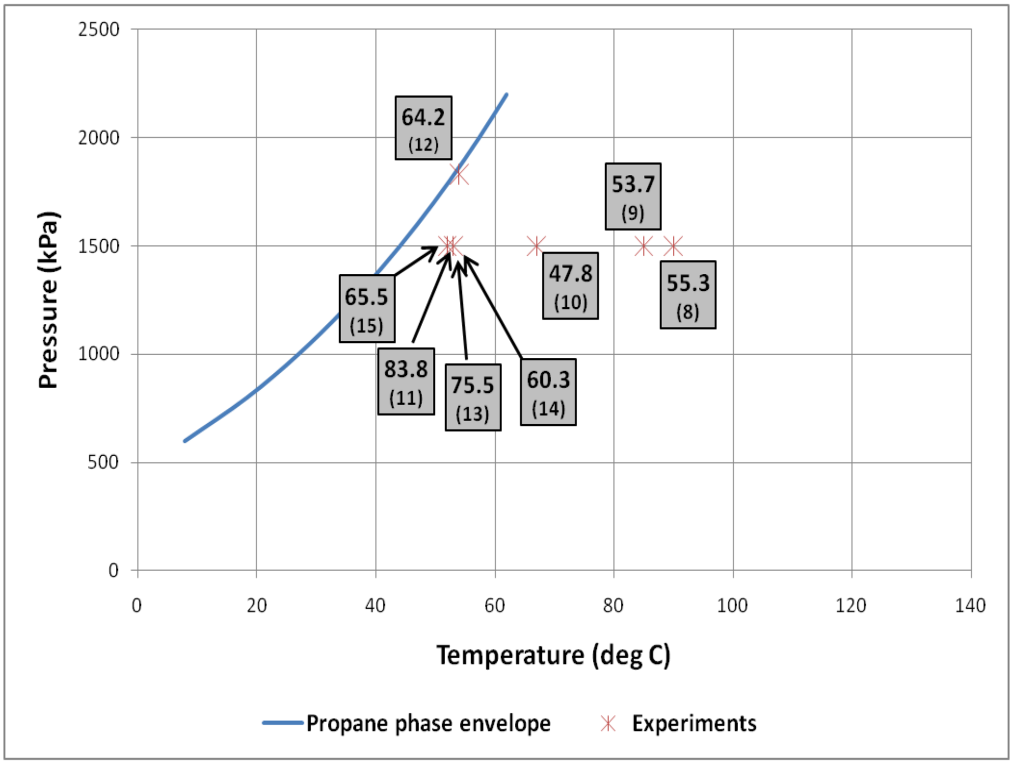

Figure 2-10: Results for propane experiments - Recovery

Phase envelope for propane with experimental pressure and temperature indicated by the red points. The numbers indicate the recovery for the corresponding experiment and the numbers in bracket indicate the experiment number, showing that recovery is higher if the experimental conditions are very slightly on the right of the phase envelope. Whereas, when the temperature is very high, the recovery falls.

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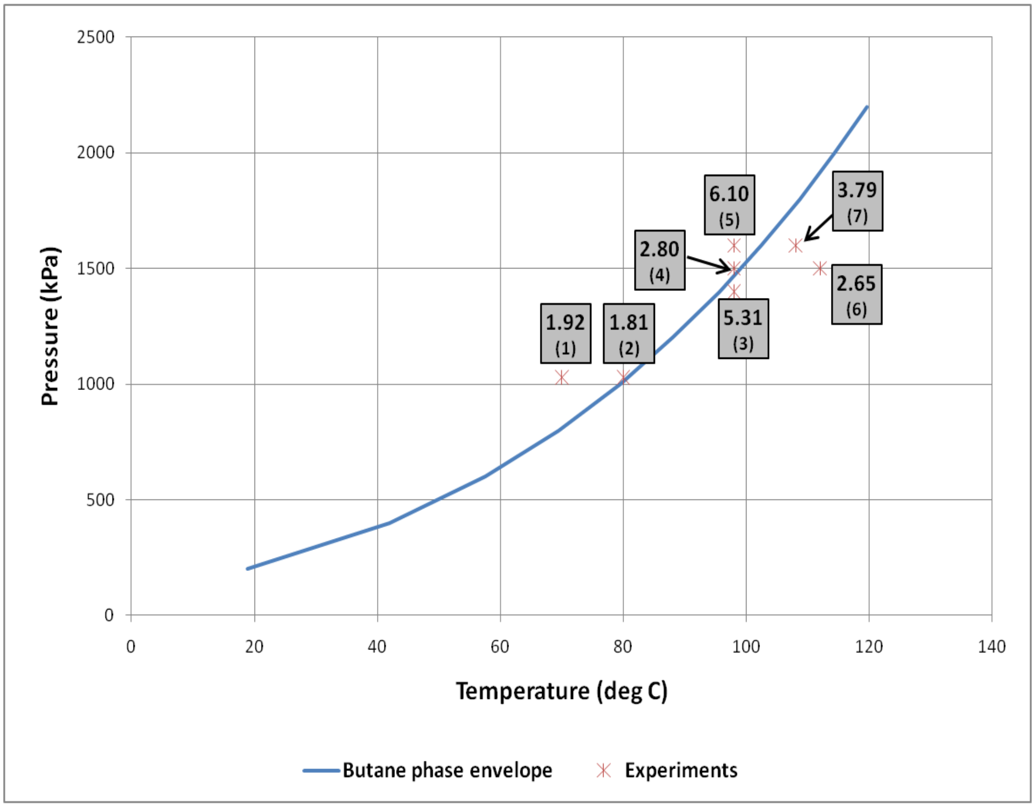

Figure 2-11: Results for butane experiments - Recovery height ratio

Phase envelope for butane with experimental pressure and temperature indicated by the red points. The numbers indicate the ratio of recovery for the corresponding experiment and sample height (in cm) giving a value of 4-6 for the best experiments. The numbers in bracket indicate the experiment number.

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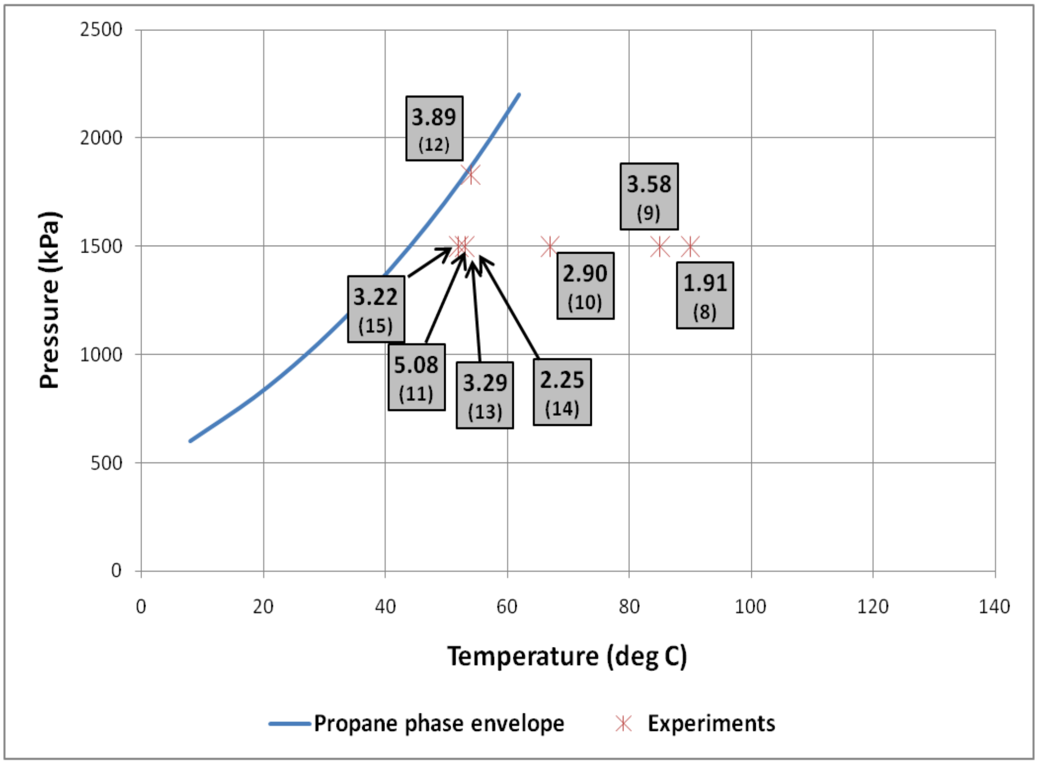

Figure 2-12: Results for propane experiments - Recovery height ratio

Phase envelope for propane with experimental pressure and temperature indicated by the red points. The numbers indicate the ratio of recovery for the corresponding experiment and sample height (in cm) also giving a value of 4-6 for the best experiments. The numbers in bracket indicate the experiment number.

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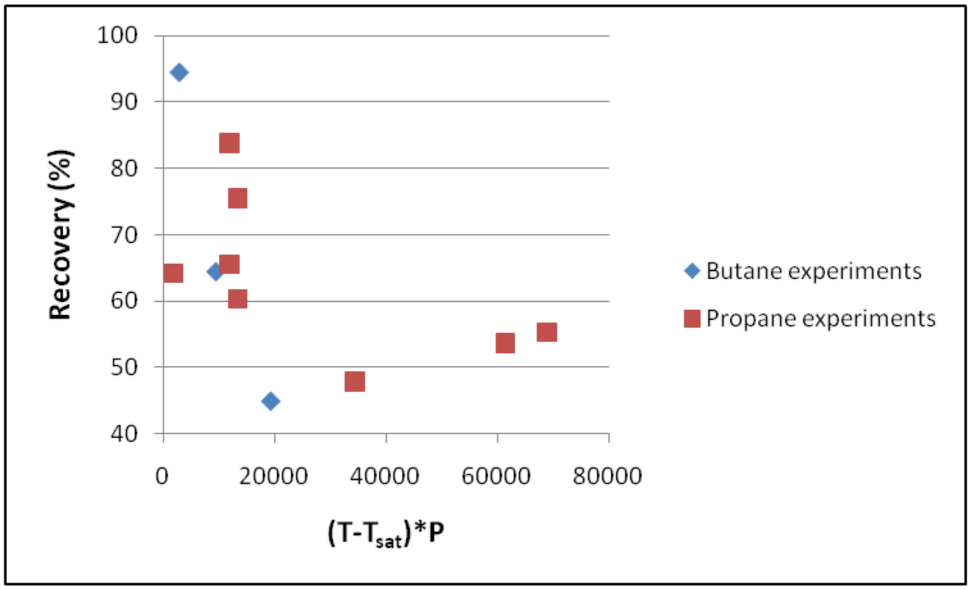

Figure 2-13: Recovery Vs product of experimental pressure and temperature in excess of solvent saturation temperature

Recovery decreases with increasing value of product of difference between experimental temperature and saturation temperature, and experimental pressure (for glass-beads experiments).

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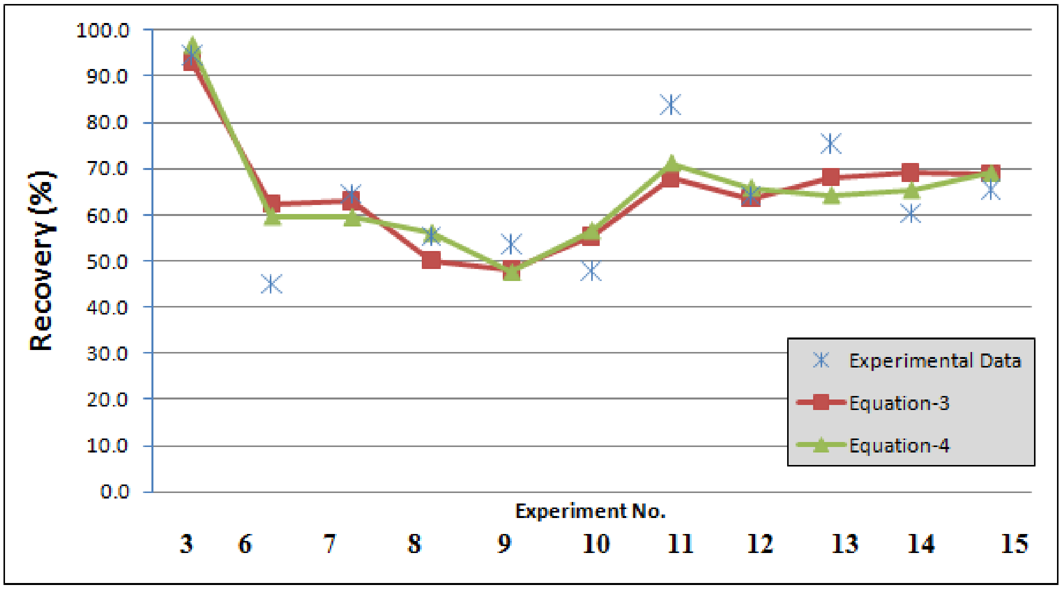

Figure 2-14: Curve fit for recovery as a function of sample height, experimental temperature and pressure

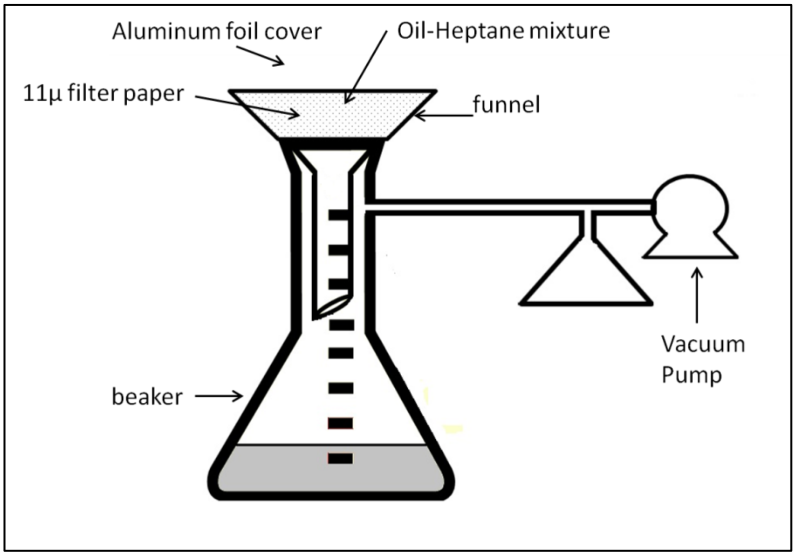

Figure 2-15: Setup for asphaltene measurement using filter paper and excess solvent

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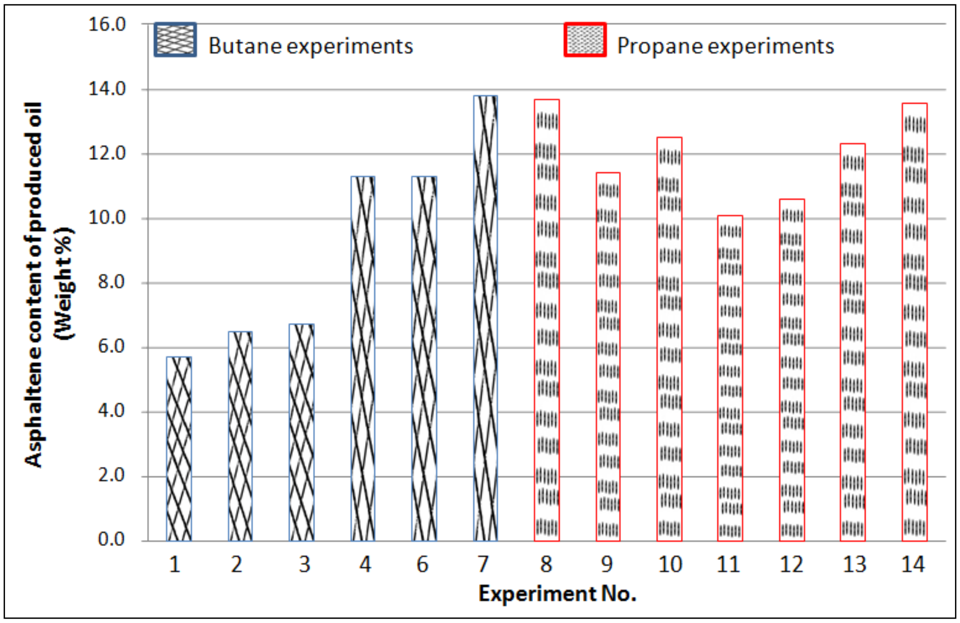

Figure 2-16: Results for asphaltene content in produced oil using filter paper and excess solvent for experiments given in Table 2-3

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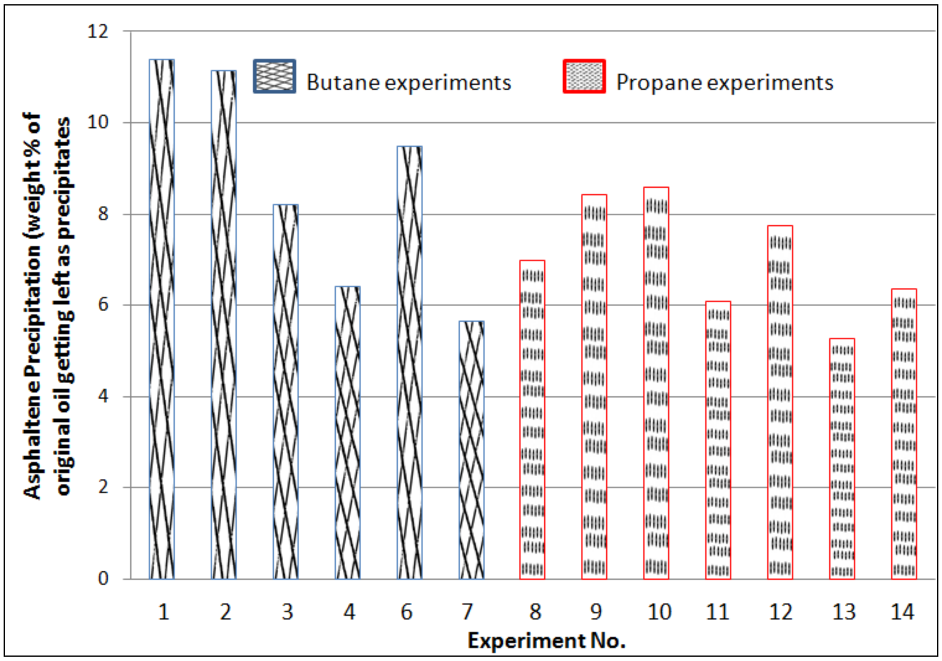

Figure 2-17: Results for asphaltene deposition on glass beads sample for experiments given in Table 2-3

Asphaltene deposition can be assumed to be equal to the weight % of original oil left as precipitates in the sample after the experiment. It can be calculated as: Asphaltene left in rock = asphaltene introduced in rock – asphaltene produced with produced oil

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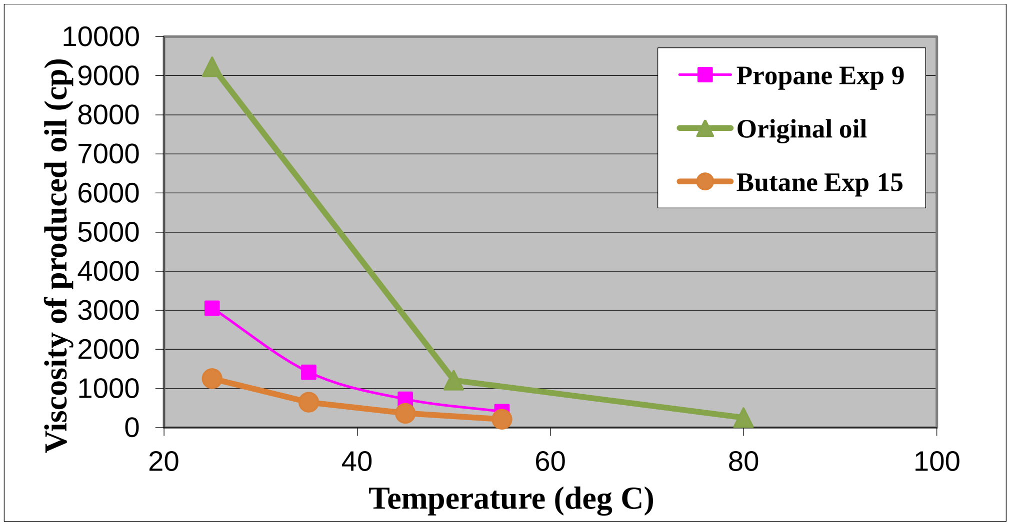

Figure 2-18: Change in viscosity with temperature for the tested heavy oil and produced oils with propane and butane

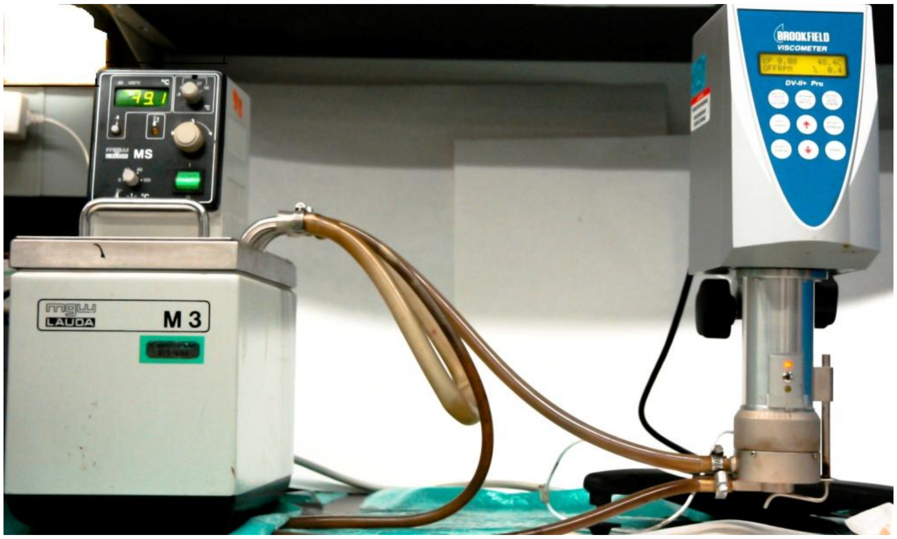

Figure 2-19: Setup for viscosity measurement: Brookfield viscometer and water bath

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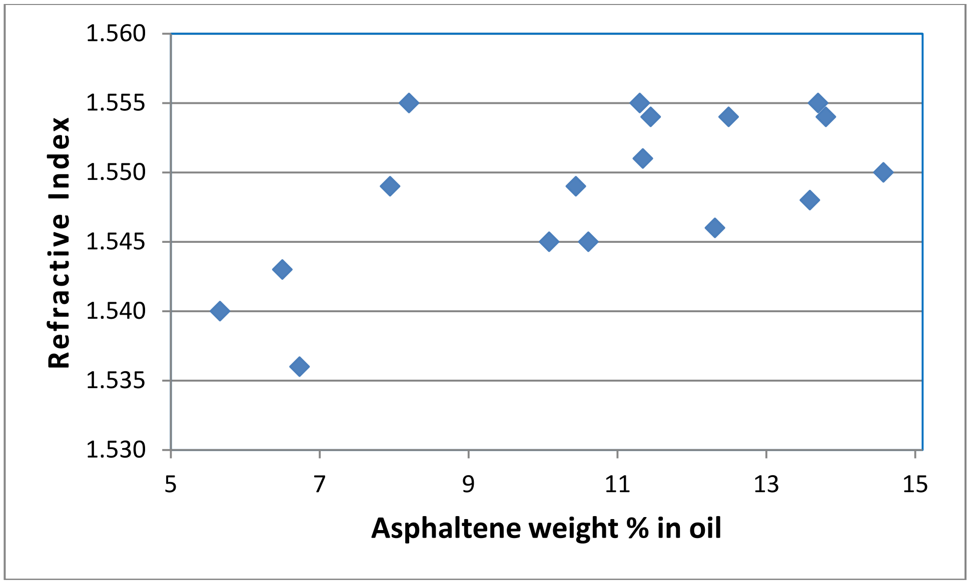

Figure 2-20: Change of refractive index with asphaltene content of produced oil

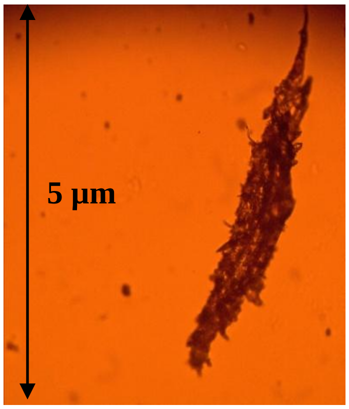

Figure 2-21: Asphaltene flocs as seen under microscope in oil produced during an experiment where propane was used as a solvent

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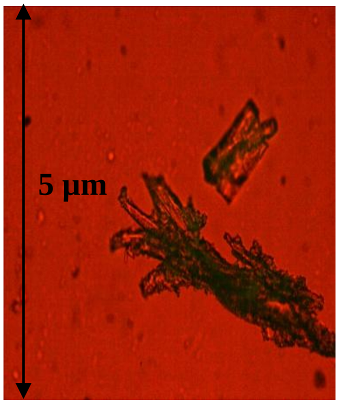

Figure 2-22: Asphaltene flocs as seen under microscope in oil produced during an experiment where butane was used as a solvent

3 SANDSTONE CORE EXPERIMENTS FOR HOT SOLVENT INJECTION

3.1 Overview

From the initial work, the basic idea of how to optimize the oil recovery was obtained. However, those experiments were conducted on glass beads samples, which are ideal in behaviour and have permeability in the order of several hundred Darcies. Hence, it is essential to test this technique on consolidated rocks (permeability in the order of millidarcies), and to observe if the findings are similar to what was obtained from the glass beads experiments given in the previous chapter.

This chapter discusses the experiments done with consolidated rocks. The first type of core tested was Berea sandstone. Several small cylindrical pieces of varying dimensions were cut from a big sandstone slab using appropriate drilling bits and core cutting system. These cores were already clean and were devoid of any fluid. Next, these cores were saturated with heavy oil, which was a very difficult task and is explained in later sections. After that, a similar methodology was followed as described in the previous chapter. The difference was that the duration of soaking of these cores was much more than the duration for the glass beads samples.

The observations made during these experiments are presented in this chapter along with discussion of results.

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3.2 Experimental Details

The experimental details for sandstone core experiments were as follows:

3.2.1 **Core**

Berea sandstone was selected as the rock for testing during this phase of the study because its properties are well defined in literature. The available Berea block was completely dry and devoid of any fluids, as it had been cut off an outcrop. 4 cylindrical pieces of varying dimensions were drilled from the block. A drilling machine was used for this purpose. A 5 cm drill bit was installed on the drilling machine and water was used as the drilling fluid. After drilling the cores, they were left in an oven for 2 days at 100°C to evaporate any water that may have remained due to the drilling process. All of these were 5 cm in diameter, and from 15-30 cm in height. The details of the cores have been provided in **Table 3-1**.

3.2.2 **Core Saturation**

All the cores were saturated with heavy oil (viscosity ~ 9000 cP). The setup for core saturation has been shown in **Figure 3-1**. Prior to starting saturation, cores were weighed and their dimensions were taken very carefully. The setup consisted of desiccator (a sealable enclosure) which was filled with heavy oil and cores were placed in it. Next, the desiccator was placed inside an oven at a constant temperature of 80°C. Temperature of the oven (80°C) is kept lower than the saturation temperature of the lightest hydrocarbon in the given heavy oil – heptane. The desiccator is also connected to vacuum. As heavy oil gets heated, it becomes mobile. Since the desiccator is sealed and connected to vacuum, the only place the mobile oil can go to are the pores.

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The core is kept in this setup for about 15 days. After that, the saturated core is weighed and its porosity is measured. A calculated porosity value close to 20% (known value for Berea sandstone) implies successful saturation. If not, the process is repeated again until saturation is complete.

3.2.3 **Experimental Setup**

The experimental setup for sandstone core experiments was exactly the same as that for the glass beads experiments and has been described in chapter-2.

3.3 Analysis of Results

3.3.1 **Effect of Solvent**

Based on the knowledge from the glass beads experiments, experimental temperatures and pressures for the core experiments were kept close to the saturation pressure and temperature for the solvent used. For the first 2 core experiments (experiments 20 and 21), the soaking time was about 2 days. For the last 2, it was decided to leave the cores soaked in solvent for a much longer duration of time – 15 days for core-1 and 10 days for core 2. This provided the opportunity to look closely at the temperature and pressure variations in the system for a longer period of time. This was not possible in shorter glass beads experiments as the time needed to reach ultimate recovery was very short. It was seen that the pressure decreased continuously with time (**Figure 3-2**). During the experiments, the production port was opened several times to take production out to analyze the recovery in real time (**Figure 3-3**). The discontinuities in pressure denote these times. The core used for the experiment with propane was

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longer (30 cm), and so the experiment was continued to about 15 days. The experiment with butane was carried out for about 10 days.

It was seen that a higher recovery was obtained in the experiment using butane as the solvent. This was observed for both, the short duration experiments as well as for the long duration experiments. This was mainly because of two reasons. One, that the butane experiment was done at a much higher temperature (101°C) as compared to the propane experiment (53°C) to be on the right side of the saturation line (to keep the solvents as gas during the process). Note that at the experimental pressure, butane has a saturation temperature of over 90°C. As a result of the experimental temperature, more heat was introduced, resulting in an enhanced gravity drainage due to faster (and more) viscosity reduction. The second reason was that the mole fraction of butane present in the oil phase in experiment-23 was greater than the mole fraction of propane in oil phase in experiment-22 because propane is more volatile than butane. This effect has been discussed in previous chapter.

3.3.2 Effect of Permeability and Soaking Time

From the recoveries obtained in core experiments, it was simple to conclude that the sample permeability hugely affects the final recovery. In fact, it was observed that the soaking time of a few hours was enough to drain significant amount of original oil from glass beads samples (permeability of the order of Darcies, results presented in Chapter-2), whereas for Berea sandstone cores (permeability of the order of milliDarcies), much less oil was recovered even after a soaking time of up to 2 weeks. Moreover, lower permeability implies smaller pore throats and thereby higher capillary pressure, which can increase the possibility of blockage if there is some asphaltene deposition on the rock grain surface. This effect has been discussed in the next chapters too. However, as expected, recoveries increased with increased soaking time, explaining the higher recoveries obtained in experiments 22 and 23 as compared to experiments 20 and 21 (Experiment numbers are in continuation with the previous chapter).

3.3.3 **Diffusion**

Diffusion of solvent into heavy oil is the most prominent process in recovery during a hot solvent (or a cold solvent) process. An evidence, diffusion could be seen on the pressure response of two core experiments (experiments 22 and 23) conducted in this study (**Figure 3-2**). The pressure continued to drop, almost linearly, during the soaking period. This can be attributed to the gas diffusion into heavy oil. As a result, there is less solvent (propane or butane) in the gas phase than there was at the beginning of the experiment. The slope of the pressure decline with time can give an idea about the amount of diffusion going on in the process, and will be studied more deeply in future studies. Solving Fick's 2nd law of diffusion with generalized assumptions and appropriate boundary conditions as outlined by Zhang et al. (1998), it was found that the diffusion coefficient of propane in the given heavy oil is in the ballpark of 6×10^{-9} m^2/s. For butane, the value was calculated as approximately 5×10^{-9} m^2/s.

Another important observation is that the decrease in pressure at constant temperature takes the experimental conditions further away from the saturation curve of the solvent, and this will affect the recovery according to the Raoult's law. Hence, the gas supply should be regulated during the experiment to maintain a constant pressure and to remain above the saturation line of the solvent, i.e., in the gas form.

Table 3-1: Summary of Berea sandstone core- heavy oil experiments

Exp. No. (Overall)	Solvent used	Height (cm)	Diameter (cm)	Porosity (%)	Temp (°C)	Pressure (kPa)	Recovery (%)	Approx. Soaking time
20	Propane	15	5	23	53	1500	27.5	48
21	Butane	15	5	21	98	1350	44.4	28
22	Propane	30	5	21	53	started at 1600	41.2	360
23	Butane	15	5	21	101	started at 1470	63.6	240

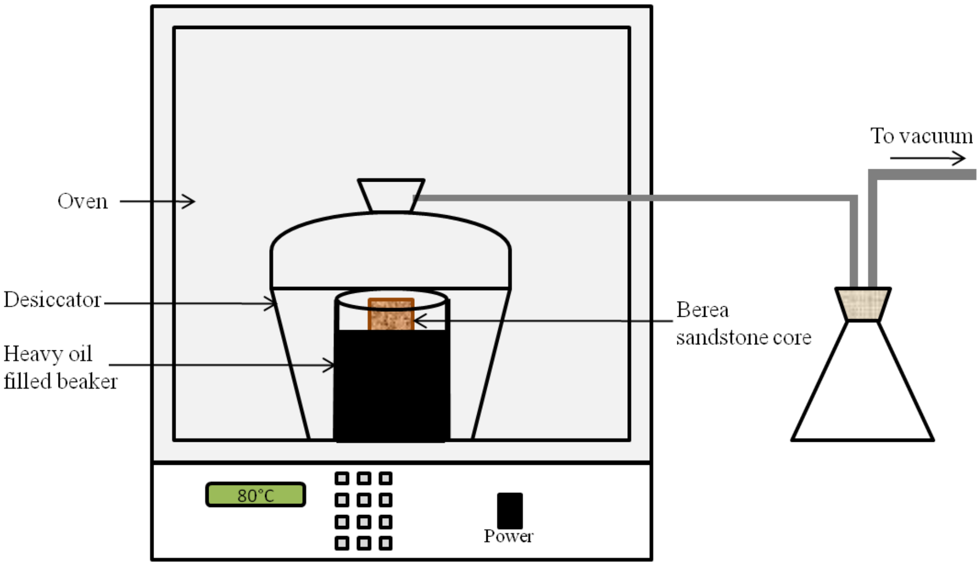

Figure 3-1: Setup for core saturation with heavy oil

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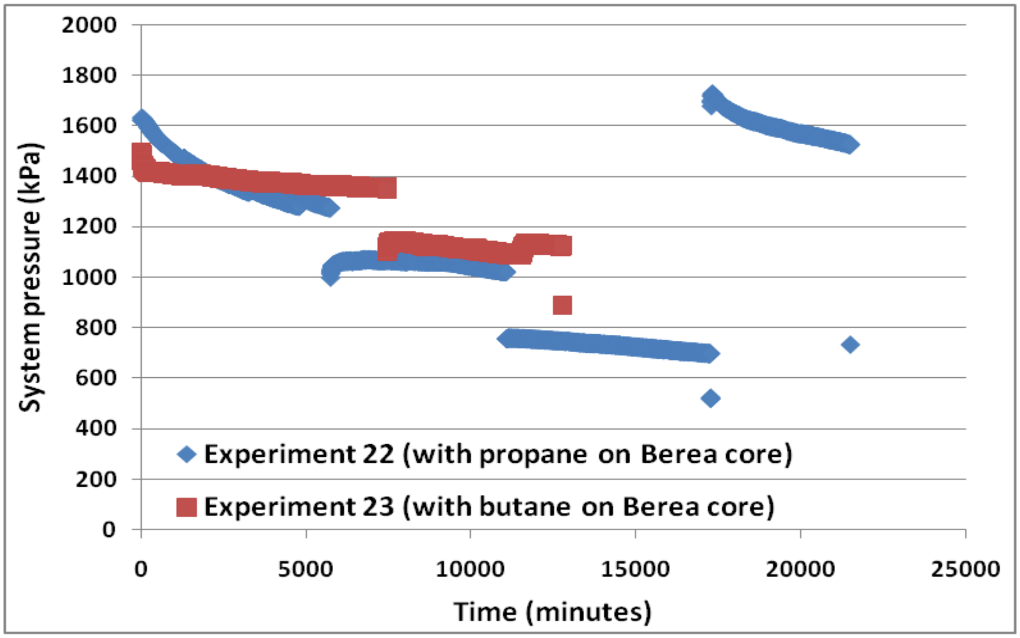

Figure 3-2: Pressure history for two Berea core experiments

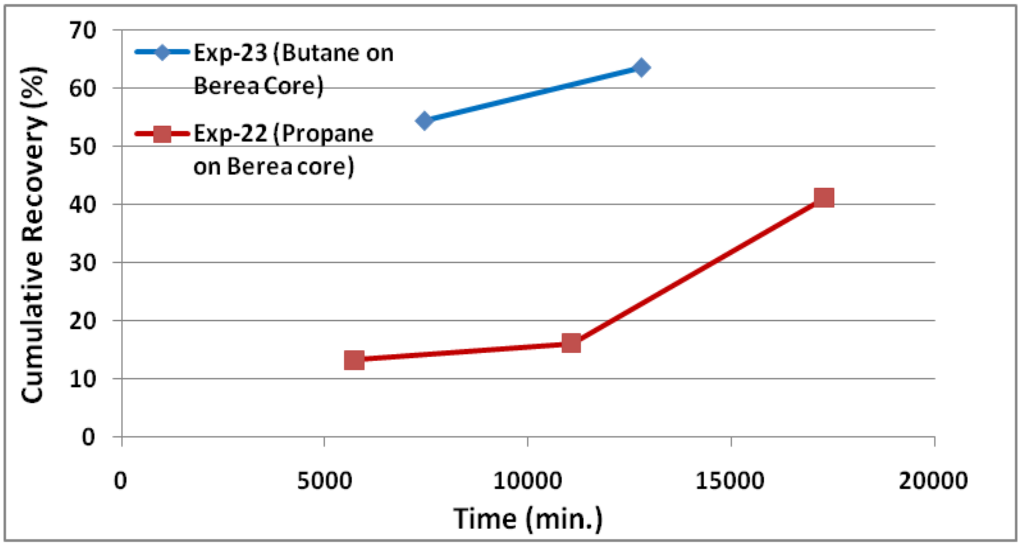

Figure 3-3: Cumulative recovery for two Berea core experiments

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4 VISUALIZATION EXPERIMENTS

4.1 Overview

This chapter discusses the 2-dimensional visualization experiments performed to understand the dynamics of the solvent based displacement process, including how asphaltene deposit and affect the displacement. 2-D Hele-Shaw models of different dimensions were constructed by joining two plexiglass sheets leaving some spacing in between to accommodate heavy oil. In some experiments, solvent injection was done from the top of the model and diluted heavy oil was drained from the bottom. In other experiments, models were left open from all sides and were exposed to different types of solvents. In each case, the setup was continuously monitored to observe fluid fronts and asphaltene precipitation.

4.2 Types of Visualization Experiments

4.2.1 **Cold liquid solvent injection experiments**

To understand how the dynamics of the process are affected by solvent type and asphaltene precipitation, two Hele-Shaw experiments were conducted. Each Hele-Shaw cell was made by cutting two plexiglass sheets in dimensions of 20 cm by 30 cm, and then joining them using epoxy with a spacer in between. Enough spacing (~ 2.5 mm) was given between the sheets so that a reasonable oil quantity could be accommodated between the sheets. Two wells – one injection and one production, were also drilled into the Hele-Shaw cell. Next, the model was put in an oven at 80°C and saturated with heavy oil (just like in previous chapter). This was done because at room temperature, the heavy oil has a viscosity of about

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9000 cp, making it extremely tough to saturate the Hele-Shaw cell. The model saturated with heavy oil is shown in **Figure 4-1**.Solvent injection was done from the top and oil production was taken from the bottom. A detailed picture of the setup is shown in **Figure 4-2**.

Two solvents were used for this purpose. The first experiment was conducted using pentane as the solvent and the second using decane as the solvent to distinguish the importance of the solvent type on asphaltene precipitation and deposition. The top part of the model was left open to fill with solvent. Hence, the injected solvent from one point filled this open part first and started diffusing downwards into the heavy oil equally through the width of the model. This made the injector well act like a horizontal well.

4.2.2 Static cold liquid solvent experiments on small scale Hele-Shaw models

The static experiments were performed on 2-D Hele-Shaw models of 2x2cm in size to confirm the findings of the larger scale Hele-Shaw dynamic injection experiments. The Hele-Shaw models were saturated again with the same heavy oil (viscosity ~ 9000 cP). Several experiments were conducted using pentane and hexane as solvents. The Hele-Shaw model was placed in a chamber filled with solvent. Displacement of oil was purely due to diffusion based dilution when the model was placed horizontally, and due to both diffusion and gravity when the model was placed vertically. The setup was monitored continuously by a camera to examine the displacement patterns. These experiments were run for 12-18 hours duration.

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4.3 Results

Figure 4-3 shows displacement patterns for the two experiments of the first type of visualization. The solvent was injected at a low rate from the top and diluted oil was produced from the bottom of the model. Since the solvent was in a liquid state and the oil was very heavy, devoid of any light fractions, the initial diffusion was slow. But as the solvent started to diffuse slowly into the oil, it was seen that asphaltene were precipitated on the Hele-Shaw cell glass wall. The diluted oil flowed down and was produced at a controlled slow rate. It was also seen that the asphaltene deposition was mainly along the initial interface of the solvent and heavy oil and was absent from the remaining part of the model. In the case of pentane, this precipitation occurred along a much wider zone as compared to decane. This was in accordance with the theory that lighter solvents precipitate more asphaltene. It was deemed that in the case of porous media with low permeabilities (of the order of few hundred millidarcies), this kind of asphaltene precipitation significantly affects the dynamics of oil flow for the hot solvent process and may result in lower recovery for lighter solvents.

Another observation was made during the visual experiments. The asphaltene deposition was significant only at the initial solvent- heavy oil interface. This is because of the fact that asphaltene precipitation depends on the concentration difference of the solvent between the two sides of the interface. Higher the concentration gradient, higher is the asphaltene precipitation. As the solvent moved into the heavy oil, it picked up other hydrocarbons, reducing the

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concentration % of solvent and limiting asphaltene precipitation. Higher asphaltene precipitation may lead to higher asphaltene deposition.

These results were later confirmed by further visualization experiments on smaller models. The results for an experiment done with pentane as a solvent and a horizontally placed model are shown in **Figure 4-4**. The results for an experiment conducted with pentane as a solvent on a vertically placed model are shown in **Figure 4-5**. Both experiments showed asphaltene deposition on the walls of the model near the initial interface of the solvent and the heavy oil. As a consequence of this, the dilution of oil was also faster. The asphaltene deposition was reduced as the diffusion front moved further into the undiluted oil and as the change in the oil composition (dilution) became more gradual. Finally, two distinct zones were formed – the first zone, which appeared darker and was the zone in which asphaltene were deposited on the wall. The second zone, which appeared lighter in color and was the zone where there was no visible asphaltene precipitation. The first zone had a quick dilution of oil, whereas it takes a long time for the oil in the second zone to get diluted. This effect was seen more prominently in the horizontal model. In case of vertical model, the displacement was assisted by gravity and thus, was much faster, confirming the importance of gravity once again.

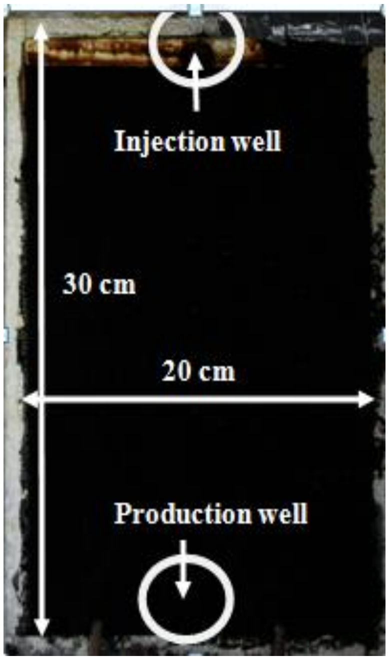

Figure 4-1: Enlarged view of the model saturated with heavy oil

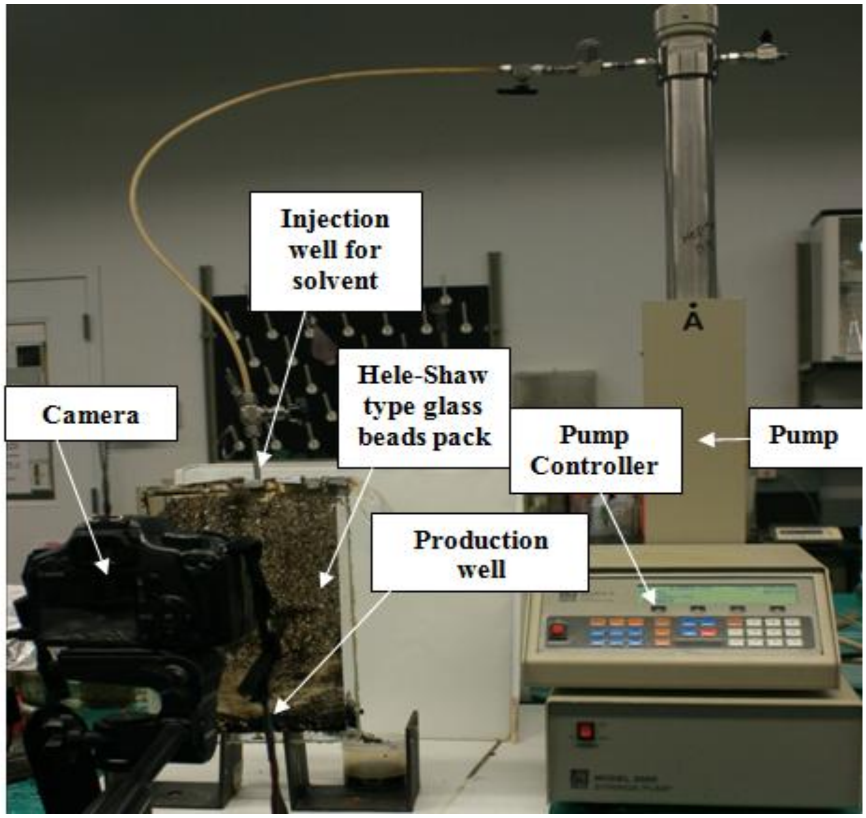

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Figure 4-2: Hele-Shaw cell experimental setup

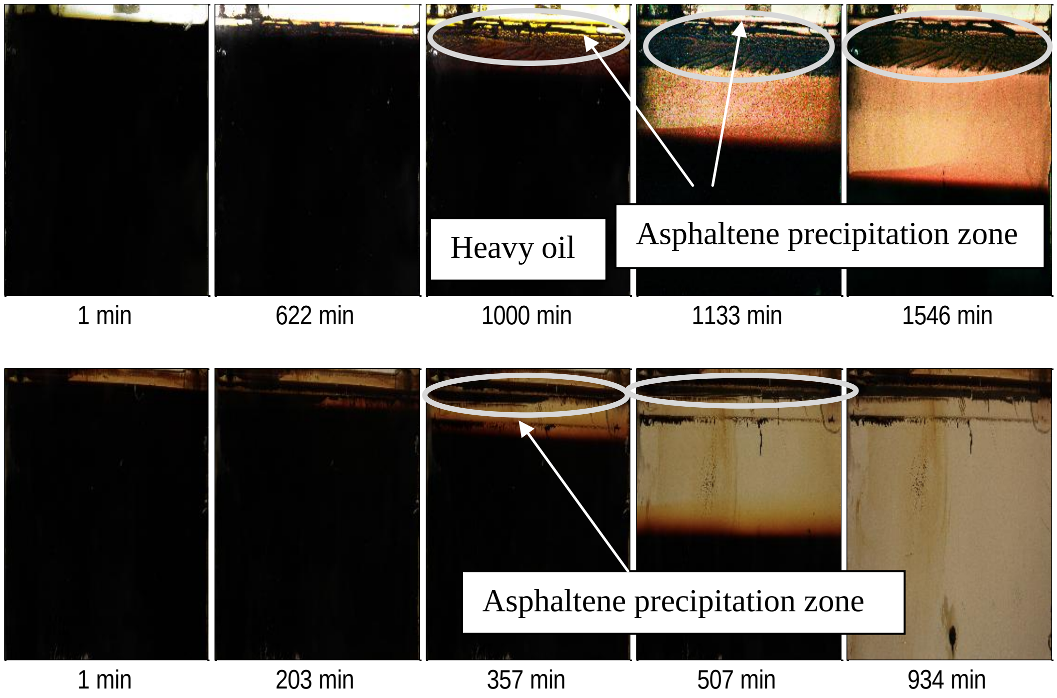

Figure 4-3: Displacement of heavy oil (9000 cp) using two different solvents

Pentane (above) and decane (below): Black color represents oil.

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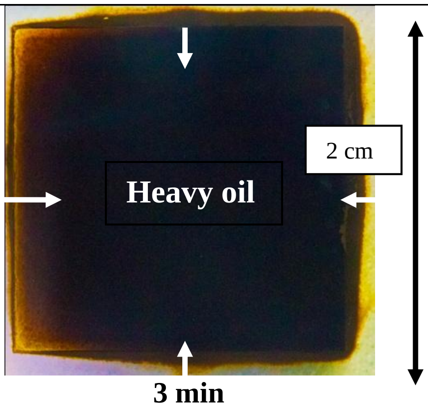
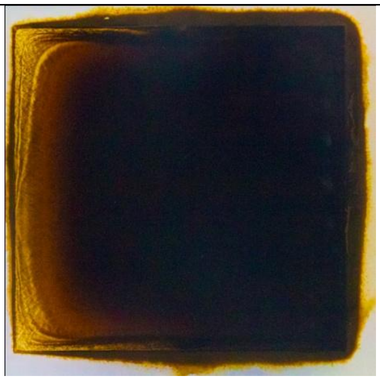
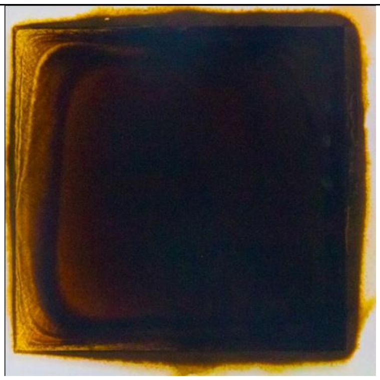
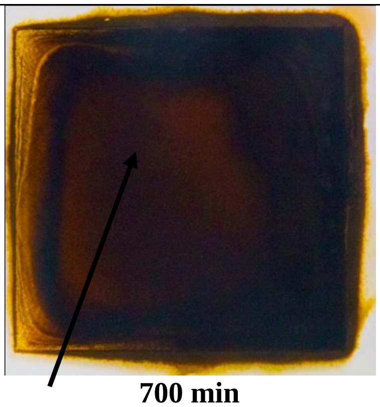
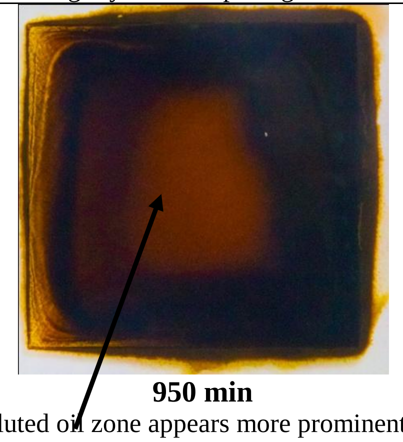
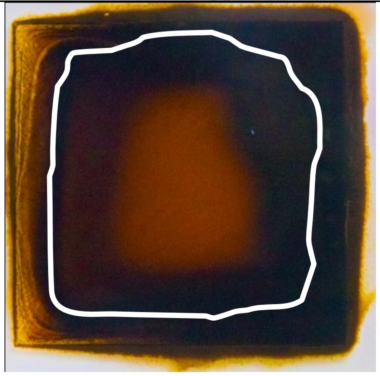
 **3 min** Heavy oil surrounded by pentane, (black color is oil). Model open to solvent on all sides	 **100 min** Solvent diffusing into heavy oil from all sides. Asphaltene deposits appear along the interface
 **400 min** Diffusion is slower from the right side possibly due to slightly uneven spacing in the model	 **700 min** Lighter colored zone containing only diluted oil starts to appear
 **950 min** Diluted oil zone appears more prominently. This zone has minimal asphaltene deposition	 **1150 min** Asphaltene deposition boundary (outside which most asphaltene deposit) shown in white color.

Figure 4-4: Miscible displacement of heavy oil by pentane in a horizontal Hele-Shaw model

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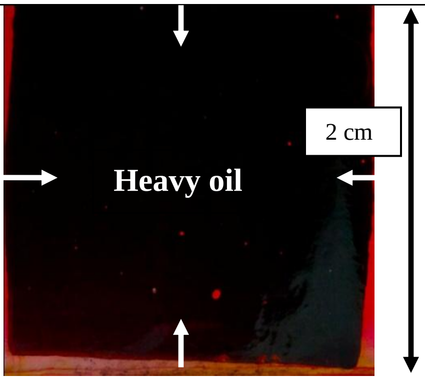
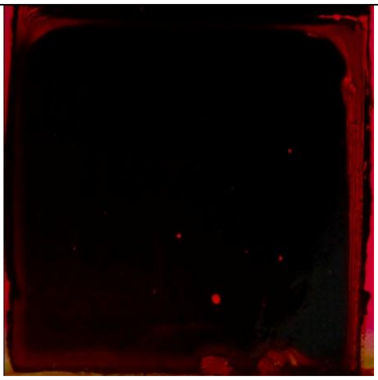
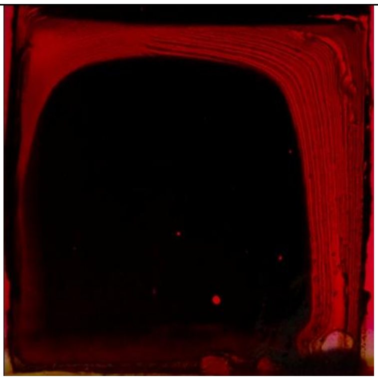


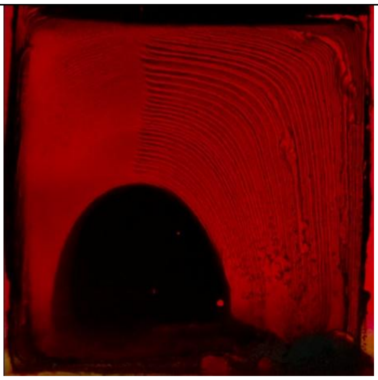
1 min
Heavy oil (black color) surrounded by pentane (red color). Model open to solvent on all sides



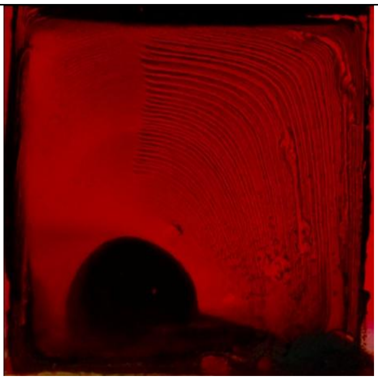
8 min
Solvent diffusing into heavy oil from all sides. Asphaltene deposits appear along the interface



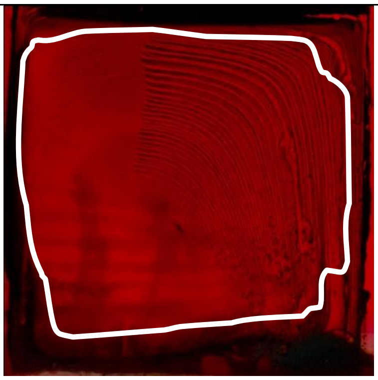
29 min
Solvent continues to diffuse into the heavy oil. Oil is displaced downwards by gravity



75 min
Oil continues to displace downwards. No visible asphaltene precipitation in the center of the model



92 min
Fast displacement of oil because of gravity



300 min
Asphaltene deposition boundary (outside which most asphaltene deposit) shown in white color.

Figure 4-5: Miscible displacement of heavy oil by pentane in a vertical Hele-Shaw model

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5 NUMERICAL SIMULATION STUDY FOR SENSITIVITY ANALYSIS AND QUANTITATIVE HISTORY MATCH

5.1 Overview

To better understand the physics of the process and to support the observations of earlier experiments, a numerical simulation study was undertaken. The simulation study also facilitated the analysis of effect of several other parameters on recovery which would have required a much more prolonged laboratory based research. Encouraging results were obtained through the numerical work, which gives a direction to an extended experimental research in future.

The effects of temperature and pressure on the recovery were studied using a commercial reservoir simulator (ECLIPSE 300). Propane, butane and pentane were used as solvents. The effects of asphaltene precipitation and deposition on the flow dynamics were also modeled. A qualitative history match with the experiments on different porous media types was achieved and results similar to the earlier experiments were obtained. Later, the numerical model was extended to investigate the effect of more parameters on recovery such as capillary pressure, vertical and horizontal permeabilities. The effect of asphaltene deposition on models of varying permeabilities was also studied. This chapter describes in detail the numerical model and the results obtained.

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5.2 Methodology and Model Details

A 2-dimensional simulation model (30 x 1 x 20) was constructed to analyze and understand the mechanics of the recovery process. The size of the model was same as the size of the physical model of plexiglass used earlier for visualization experiments. A compositional simulator, ECLIPSE 300, was used for this purpose. Heavy oil composition was simplified and was represented by only three heavy components, and the Peng-Robinson equation of state was used. An injector well was defined at the top and a producer well at the bottom of the model. The rates were kept small enough to be able to maintain a fairly constant pressure, which was true for most experiments.

Asphaltene effect on flow dynamics was also modeled. In the case of heavy oils, asphaltene are generally stable and do not create problems of permeability reduction of the porous media. However, in miscible displacement, the oil undergoes a composition change and thus the thermodynamic equilibrium needed for the stability of asphaltene is broken. As a result, asphaltene accumulate and make “flocs”. This process can be termed as asphaltene flocculation and is reversible. Flocculation is beneficial because it contributes to viscosity reduction of heavy oil, but can be troublesome at the same time because it increases the chance of asphaltene precipitation on porous media. In general, not all the asphaltene that was flocculated will also be precipitated. An attempt has been made to model these processes using ECLIPSE 300. It was also attempted to clarify the difference between asphaltene flocculation, precipitation and

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deposition. A number of factors were considered and engineering assumptions were made for modeling asphaltene:

- First, asphaltene were assumed to be precipitating from only the heaviest component. Second, the reversibility of asphaltene flocculation was assumed to be small.
- It was also assumed that the viscosity of oil changes slightly because of asphaltene precipitation.
- In the absence of any PVT data showing how much asphaltene is precipitated by using propane as a solvent for the heavy oil under study, this value was also assumed in form of a look-up table.

Very importantly, it must be noted that because of these assumptions, the exact modeling of the experiments could not be performed. However, simulations with these assumptions still gave a good idea of the physics of the process and the dominant mechanisms.

Permeability damage to the porous media was based on the following equation as defined in the technical description of the simulator used:

$$\frac{K}{K_o} = \left(1 - \frac{\varepsilon}{\phi_o}\right)^{\delta} \tag{1}$$

Where,

K = permeability at any time

K_o=Initial permeability

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ϕ_o=Initial porosity

ε=Volume fraction of asphaltene deposit

δ=User input which relates permeability reduction to porosity reduction (because of asphaltene precipitation)

'δ' was chosen as one of the variables for the sensitivity study.

The deposition of asphaltene in the system was modeled using the following equation (from the ECLIPSE technical description and Wang et al. 1999):

$$\frac{d\varepsilon_i}{dt} = \frac{\alpha}{d}\ \phi\, C_a + \gamma \left| \ F_{oi} \ \right| C_a - \beta\ (\left|U_{oi}\ \right| - U_{cr})^{+}\ \varepsilon_i \qquad (2)$$

Where,

ε_i = Volume fraction of asphaltene deposit in the 'i'direction of flow

α = User input, and is the adsorption or the deposition coefficient

d =dimension of the problem (1, 2 or 3)

ϕ = Porosity at time't'

C_a = Concentration of asphaltene flocs in flowing oil phase

γ = Plugging coefficient

F_{oi} = Oil Darcy flux

β = Entrainment coefficient

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U_{oi}=Oil phase velocity

U_{cr}=User input, entrainment is zero when $U_{oi}<U_{cr}$

The parameter 'α' directly controls the deposition of asphaltene on the rock. However, just the deposition of asphaltene may not mean pore plugging. Pore plugging is controlled by the plugging coefficient, 'γ'. Entrainment means how much asphaltene is carried by the oil phase by virtue of its velocity. These asphaltene may have been deposited but are returned back to the oil phase because of shear forces. This is controlled by the parameters 'β' and 'U_{cr}'. These four parameters were also considered for the sensitivity study.

5.3 Analysis of Results

Various operating conditions and various solvents were tried for each of the following results, and the analysis is as follows:

5.3.1 Effect of Temperature

In addition to the observations made during the experiments, the effect of temperature was also studied using the numerical model. All other parameters were fixed and temperature was changed for several runs. It was observed that the trend seen from the experiments matched the trend seen in simulations, i.e., recovery increases when the temperature is near the saturation temperature of the solvent, and decreases when the temperature increases. Recovery is also poorer when temperature is lower than the saturation temperature of the solvent as all the solvent exists only in the liquid phase and the diffusion coefficient for liquid (solvent)-liquid (oil) is much less as compared to the diffusion coefficient for gas-

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liquid. The results obtained for propane are shown in **Figure 5-1**. The simulation was done assuming a constant pressure of 10 atm. At this pressure, propane has a saturation temperature of about 27.5°C. When the temperature was increased from 28°C to 35°C, a decrease in the recovery factor was seen. This is in accordance with the above discussion. However, when the temperature was raised beyond 60°C, an increase in recovery was seen. This was due to the fact that the viscosity of heavy oil is a strong function of temperature, and the reduction in viscosity by increasing temperature becomes the main driving force (enhanced gravity drainage) for the process, rather than miscibility.

5.3.2 **Effect of Pressure**

For a fixed temperature, for a pressure closer to the saturation pressure, a greater recovery was achieved. This was in accordance with the experiments too, as shown in the earlier discussion. The results are shown in **Figure 5-2**. The solvent used for the study was propane and the temperature was fixed at 35°C. At this temperature, the saturation pressure of propane is about 12 atm.

5.3.3 **Effect of Gravity**

In addition to the observations made during experiments about the role of gravity in hot solvent displacement process, two simulation based approaches were also taken. These were as follows:

- The simulation model was changed into a horizontal model by making the grid 20 x 30 x 1 instead of 20 x 1 x 30. The location of the wells was also changed accordingly. It was seen that the vertical model gave a slightly

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higher recovery than the horizontal model using butane as a solvent at 140°C and 25 atm (~5% difference in cumulative recovery after 12 hours) as shown in **Figure 5-3**. This confirms the role of gravity in displacing the diluted oil during a hot solvent process.

- To ascertain the role of gravity further, more simulation runs were done with varying heights of the model. All other parameters were kept constant. Pore volume was also kept constant by changing the horizontal cross sectional area of the model. The results are shown in **Figure 5-4**. This indicates that an increase in model height increases the recovery. Similar results have been showed for gravity drainage by other researchers (Darvish et al. 2004). However, beyond a certain height of the model (in this case, ~40 cm), the change becomes insignificant. This is the critical height needed to overcome the capillary forces inhibiting production. Once these are overcome, increasing height does not have much effect on recovery.

  This explains the observations made during the glass beads experiments where recovery was found to be a weak function of height, possibly because the capillary forces were already overcome by the model heights used during experiments. For a lower permeability medium, pore throats (or capillary radius) are smaller. Thus capillary force will be bigger as well. To overcome this capillary force, a much longer model will be needed for an effective drainage.

5.3.4 **Effect of Asphaltene Precipitation, Flocculation and Deposition**

Asphaltene precipitation in porous media is likely to affect recovery in cases of low permeability media only. For glass beads experiments (where permeability was of the order of Darcies), it was seen that asphaltene precipitation did not create a significant effect on the recovery process or the ultimate recovery. To some extent, it was observed that butane experiments gave higher asphaltene deposition on the porous media surface and also yielded a slightly higher recovery in comparison the the propane experiments.

As an attempt to replicate this situation in the simulation model, the reservoir was assigned a very high initial permeability (200 Darcies). Three cases were considered - no asphaltene precipitation, small amount of asphaltene precipitation, and high asphaltene precipitation**. Figure 5-5** shows oil saturation the reservoir grid after 12 hours during a miscible displacement using butane. The recovery pattern seemed different for the three cases. The recovery curves gave a better indication of the effect of asphaltene precipitation and deposition (**Figure 5-6**). The curves showed that when there was a slight amount of asphaltene precipitation, the recovery improved slightly as compared to the case with no asphaltene precipitation. This infers that the oil displacement is accelerated by asphaltene flocculation and deposition, mainly because the viscosity of oil is reduced. The permeability in this case is very high (200 Darcies), so even minor permeability damage due to asphaltene precipitation did not affect the recovery. When parameters were tweaked to give a higher amount of asphaltene flocculation, the recovery increased even further (**Figure 5-6**). However, because of the assumptions associated with the fluid and asphaltene precipitation modeling in this study, these results must only be taken for understanding the process and not quantitatively. The observations from the reservoir model were similar to the experiments, but not the same because the fluid definition was different from the experimental fluid.

When the same simulations were done on models with much less permeability, it was found that the two contrasting effects – dilution of heavy oil by asphaltene dropping out of it, and asphaltene precipitating in the pores and causing permeability reduction, almost negated each other. Recoveries obtained in these cases were almost same.

A sensitivity study was also done to analyze the effect of asphaltene deposition parameters mentioned in equation (2) on recovery. Results are shown in the form of a Pareto chart (**Figure 5-7**). This shows that asphaltene deposition on the rock surface and plugging due to this deposition can affect the recovery a lot more than entrainment. This study was done for both, a low permeability medium (20 mD) and a high permeability medium (2000 mD). This shows that excessive flocculation and subsequent deposition of asphaltene will reduce the recovery, and the effect will be more critical in case of low permeability medium.

5.3.5 **Effect of Vertical Permeability**

According to Darcy's law, a higher permeability implies higher flow rates and higher production. Since the hot solvent process depends on gravity drainage, it was expected to be highly dependent on the vertical permeability, besides the

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horizontal permeability. The effect of vertical permeability was analyzed using the simulation model. Vertical permeability was changed in the model and its effect on recovery was monitored. Several cases were considered where permeability anisotropy (the ratio of vertical permeability to horizontal permeability) was changed while keeping all other parameters fixed. It was observed that even though some difference was seen in the values of total oil produced after 100 hours (**Figure 5-8**), the difference was not significant for the cases when horizontal permeability was low. However, when horizontal permeability was high, the production increased significantly with an increase in vertical permeability.

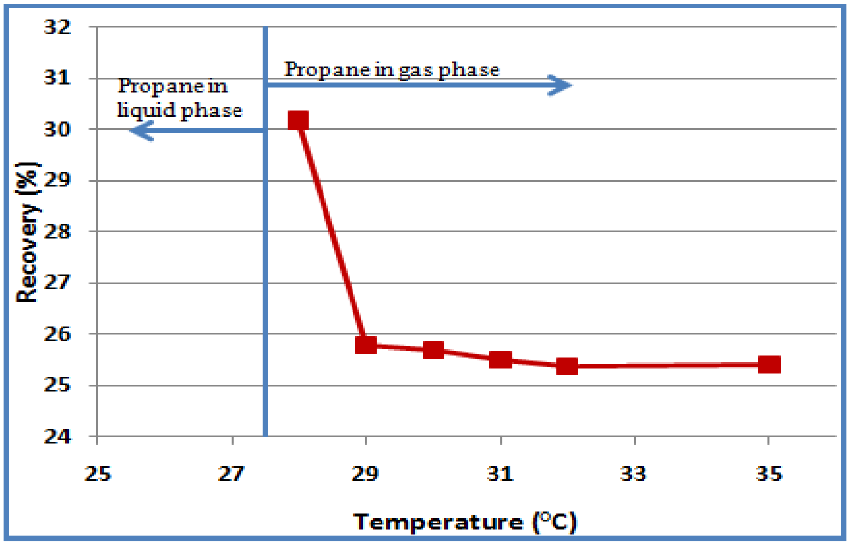

Figure 5-1: Effect of increase in temperature upon recovery.

The solvent used here is propane (saturation temperature = 27.5 °C at 10 atm)

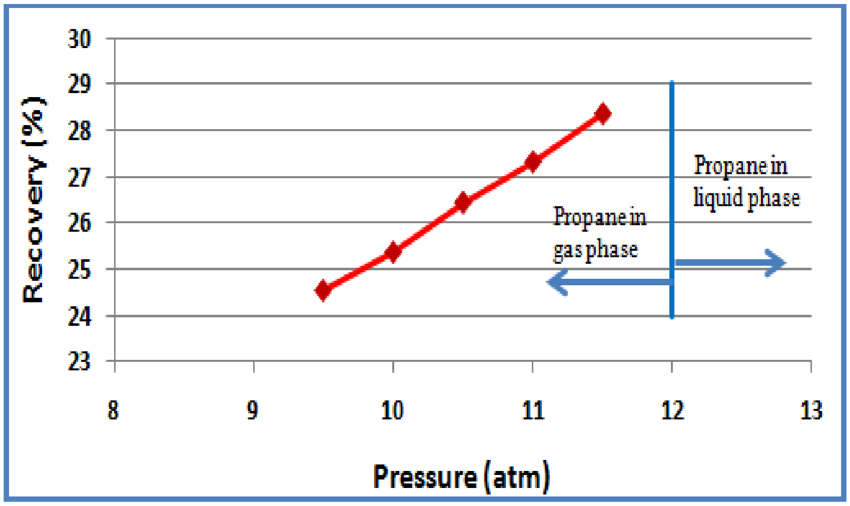

Figure 5-2: Effect of system pressure on the recovery for a hot solvent process

Considering only gaseous phase of solvent for a fixed temperature of the system (35°C)

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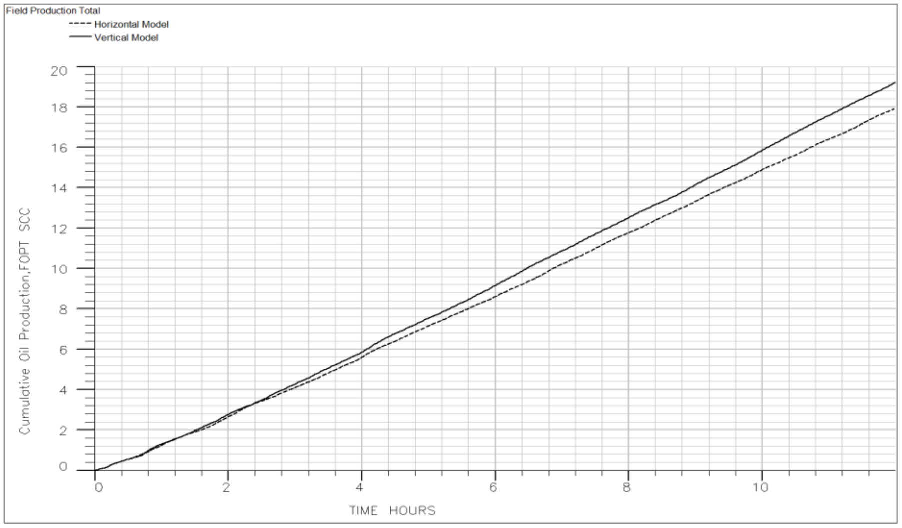

Figure 5-3: Effect of gravity on the final recovery

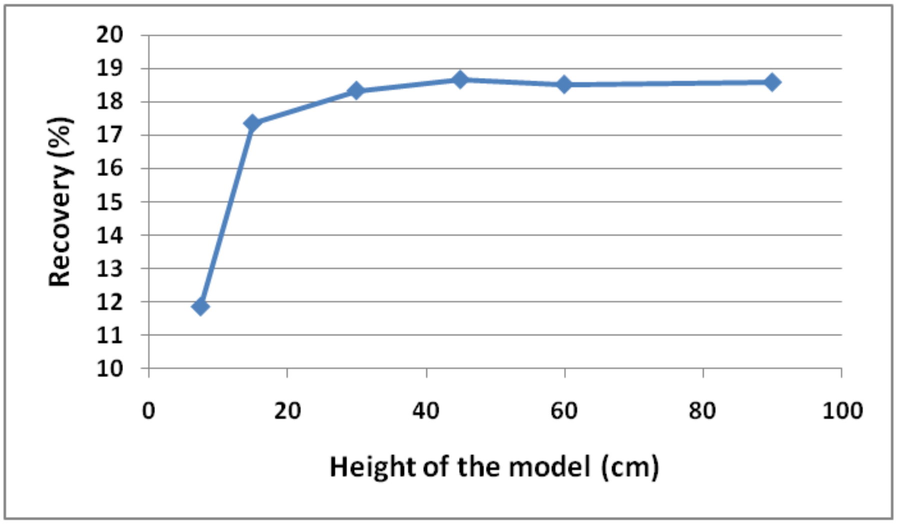

Figure 5-4: Effect of model height on recovery keeping all other parameters constant

The height of 45 cm in this case can be termed as the critical height needed by the gravity force to overcome the capillary force. The recoveries are small because a small value of permeability was chosen to see the effect of only height (5 mD)

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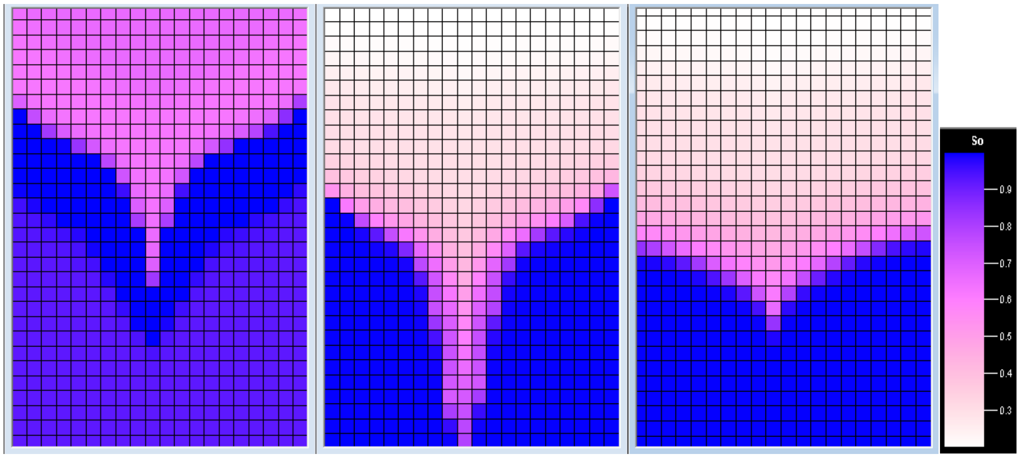

(a) **(b)** **(c)**

Figure 5-5: Oil saturation in the grid, miscible displacement using butane

Solvent draining oil downwards: (a) No asphaltene precipitation (b) Low amount of asphaltene precipitation (c) High amount of asphaltene precipitation

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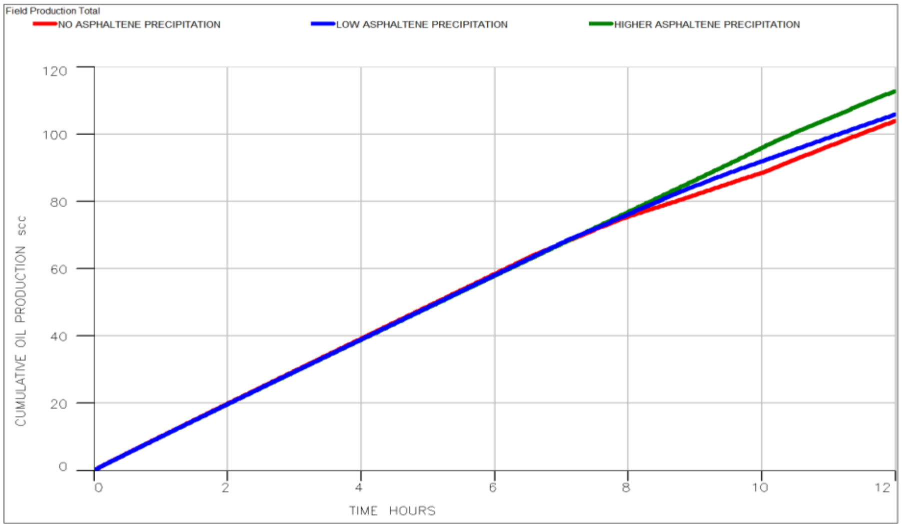

Figure 5-6: Cumulative recoveries for the simulations showed in Figure 5-5

The red curve shows simulation with no asphaltene precipitation, blue curve shows simulation with low amount of asphaltene precipitation and the green one shows simulation with high amount of asphaltene precipitation.

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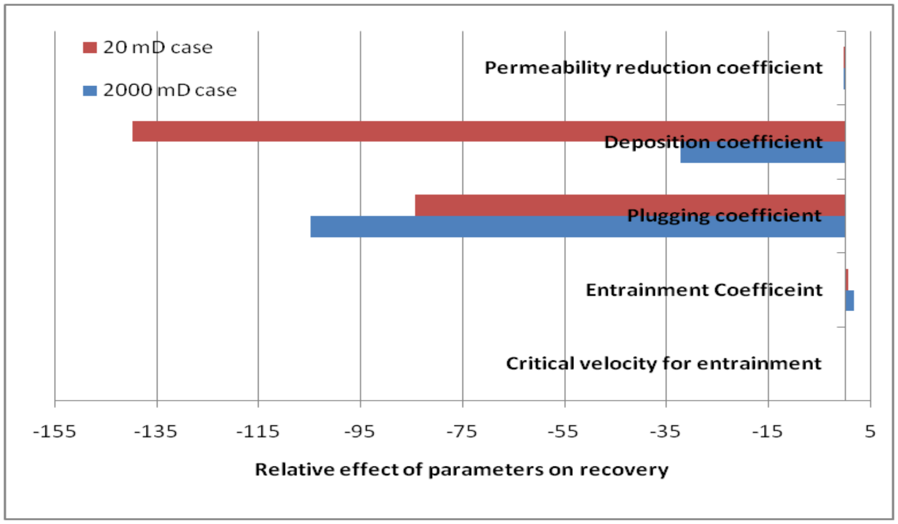

Figure 5-7: Pareto chart showing effect of various asphaltene model parameters on the cumulative recovery for two permeability cases

A negative value means increasing the parameter value causes a decrease in recovery and vice versa.

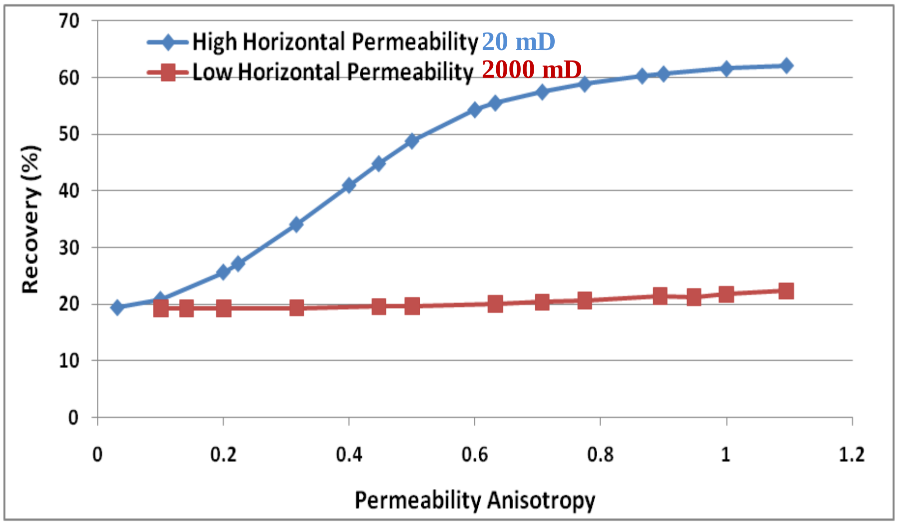

Figure 5-8: Effect of permeability anisotropy on the recovery for two different porous media

Permeability Anisotropy = Vertical permeability / Horizontal permeability

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6 CARBONATE CORE EXPERIMENTS

6.1 Overview

With the decrease in conventional oil and gas reserves throughout the world, an ever-increasing demand for fossil-fuel based energy and resultant high oil prices, the focus has been shifting to unconventional and heavy oil and bitumen. Grosmont carbonates in Northern Alberta have been estimated to contain at least 300 billion barrels of oil in place (Solanki et al. 2011). However, recovering this oil is extremely difficult because of the complexity associated with carbonate reservoirs in general. Grosmont reservoir is known to have triple porosity – matrix, fractures and vugs, based on several core studies. The second problem is the fluid itself, which in this case is highly viscous bitumen, immobile at reservoir conditions. To recover this bitumen, both heat and dilution using solvents may be needed. This chapter describes three hot solvent soaking experiments conducted on original Grosmont carbonate cores.

6.2 Experimental Procedure and Setup

Experimental procedure was the same as that for glass beads and sandstone core experiments. The only change in the setup was the cylinder. The carbonate cores used in this study were preserved original cores from the field obtained after a well coring operation. The diameter of these cores was 4 inches (about 10 cm), and that meant a wider cylinder was needed for the experiments. The cylinder has been showed in **Figure 6-1**. All the fittings were modified accordingly.

The contents of this chapter will be submitted for publication in a peer reviewed journal after obtaining confidentiality clearance: Pathak, V., Babadagli, T. and Edmunds, N.R. 2011. Bitumen Extraction Using Hot-Solvent Soaking in Grosmont Carbonates

6.3 Description of Experiments

Three cores were tested during the study. These were original cores with original fluid saturations. The description of experiments is as follows:

6.3.1 **Experiment-1**

The core was extremely fragile and susceptible to breaking while handling. A huge crack was visible right in the middle (**Figure 6-2**). The vugs and natural fractures were quite obvious and the bitumen was seen stuck in the vugs (**Figure 6-3**).

The solvent used was propane. Experimental pressure was kept almost constant at 1550-1600 kPa. The pressure was maintained by introducing more gas whenever the pressure was observed to drop as a constant pressure was desired, close to the reservoir pressure. The temperature was constant at 54°-55°C.

After a 12 day soaking period, the produced volume was measured to be 30 cc. Connate water was also seen in the form of droplets on the inner wall of the cylinder. The connate water volume could not be exactly measured, but it was estimated to be about 10 cc. A summary of the results is given in **Table 6-1**. **Figure 6-4** shows the picture of the core taken out of the apparatus after the experiment. The oil recovered was analyzed for viscosity and asphaltene content.

6.3.2 **Experiment-2**

Experiments 2 and 3 were conducted using the two halves of a core piece, so they are identical from a properties point of view. This core was less fragile than the core used for first experiment and it was smaller too. The vugs and natural

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fractures were clear and the bitumen was seen stuck in the vugs in this core too (**Figure 6-5**). The solvent used for this experiment was butane. Experimental pressure was kept almost constant at 1400-1500 kPa as in Experiment-1. The temperature varied in the range of 115°-120°C.

The produced volume for this experiment was about 83 cc which was very encouraging. No water was produced in this experiment. A summary of the results is given in **Table 6-1**. **Figure 6-6** shows the picture of the core taken out of the apparatus after the experiment and it can be noted that the core crumbled under the conditions of normal handling and gas pressure. **Figure 6-7** shows a cross section of the core after the experiment. Again, the recovered oil was analyzed for viscosity and asphaltene content.

Later, the core from this experiment was cleaned using Soxhlet extractor. Based on the weight of the core before and after cleaning, the pore volume was calculated to be 143 cc, implying an average porosity value of 0.2. Based on this porosity value, the recovery for experiment-2 was 58%. The results are shown in **Table 6-1**.

6.3.3 **Experiment-3**

This experiment was conducted with the other half of the 2nd core piece. It was expected that the recovery for the butane experiment would be better than that for the experiment conducted with propane as solvent based on previous observations by Pathak et al. (2010, 2011a). However, the results of 2nd experiment were so encouraging that it was decided to re-do the propane experiment to be sure that propane recovery was indeed much lower. This core was similar to the core used for experiment-2 and vugs and natural fractures could be seen. A lot more bitumen was seen to be stuck in the vugs and on the outer surface of the core in general (**Figure 6-8**). The solvent used for this experiment was propane. Experimental pressure was kept in the range of 1400-1600 kPa, as similar to the previous two experiments. The temperature was maintained in the range of 54°-57°C.

The produced volume for this experiment was about only 27 cc. This was similar to what was achieved in Experiment-1, thus increasing the faith in the experimental results. No water was produced in this experiment. A summary is given in **Table 6-1**. This core also crumbled under the operational pressure and handling, suggesting its brittle nature. Moreover, a significant amount of sand and fines were found inside the cylinder on the lower surface of the cylinder. This may become an issue during field applications and needs to be controlled. A lot of bitumen was found stuck in and on the core and the cross section appeared black in color (**Figure 6-9**), suggesting that the drainage was not very efficient. Again, the recovered oil was analyzed for viscosity and asphaltene content. Pore volume was measured using Soxhlet extraction, and resulting pore volume was found to be 134 cc. This gave a porosity value of 0.19 (which was close to the porosity obtained from the core used in experiment-2) and a recovery of 20%. The core used for experiment-1 was assumed to have the same porosity as the other two and recovery for experiment-1 was calculated on this basis. The results are shown in **Table 6-1**.

6.4 Analysis of Results

In the previous chapters, how temperature, pressure and solvent type affect the recovery of heavy oil and bitumen during a hot solvent process was discussed. The temperature and pressure for the carbonate experiments were maintained close to the saturation conditions of the solvent used in order to maximize the recovery.

6.4.1 Solvent Type and Recovery

The most important finding of these experiments was that butane is a more suitable solvent than propane for a hot solvent process from the ultimate recovery point of view. The highest recovery was achieved in Experiment-2, where butane was used as the solvent. The recovery for experiment-2 was close to 58% as shown in **Table 6-1**. For the remaining 2 experiments it was only about 20-23%. Further evidence of an efficient recovery was the cross-sectional image of the core after the experiment was finished (**Figure 6-7**). This image shows mostly light color, which means that most of the bitumen from this particular cross-section was extracted and produced. It must be noted that the butane experiment was performed at a significantly higher temperature as compared to the propane experiments, to be just above the saturation curve for a given (and fixed) pressure (1500-1600 kPa). Some of the incremental recovery can be attributed to high temperature, but it is expected that most of the recovery is because of dilution by solvent. However, to achieve such a high temperature to keep the butane in the vapour phase may be a challenging task in the field, and may increase the cost,

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too. These considerations must be kept in mind before choosing a solvent for any field application.

Figure 6-10 shows the saturation curve for propane. Experiments 1 and 3 were carried out for 12 and 8 days, respectively. As a result, pressure and temperature fluctuated throughout. However, the zones of fluctuations were very similar for both the experiments as shown in the figure, and thus similar results could be expected for both experiments. **Figure 6-11** shows the saturation curve for butane and the experimental conditions for Experiment-2. It should be noted that, in all experiments, an attempt was made to keep the experimental conditions close to the solvent saturation conditions.

6.4.2 Oil Dilution

Not only the amount of recovery was higher for the butane experiment, but also the bitumen was diluted far more compared to the propane experiments. The original bitumen had an estimated viscosity of over 22,000 cP at 60°C. The viscosity value at room temperature was not known. After upgrading this bitumen during the propane experiments, the viscosity of the produced oil was measured at about 1400 cP at 60°C. Thus, a viscosity reduction of over 15 times was achieved. However, the upgraded produced oil from Experiment-2 (conducted with butane) had a viscosity value of only about 500 cP at 60°C resulting in a viscosity reduction of 44 times with butane. This was expected, and has been discussed in the previous chapters. Since propane is more volatile than butane, less propane was present in the liquid (bitumen) phase during Experiments 1 and 3 than butane (Experiment-2). Hence, the degree of dilution and upgrading was less for the propane experiments and, as a result, the produced oil was more viscous for Experiments 1 and 3. This directly affected the overall recovery also and provided an explanation for better recovery for Experiment-2. **Figure 6-12** shows the viscosity of the produced oil from all three experiments. Note that there was only one viscosity measurement possible for the oil obtained in experiment 1 (at 28.1° C). The lower viscosity of the oil in Experiment-2 indicates a better dilution with butane. The refractive index is also a good indication of the degree of dilution, and the amount of lighter components present in the oil. **Figure 6-13** shows the refractive index plot for oils produced from all 3 experiments at varying temperatures and at constant pressure. The oil produced from Experiment-2 showed the least refractive index.

6.4.3 Asphaltene Content of Produced Oil and Inferred Asphaltene Deposition

Asphaltene content of the produced oil was also measured using the excess solvent - filter paper method outlined in Chapter-2. The asphaltene content of the oil produced with propane as a solvent was more than the asphaltene content of the oil produced with butane as a solvent. This was in line with the earlier results obtained from glass beads experiments given in Chapter-2. A higher asphaltene content in the produced oil also contributed towards its higher viscosity in the case of experiments where propane was used as a solvent. This also means that the amount of asphaltene left in the rock was more in the case of Experiment-2 with butane. The results are given in **Table 1** and **Figure 6-14**. Refractive index is also a good indicator of the asphaltene content of oil and the least refractive index and least asphaltene content were observed for the oil from Experiment-2.

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Table 6-1: Summary of carbonate experiments

(* indicates that pore volume was calculated based on porosity values obtained from experiments 1 and 2)

Experiment No.	1	2	3
Height of core (cm)	16.4	12.1	12.1
Avg. diameter of core (cm)	8.99	8.71	8.67
Soaking time (days)	12	11	8
Solvent used	Propane	Butane	Propane
Experimental temperature (°C)	53-55	115-120	54-57
Experimental pressure (kPa)	1500-1600	1400-1500	1400-1600
Oil produced (cc)	30	83	27
Pore Volume (cc)	197*	143	134
Recovery (%)	~23	58	20
Water produced (cc)	>10	0	0
Asphaltene % of produced oil	13.2	7.3	13.9

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Figure 6-1: High pressure /temperature cylinder used for carbonate experiments

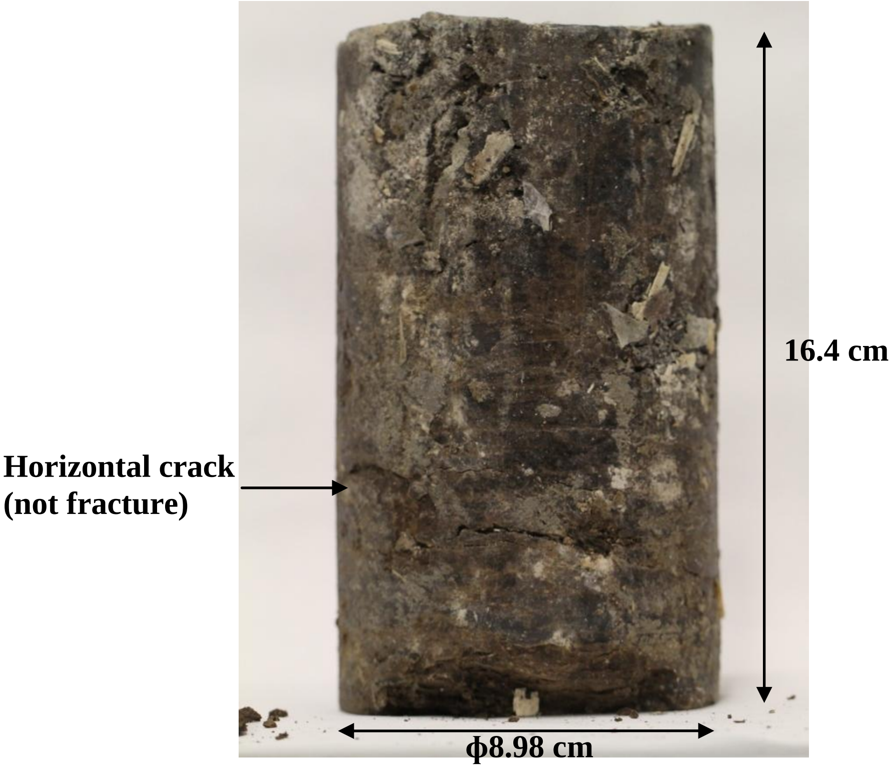

Figure 6-2: Core used in 1st carbonate experiment

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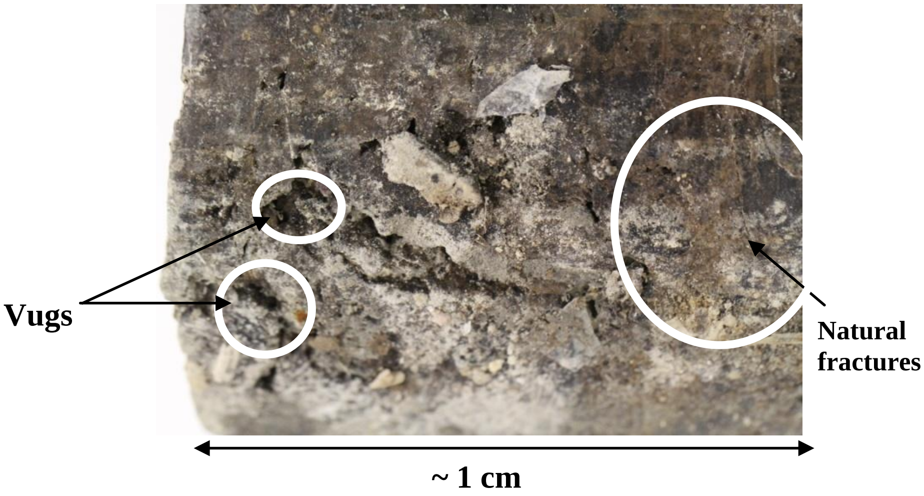

Figure 6-3: Enlarged view of 1st carbonate core showing vugs and fractures

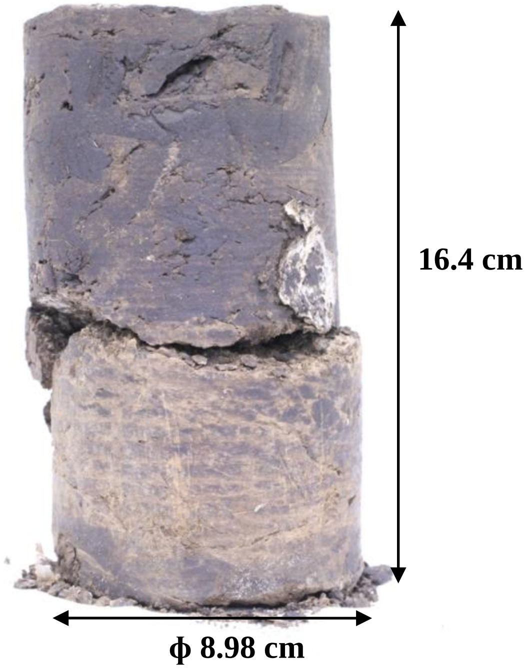

Figure 6-4: Core after the 1st experiment

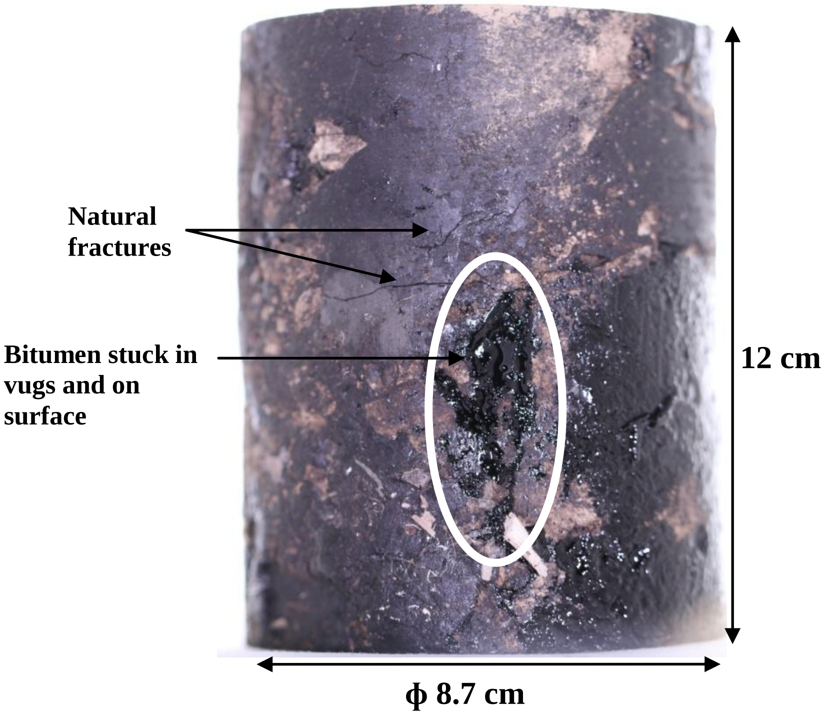

Figure 6-5: Core used in 2nd carbonate experiment

Figure 6-6: Core after the 2nd experiment

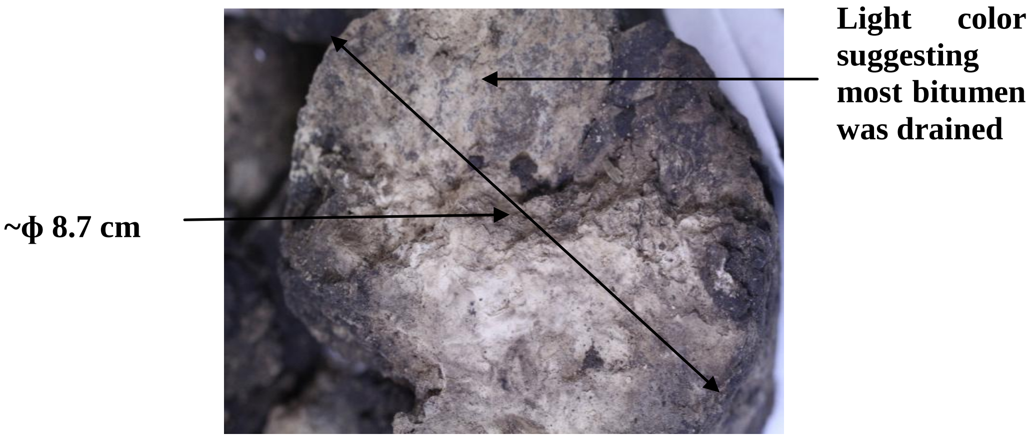

Figure 6-7: Cross section of the core after the 2nd experiment

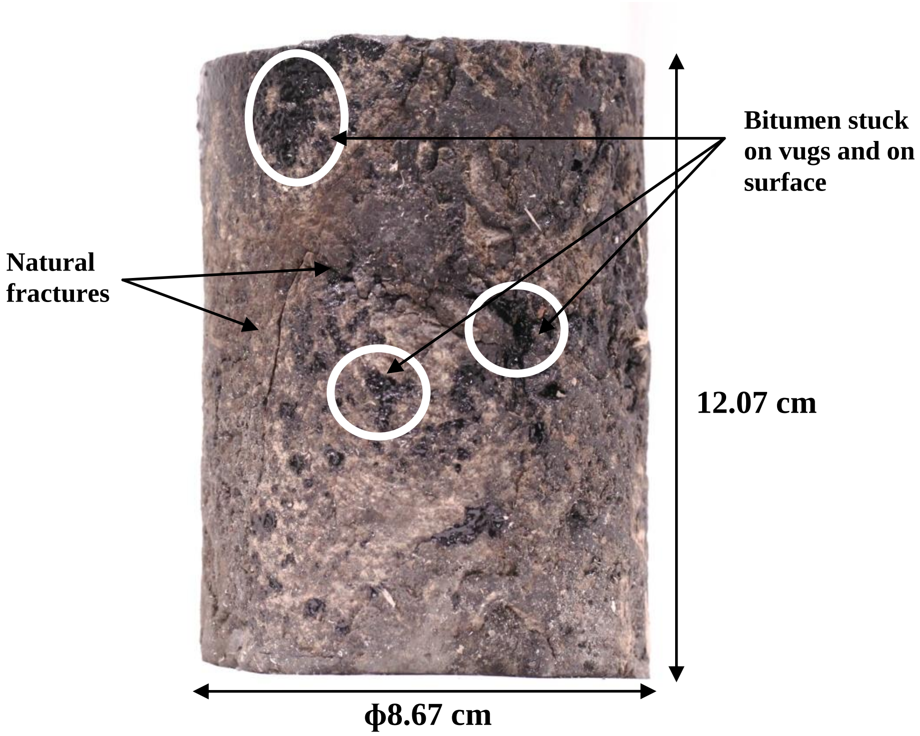

Figure 6-8: Core used in 3rd carbonate experiment

Figure 6-9: Core after the 3rd experiment

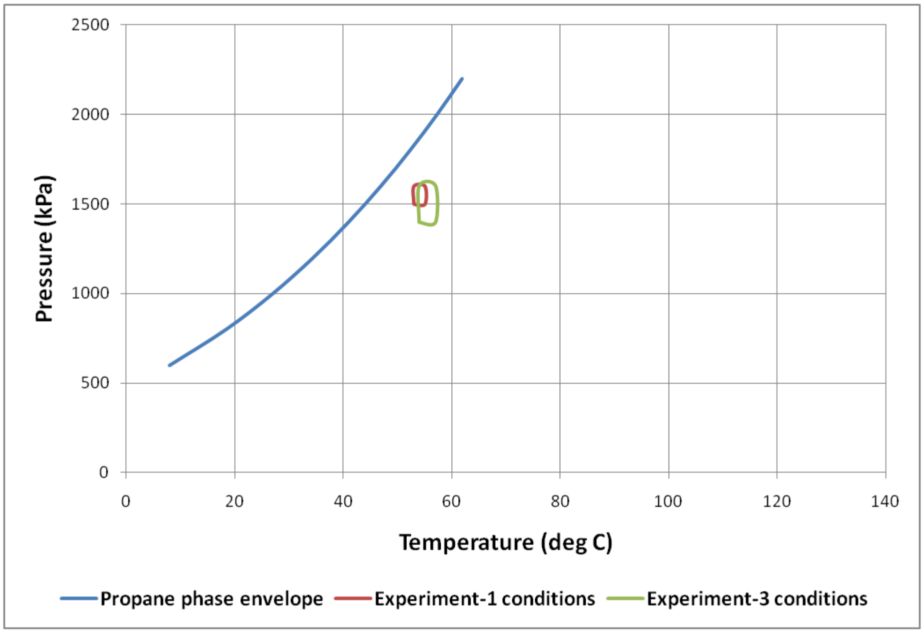

Figure 6-10: Propane phase envelope and pressure temperature conditions for experiments 1 and 3.

It can be seen that temperature and pressure varied in a zone, but it was attempted to keep this zone fairly close to the saturation conditions of propane.

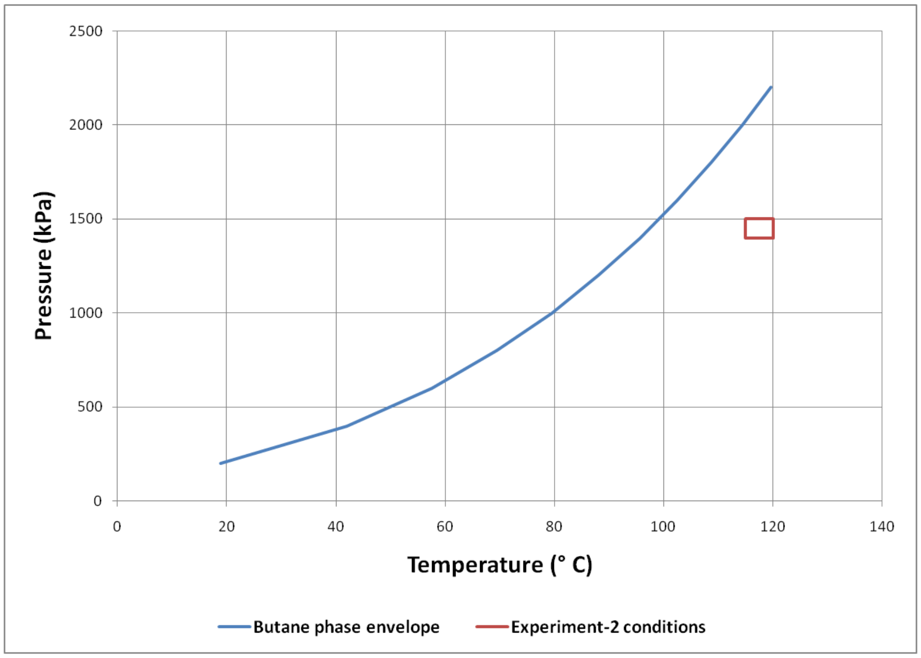

Figure 6-11: Butane phase envelope and pressure temperature conditions for experiment-2.

It can be seen that temperature and pressure varied in a zone, but it was attempted to keep this zone fairly close to the saturation conditions of butane.

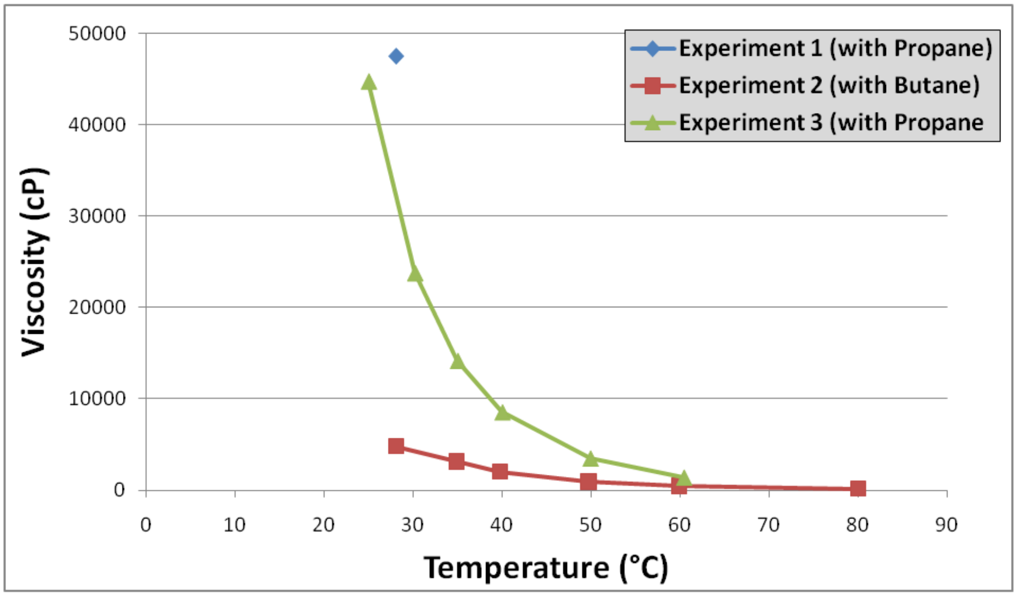

Figure 6-12: Viscosity of the produced oils with temperature

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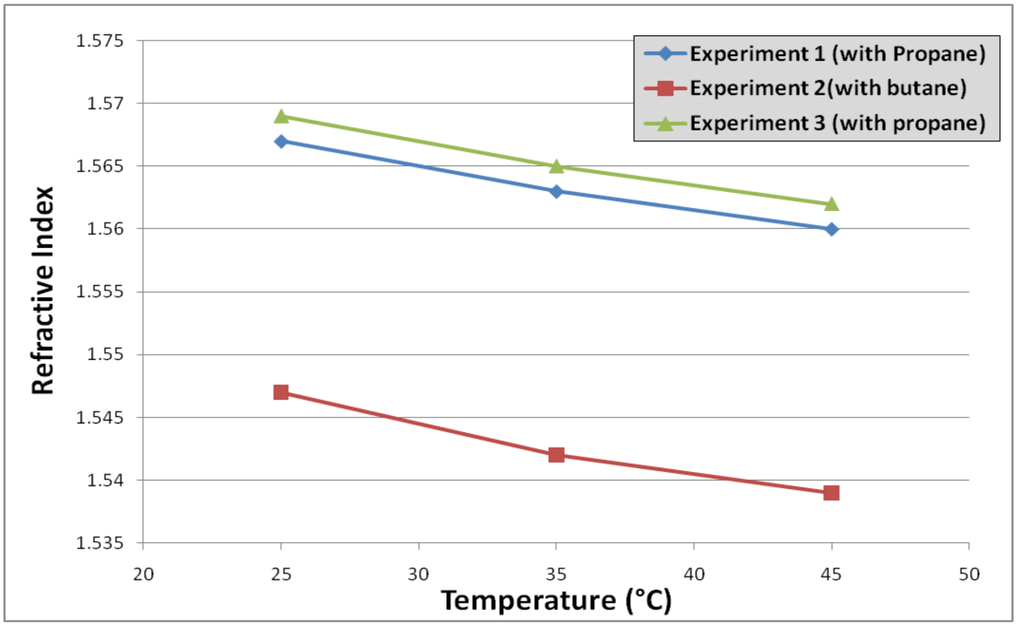

Figure 6-13: Refractive Indices of produced oils with temperature

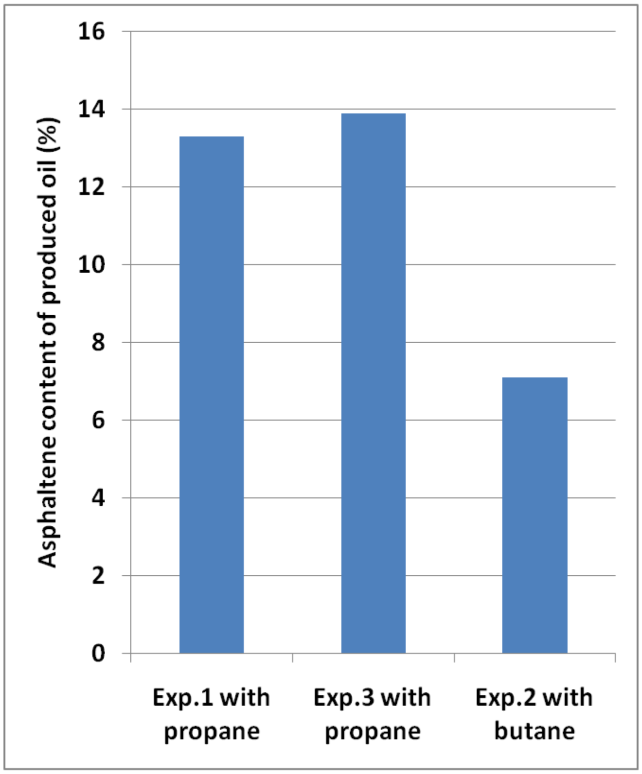

Figure 6-14: Asphaltene content of produced oils for the 3 experiments.

Note that % asphaltene in oil produced with propane is higher

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7 CONCLUSIONS, CONTRIBUTIONS AND RECOMMENDATIONS

The overall conclusions of the study from all previous chapters are presented in this chapter. These conclusions have been published and presented in papers and are presented in a combined format here. This study paves the way for further research in this area and at the end, some recommendations for future research are provided.

7.1 Conclusions

- Hot solvent experiments were conducted using propane and butane on glass beads packs, sandstone cores and original carbonate cores.
- Produced oils were analyzed and the asphaltene content was measured using the excess solvent (heptane)-filter paper method. Asphaltene deposited inside the porous media was also inferred from this result.
- Butane was found to “up-grade” the oil more than propane. The asphaltene content of the oil produced with propane as a solvent was found to be higher than the asphaltene content of the oil produced with butane as a solvent. Viscosity was also higher for the oil produced with propane as a solvent as compared to the oil produced with butane as a solvent. One of the reasons for this may be a higher amount of mass transfer of butane into the oil as compared to propane into the oil. Another reason may be that butane experiments were conducted at a higher temperature than propane experiments, which assisted in reduction of oil viscosity too.

The contents of this chapter were published in the various papers published during this study as listed in section 1.4

- Oil recovery was observed to decrease with increase in temperature and pressure. The recovery was observed to decrease with the increase in product of temperature difference between experiment temperature and saturation temperature, and experimental pressure. The recovery was more sensitive to temperature and a significant change in recovery was obtained with increasing temperature. The recovery reduced if temperature was much higher than the saturation temperature at experimental pressure. This was in accordance with the Raoult's law for mixtures.
- A non-linear correlation between the recovery and these three quantities was reported based on the best fit of the experimental data using various functions. This correlation also showed that recovery was more sensitive to temperature and is adversely affected by increase in temperature and pressure. Increase in sample height favoured higher recovery.
- The peak recovery was reached when the pressure and temperature were maintained near the saturation line but in the region where solvent was in the gaseous phase. For field cases, this means that a careful choice of solvent according to the field pressure and temperature, or heating up the reservoir prior to the injection of solvent is essential.
- Diffusion, heat transfer, gravity and capillary forces were identified as the dominant mechanisms for recovery during a hot solvent process. Values of diffusion coefficients for propane and butane in the given heavy oil were also estimated by fitting the pressure history data by the analytical solution to Fick's 2nd law of diffusion. The value for propane was calculated as

approximately $6x10^{-9}$ m^2/s. For butane, the value was calculated as approximately $5x10^{-9}$ m^2/s.

- Gravity was important for an effective drainage in the case of the hot solvent process. However, gravity can play a part in the dynamics of the process only when assisted by heat and mass transfer. It was also shown that height of the model positively affects the recovery, but this effect becomes small when the height of the sample is more than a certain value.
- Asphaltene precipitation was modeled numerically and also observed during visualization experiments. Asphaltene flocculation happens when the equilibrium of the heavy oil system is broken by changing composition due to solvent injection. Flocculation is higher for lighter paraffinic solvents as compared to heavier paraffinic solvents. However, more flocculation does not necessarily mean more asphaltene deposition on the porous media.
- It was shown that the maximum amount of asphaltene flocculation (and deposition) occurs at the interface of pure solvent and heavy oil, where the concentration gradient of the solvent is at its maximum. As the solvent continues to diffuse in the oil zone, asphaltene deposition keeps reducing.
- Asphaltene precipitation did not show a significant impact on recovery for extremely high permeability mediums like a glass-beads pack. In such cases, recovery was enhanced by asphaltene precipitation because of reduction in oil viscosity. For lower permeability media, asphaltene precipitation may play a significant role in the process dynamics.

- Solvent type affected the recovery because of the different amounts of dilution achieved. Moreover, the types of asphaltene flocculated with different solvents and their properties can be significantly different, which can create a big impact on the dynamics of the process.
- The produced oil did not seem to have any light components as shown by the GC-MS analysis. This means that the original oil has been up-graded but still did not have any light (C7 and lower) components. However, it should be kept in mind that GC-MS is not the most suitable technique to analyze oil samples as the amount of the sample introduced into the instrument is very small and that makes it difficult to detect traces of light hydrocarbons. A headspace-GC analysis is more recommended in this type of analyses as this technique involves an instrument which allows a much larger sample size to be introduced and tested.
- The carbonate experiments showed that hot solvent technique can give promising results even for thick bitumen saturated complex carbonate rock. Oil was diluted in all the experiments and was produced along with the solvent. It was found that the dilution achieved by butane was significantly more than the dilution achieved by propane. Subsequently, the recovery was higher when butane was used as solvent. Moreover, asphaltene content of the oil produced when butane was used as solvent was lesser than the asphaltene content of the oil produced when propane was used as solvent. In other words, asphaltene deposition on the rock surface was more in the case when butane was the solvent.

7.2 Contributions

- The hot solvent process was modeled in the laboratory and an in-depth analysis of the parameters affecting recovery in such a process was provided. This included innovative experimental setup, sample collection system design, asphaltene measurements, numerical simulations and visualization experiments.
- It was repeatedly shown that temperature of the system plays a vital role in determining the degree of dilution of heavy oil, and thereby impacts the recovery significantly. It was concluded that pressure and temperature of the system (field or lab) should be kept close to the saturation conditions of the solvent being used. Thus, optimum operating conditions for hot solvent process were identified successfully.
- The mechanics of hot solvent process was studied and various phenomena affecting the performance of such a process were identified. These included the effect of horizontal permeability, permeability anisotropy, capillary pressure, gravity and solvent type.
- Impact of asphaltene precipitation on recovery was studied in detail. A sensitivity study of how asphaltene precipitation affects recovery was performed. It was observed that the nature of asphaltene precipitated with different solvents is different. As a result, some asphaltene will be more susceptible to entrainment with the produced oil, while others will be more susceptible to deposition on the rock surface. In low-to-medium porosity systems, this will have a significant effect on the flow dynamics of the

The contents of this chapter were published in the various papers published during this study as listed in section 1.4

process. It was also shown that asphaltene deposition was the most prominent at the initial interface of pure solvent and heavy oil because of the high concentration gradient of solvent.

- Original carbonate core experiments were performed for hot solvent injection (only for the second time to the best of our knowledge) and very viscous bitumen was diluted and recovered. A major finding of this research is that hot solvent process has shown highly promising results at a lab-scale, and makes a case for field testing of this technique to recover the billions of barrels of bitumen located in Albertan carbonate reservoirs. Another major finding was that butane was observed to be a better solvent for field testing than propane based on the high degree of dilution achieved using butane in these experiments.

7.3 Recommendations for Future Work

- The experiments conducted in this study were hot solvent soaking experiments without continuous injection and production. Thus there was no question of measuring solvent injection and oil production rates. Doing an experimental study of hot solvent injection with continuous injection and production can lead to very interesting results which can improve our understanding of this process and its applicability in the field.
- The solvent gas produced in the experiments was vented out and was not analyzed for composition. This was because analyzing gas was out of scope of the current study. The next step in this research can be to install a gas chromatograph and a gas flow meter at the outlet gas line so that the

composition and the amount of gas liberated can be measured. Later, an effort can be made to re-cycle the solvent gas. This will help in making this process economical.

- For the current study, only hydrocarbon gases were used as solvents for hot solvent experiments. However, these gases are expensive. Another study can be done to identify the applicability of gases like CO_2 for the same process. In fact, CO_2 is cheaper and easily available and CO_2 sequestration can also make this process even more environmentally friendly.
- Most of the visualization done in this study was 2-dimensional. Although 2-D visualization was helpful in showing displacement patterns in miscible injection and asphaltene deposition pattern, 3-D porous media visualization can show these patterns in more detail and improve our understanding significantly. This will be a highly challenging task. It may involve the use of multiple sensors like salinity sensor, resistivity sensor, optical sensor etc. It may even involve highly sophisticated techniques such as laser combined with a high speed camera or continuous CT scans.
- In the absence of accurate fluid properties, the fluid model used for numerical simulations was simplified based on assumptions about the fluid composition. This was sufficient to obtain a qualitative history match of the experiments and also to investigate the various parameters affecting recovery. However, a good quality fluid model can help in achieving a quantitative history match. For this, it will be needed to analyze the tested

oil for composition, conduct PVT experiments on this fluid, select an Equation-of-State (EoS) to represent the fluid, tune this EoS to match the PVT experiments, generate the fluid model based on tuned EoS, and finally use this fluid model in compositional or thermal simulations.

- The asphaltene deposition, precipitation and entrainment properties were also assumed for the numerical simulations during this study. These properties should also be measured for future work by conducting asphaltene deposition and precipitation measurements.

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9 APPENDIX

ECLIPSE code for a sample simulation run

```
----------------------------------------------------------------------
--Simulating miscible injection
--Propane being injected in a model 16 cm by 24 cm
-- LAB units
-- OIL and GAS only, no water
--------------------------------------------------------------------------------------------------
RUNSPEC  -- Model dimensions and details
--------------------------------------------------------------------------------------------------
OIL – Oil phase
GAS – Gas phase
FULLIMP – Fully implicit solution scheme
DIMENS – Model dimensions 20x1x30
--ni nj nk
20  1  30  /
CART -- Cartesian co-ordinate system
LAB – Lab units
COMPS -- Number of components: implies compositional run
--nc
```

7 /

MISCIBLE – Declaring miscibility

UNIFOUT – Unified output file, easier to deal with

ASPHALTE – Allowing asphaltene deposition

 WEIGHT PORO   KD/

GRID – Grid Properties

DX – x-dimension of each grid block, 0.8 cm for each of the 600 grid blocks

600*0.8 /

DY – y-dimension of each grid block, 0.8 cm for each of the 600 grid blocks

600*0.8 /

DZ – z-dimension of each grid block, 0.8 cm for each of the 600 grid blocks

600*0.8 /

PORO – Porosity of 20% for all 600 grid blocks

600*0.2 /

PERMX – x-permeability of 200 Darcies for all 600 grid blocks

600*200 /

PERMY – y-permeability of 200 Darcies for all 600 grid blocks

600*200 /

PERMZ – z-permeability of 200 Darcies for all 600 grid blocks

```
600*20 /

BOX

1 20 1 1 1 1 / -- Box from i=1 to 20, j=1 and k=1 for assigning property

/

TOPS – Layer top for the box

20*0 /

/

ENDBOX

--Depth of cell centres

INIT – To write initial properties to an output file

RPTGRID – to write grid properties to an output file

'DX' 'DY' 'DZ' 'PERMX' 'PERMY' 'PERMZ' 'MULTZ'

'PORO' 'TOPS' 'PORV' 'TRANX' 'TRANY' 'TRANZ' /

-----------------------------------------------------------------------------------------------

PROPS – Rock and fluid properties, fluid PVT generated in PVTi

-----------------------------------------------------------------------------------------------

STCOND – Standard temperature and pressure

50.0 10.0 /

GRAVITY –Fluid specific gravities, oil gravity is not used from this keyword. Its
calculated from the EoS. Only water gravity is needed from this keyword here.

1* 1.01 1* /
```

```
RTEMP -- Reservoir temperature: Deg C

40.0 /

----------------------------------------------------------------------------------------------
--From  PVTi------------------------------------------------------------------------------
----------------------------------------------------------------------------------------------

ECHO

EOS -- Equation of State (Reservoir EoS)

   PR3 – Peng Robinson

/

 NCOMPS -- Number of Components

       7

/

PRCORR -- Modified Peng-Robinson EoS

CNAMES -- Component Names

   'C3'

   'C4'

   'C5'

   'C20+'

   'C35+'

   'C45+'

   'ASPH'

/
```

```
MW -- Molecular Weights (Reservoir EoS)
     44.097
     58.124
     72.151
       600
       800
       900
       900
/
 OMEGAA -- EoS Omega-a Coefficient (Reservoir EoS)
  0.457235529
  0.457235529
  0.457235529
  0.457235529
  0.457235529
  0.457235529
  0.457235529
/
OMEGAB -- EoS Omega-b Coefficient (Reservoir EoS)
  0.077796074
  0.077796074
```

```
  0.077796074

  0.077796074

  0.077796074

  0.077796074

  0.077796074

/

TCRIT -- Critical Temperatures (Reservoir EoS) Units: K

      369.8

      419.5

      465.9

  1026.29859917674

  1129.71599145143

  1177.59990616957

  1177.59990616957

/

PCRIT -- Critical Pressures (Reservoir EoS) Units: atmospheres

       41.9

      36.98

      33.15

  3.97882473515204

  2.15906635658273
```

```
  1.61991680663811
  1.61991680663811
/
 VCRIT -- Critical Volumes (Reservoir EoS) Units: cc /gm-mole
          200
          258
          310
  2417.01010219197
  3245.06900981825
  3655.97611177161
  3655.97611177161
/
 ZCRIT -- Critical Z-Factors (Reservoir EoS)
  0.276164620041118
  0.27716958741494
  0.268808776316087
  0.114195888099218
  0.0755808163533369
  0.0612899442011293
  0.0612899442011293
/
```

```
SSHIFT -- EoS Volume Shift (Reservoir EoS)

  -0.0775013814750784

  -0.0568111730400199

  -0.0349236145797843

  0.631193548754501

  0.767001599953315

  0.815478743564174

  0.815478743564174

/

ACF -- Acentric Factors (Reservoir EoS)

       0.1524

       0.1956

       0.2413

  1.6370011798811

  1.93773086371651

  2.06136220900822

  2.06136220900822

/

 BIC -- Binary Interaction Coefficients (Reservoir EoS)

      0

      0       0
```

```
   0.01    0.01     0.01
   0.04    0.04     0.04      0
   0.08    0.08     0.07      0      0
   0.08    0.08     0.07      0      0     0
/
 PARACHOR -- Component Parachors
      150.3
      187.2
      228.9
    1506.668
    2000.002
    2246.669
    2246.669
/
 VCRITVIS -- Critical Volumes for Viscosity Calc (Reservoir EoS) Units: cc /gm-mole

        200
        258
        310
  2417.01010219197
```

```
   3245.06900981825
   3655.97611177161
   3655.97611177161
/
ZCRITVIS -- Critical Z-Factors for Viscosity Calculation (Reservoir EoS)
   0.276164620041118
   0.27716958741494
   0.268808776316087
   0.114195888099218
   0.0755808163533369
   0.0612899442011293
   0.0612899442011293
/
 LBCCOEF -- Lorentz-Bray-Clark Viscosity Correlation Coefficients
    0.1023 0.023364 0.058533 -0.040758 0.0093324
/
ZI -- Overall Composition
             0
             0
             0
           0.2
```

```
        0.4
        0.4
          0
/
 -- Rock properties
ROCK
10.0  0.000004  / -- Rock compressibility at 10 atm pressure
SGFN – Gas relative permeability and oil-gas capillary pressure
0.00  0.0000  0.0
0.10  0.0156  0.0
0.20  0.0625  0.0
0.30  0.1406  0.0
0.40  0.2500  0.0
0.50  0.3906  0.0
0.60  0.5625  0.0
0.70  0.7656  0.0
0.80  1.0000  0.0  /
SOF2 – Oil relative permeability
0.20  0.0000
0.30  0.0278
0.40  0.1109
```

```
0.50  0.2500

0.60  0.4444

0.70  0.6944

0.75  0.8403

0.80  1.0000 /

ASPFLOC – Asphaltene flocculation properties

-- first  last  floc

    6     6     7  / -- Component no. 6 flocculates and precipitates as asphaltene

ASPP1P -- concentration 1st component

Z  1/

ASPREWG – Asphaltene precipitation table asphaltene in oil against mole fraction of solvent in oil

-- Z1 % weight

0.001     100.0

0.01       50.0

0.05        5.0 /

ASPVISO – Viscosity change due to asphaltene precipitation

-- Conc. max pack.       int. visco

      1                 2   /

ASPFLRT – Asphatlene flocculation and dissociation rates

-- CMP6
```

```
   0.100
   0.01  /
ASPDEPO -- Asphaltene deposition
-- adsorp   plug    entrain    Vcr
      0.1     1.e-4     1.e-5      1 /
ASPKDAM – Pemeability damage due to asphaltene
-- exponent
    3 /
-----------------------------------------------------------------------------------------------
SOLUTION – Defining initial conditions for the model, explicitly in this case
-----------------------------------------------------------------------------------------------
PRESSURE – Entire grid at 10 atmospheres initial pressure
600*10.0 /
SGAS – Zero initial gas saturation in entire grid
600*0.0 /
ZMF – initial mole fractions of individual components in the entire grid
600*0.0 600*0.0 600*0.0 600*0.2 600*0.4 600*0.4 600*0 /
--  Calculate initial oil and gas in place at surface conditions
FIELDSEP – Defining initial oil and gas in place by putting field separator
1 15.0 1.0 /
/
```

```
RPTSOL

PRES  SOIL  SGAS  /

OUTSOL

PRES  SOIL  SGAS /

RPTRST

  PRESSURE  DENO  SOIL  SGAS  SWAT  XMF  YMF  ASPADS  ASPDOT
ASPEN ASPFL ASPKDM ASPLU ASPREW ASPVOM  /

--------------------------------------------------------------------------------------------------

SUMMARY – Line plots generated for these properties

--------------------------------------------------------------------------------------------------

WOPR – Well oil production rate for production well

PRODUCER  /

FOPR – Field oil production rate

FGPR – Field gas production rate

FPR – Field average pressure

FOPT – Field oil production total (cumulative)

WGOR – Well Gas-Oil-Ratio (GOR) for the production well

PRODUCER  /

RUNSUM – Tabulated output from this section also generated

EXCEL – For run summary output in Excel format

--------------------------------------------------------------------------------------------------
```

```
SCHEDULE – Scheduling the well events

-------------------------------------------------------------------------------------------------

RPTRST – Outputs for the restart file

BASIC=2 DENO SOIL SGAS VOIL XMF YMF /

/

CVCRIT – Convergence criteria

-0.001 /

WELSPECS – Specifications of the wells- names, x- and y- locations and type

INJECTOR G1   10 1 1* OIL  /

PRODUCER G2   10 1 1* OIL  /

/

COMPDAT – Perforations for the injection and production wells

INJECTOR   10 1  1   1  OPEN 1 5000 /

PRODUCER   10 1  30  30  OPEN 1 5000 /

/

WELLSTRE – Composition of the injection stream

--name         z1 z2 z3 z4 z5 z6 z7

LEANGAS  1   0   0   0   0   0   0 /

/

WCONINJE – Reservoir volume control of injection well

INJECTOR  GAS OPEN RESV 1* 1 /
```

/

WINJGAS – Specifying that the gas being injected is called “LEANGAS”

INJECTOR STREAM LEANGAS /

/

WCONPROD – Producer on BHP control of 10 atmospheres

PRODUCER OPEN BHP 5* 10.0 /

/

RPTPRINT – Controlling the output of printed reports

1 1 1 1 1   1 1 1 0 0 /

TSCRIT – setting time stepping criteria

0.001 0.0001 0.02 /

TSTEP

100*1 / --Run for 100 hours : 100 time steps of 1 hour each

END