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Experimental Study of Interfacial Phenomena between the Heavy Oil and Maximum Solvent Concentration as Function of Injection Pressures

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Abstract Heavy Oil is an up and coming energy resource that is aggressively being sought after as the world's energy demand increases. As technology continues to improve, this once costly energy source is quickly becoming a more viable alternative. Vapor extraction (Vapex) process is an emerging technology for viscous oil recovery that has gained much attention in the oil industry. The vapor extraction of heavy oil system is presented to describe experimental setups and procedures used to perform different experiments of vape extraction process. The generated experimental data were used to calculate the live oil maximum interfacial solvent concentration as function of injection pressures. In this work the effect of solvent injection pressure pulsing on oil production rates and recovery was investigated. The lab-scale experiments were designed and carried out to investigate this concept. The experiments were performed injecting pure butane at injection pressures of 91.01, 97.90, 104.80, and 111.69 kPa and 21℃ for about 6 to 7 hours. A cylindrical physical model with 25 cm heights was packed with permeability 204 Darcy and saturated with heavy oil at high viscosity. The experiments were performed with different policies of solvent injection pressure versus time. Pressure pulsing was introduced by sudden release and re-injection of the solvent gas. Compared to constant injection pressure the pressure pulsing further enhanced the oil production rates and recoveries in Vapex process.

Keywords: Heavy oil, vapex, vapor extraction, solvent gas.

1 Introduction

Petroleum is the world's primary energy source and is a key factor in the continued development of world economies. The deflection of conventional oil resources all around the world has become a serious source of concern for industry and government and is a reason to think about other energy alternatives. On the other hand there are huge and virtually untouched reserves of heavy oil and bitumen deposits in the globe especially in Canada and United States, which are almost six times of total conventional resources.

In Canada, the estimated original oil in place (OOIP) is more than 400 billion m^3 (2.5 trillion barrels) approximately twice that of the total conventional oil reserves in the Middle East [ERCB, (1989)].

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In Canada, Alberta's in-place oil sands reserves are about 1.7 trillion bbl. More than 175 billion bbl is recoverable with current technology. With technical advances, about 315 billion bbl could be recovered. However, the main difficulty in the oil recovery from these vast reserves is their immobility under reservoir conditions due to their high viscosity (10^4–10^6cP or even higher) [Das, and Butler (1996)].

The recovery of heavy oil and bitumen is difficult, as 90% of these reserves lie deep inside the earth crust and are not easily recoverable owing to their high viscosity and immobility. The objective of recovery process is to reduce the viscosity, or equivalently to increase the mobility of heavy oil and bitumen. This objective is achieved by providing additional energy to heavy oil and bitumen reserves [El-Haj, Lohi, and Upreti, (2009)].

Vapor Extraction (Vapex) of Heavy Oil and Bitumen is a promising recovery technology that involves the injection of gaseous solvents into the reservoir [Das, (1998)].Typically, in VAPEX process light hydrocarbon solvent or mixture of them at the dew point or close to it is used to reduce the viscosity of the heavy oil in a reservoir [Butler and Mokrys (1993)]. Petroleum reserves are classified as conventional and unconventional based on their viscosities and API gravities [Imran, Upreti and Lohi (2008)]. The viscosity of conventional reserves is lower than 100 mPa-s (100 cP) with API gravity of 21º or greater, while unconventional reserves have viscosity greater than 100 mPa-s (100 cP) with API gravity of 20º or less [Speight, (1991)].

The predominant mechanism for Vapex process is the diffusion of solvent into the heavy oil and bitumen. The viscosity reduction depends predominantly on the molecular diffusion of the solvent. The molecular diffusion however is considerably less than thermal diffusion. Because of this fact, the initial oil recovery starts later and is slower than that in a thermal oil recovery process even though the solvent dispersion effects help augment the mass transfer [Jiang, and Butler (1996)]. The Production rates are directly related to viscosity reduction, which in turn depends on the amount of solvent dissolved in the oil. Mixing of the solvent with heavy oil and bitumen is slow because it occurs only when solvent diffuses through the pores [Karmaker and Maini (2003)].

2 Experimental set-up and procedures

This study describes experimental set-up and procedure used to perform vapor extraction (Vapex) of heavy oil using propane as well as butane gas as a solvent. Generated experimental data were used to calculate the live oil viscosity, density, cumulative production rate, solubility of solvent gas in heavy oil and maximum interfacial solvent concentration as function of injection pressures. This work also includes details of experimental permeability determination for different physical models.

Two different experimental setups were designed to perform these studies. 1) First setup was used to perform two different sets of Vapex experiments. i) First set of experiments was performed with constant solvent injection pressure. ii) In the second set of experiments, the solvent injection pressure was varied to examine the effect on oil production injection.

2) Second setup was design to evaluate relationship between the solvent injection pressure and maximum solvent concentration at the solvent-oil interface. This

evaluation was required to map the interfacial solvent concentration with solvent injection pressure. Below are the details for experimental setups and procedures.

2.1 Vapex experimental set-up

The schematic of the experimental set up used in this work is shown in Figure 3.1. This set up was used to perform Vapex experiments in order to study the production rates of the live oil and measured the required data to calculate the variation of injection pressure to enhance oil production rate in Vapex process**.** The schematic diagram of the experimental set up is shown in Figure 1. The experiments were performed using two electronically regulated proportional valves (Model, PV101-10V, Omega Engineering, Inc. Canada) to control pressure.

The set up consists of a cylindrical pressure vessel of 15 cm internal diameter and 80 cm height with the arrangement of a load cell (LC, capacity: 4500g, LSB200, JR S-Beam , provided by FUTAK advance sensor technology. INC., Irvine, CA, USA), and monitoring instruments for temperature of the vessel, pressure inside the vessel, temperature of the sample and temperature of water bath. Proportional control valves are placed in the butane gas line and the other is attached to the pressure vessel. The pressure inside the vessel is either kept constant or temporally varied. The vessel is placed inside a temperature-controlled water bath. The temperature controller is designed to maintain the temperature within ±0.5 °C of the set point.

In a given experiment, oil saturated porous medium with glass beads of known size was packed in one of the cylindrical models comprising of a stainless steel wire mesh and attached with the load cell hook, fitted on the top flange of the pressure vessel. The load cell was used to record the weight change in the sample model resulted from dispersive action of the solvent gas that dilute the heavy oil. All the temperature sensors, pressure transducers, flow meter of input gas, load cell, and two pressure valves were connected to a data acquisition system (DAS), which was connected to a computer. Labview version 7.1 software provided by National instruments was used for graphical user interface and online monitoring of all input and output data of the setup. Research grade butane and propane with purity of 99.99% (MEGS specialty gases Inc., Montreal, Quebec) were used as solvents at laboratory ambient temperature, which varied between 21ºC and 22ºC, for all experiments.

To collect the produced oil, a small carbon steel funnel at the vessel bottom was used. The funnel collected the diluted drain oil and directed it towards the collection tube calibrated to 25 cm^3. The collection tube was connected to a stainless steel capillary tube of length 50 cm with an internal inside diameter of 0.1016 cm. The capillary tube was used to measure the viscosity of live oil. A differential pressure transducer was connected to both ends of the capillary tube. Through the capillary tube, oil was directed to a stainless steel flash tank with holding capacity of 300 cm^3. The flash tank was wrapped with an electrical heating tape (HTWC 101, heat tape with controller) and a controller to maintain the temperature of the live oil. Flash separation tank was used to remove the dissolved solvent gas from the produced live oil.

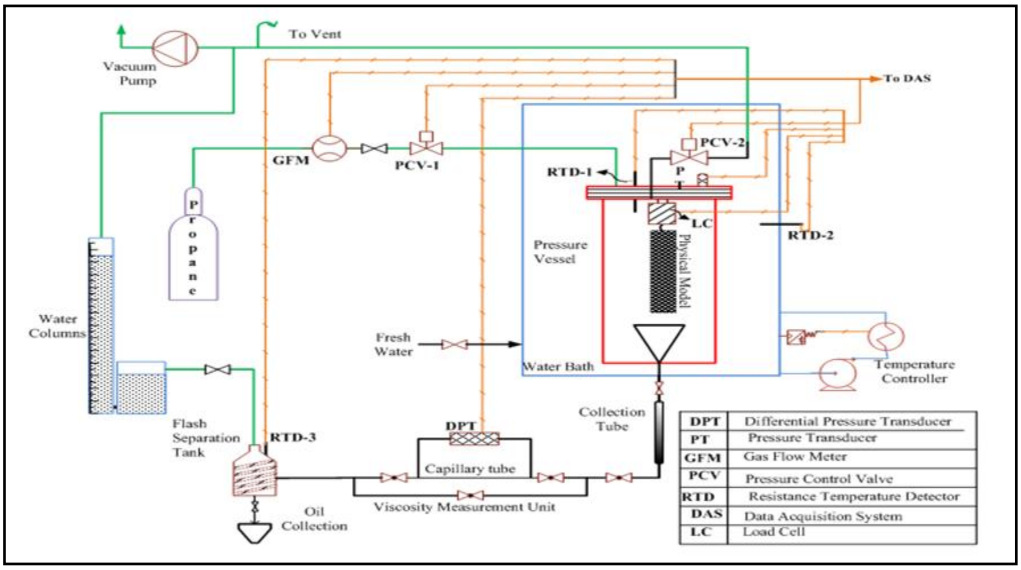

Figure 1: Schematic diagram of the experimental setup.

2.1.1 Heavy oil properties

The heavy oil used in this study was obtained from Saskatchewan Research Council (SRC), Regina. The viscosity of heavy oil was determined by using Bohlin Viscometer. A small amount of oil (10 grams) was placed in the cone and plate arrangement of the viscometer. The viscosity of the heavy oil was determined at different temperatures starting from 20^{o}C to 40^{o}C. The viscosity of the oil at the experimental temperature was found to be 14,500 mPa.s. Figure 2 shows viscosity of heavy oil versus temperature. The heavy oil density, molecular weight, and SARA (wt %) are shown in Table 1.

Table 1: Properties of the heavy oil

Heavy Oil Properties	(^{o}C)	(kg/m^3)
Density (kg/m^3) at ^{o}C	15	984
	25	977
	40	968
Mol Weight (kg/kmol)		496
SARA (wt %)		
Saturates	29	
Aromatics	31	
Resins	22	
Asphaltenes	14	

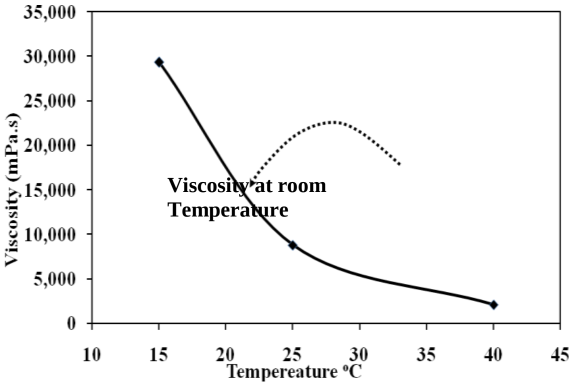

Figure 2: Viscosity of heavy oil versus temperature

2.1.2 Live oil viscosity

Reduced viscosity of heavy oil results from solvent concentration, that augments as solvent penetrates and mixes with the heavy oil. Viscosity reduction of the mixture would affect the mobility and the fluid flow mechanism of the process. A viscosity model is crucial in Vapex since it governs the movement of live oil in the reservoir, and thus has a direct bearing on oil production. Figure 1 shows the unit of the experimental setup used for live oil viscosity determination. The setup comprises of a collection tube, capillary tube, pressure transducer, and needle valve. After the collection tube was filled with produced live oil, the live oil was allowed to flow though a viscosity measuring unit via a stainless steel tube of 12 mm outside diameter, and 2 mm thickness. The viscosity was determined by passing the live oil through a capillary tube of 0.1016 cm diameter and 50 cm length. A pressure transducer was connected at both sides of tube to measure pressure drop across the tube. To make the live oil flow from the calibrated collection tube, the valve situated between the funnel and calibrated collection tube was opened. The flow rate of live oil was determined by measuring the time required by known volume of live oil to pass through the collection tube. The viscosity of live oil was determined by using the Hagen-Pioseulle equation.

$$Q = \frac{\pi \mathrm{d}^4 \Delta P}{128 \mu L} \tag{1}$$

with knowing the diameter of the capillary tube (d), (ΔP) across the tube, length of the capillary tube (L) and flow of live oil across the tube (Q). The live oil viscosity is a strong function of propane mass fraction. It was reduced by four orders of magnitude and this would affect the mobility of the diluted oil.

Figure 3 is showing the viscosity as a function of propane mass fraction described by the power law relationship. The empirical correlation for the propane-heavy oil system during the process at the operating temperature and pressure is:

$$\mu = 1.361 \omega^{-2} \qquad 0.25 \le \omega \le 0.51 \tag{2}$$

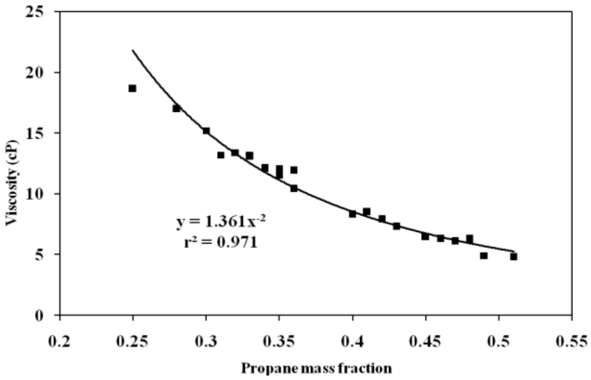

Figure 3: Live oil viscosity versus propane mass fraction

2.1.3 *Solvent gas solubility and live oil density*

In this experimental work, butane and propane were used separately as solvents. The collected live oil was periodically flashed inside a stainless steel flash separation tank (300 cm^3 capacity) wrapped with a flexible electrical heating tap. The temperature of the tank was kept around 60ºC. The amounts of (i) absorbed gas transferring the liberated gas to gas measuring column initially filled with water, and (ii) residual gas free oil (dead oil) were measured. The flashed liberated solvent gas was allowed to collect into a transparent gas-measuring column (3000 cm^3) for volume measurement.

The mass of the solvent gas was determined as follows. A known amount of live oil was transferred to flash tank through capillary tube by controlling the amount of oil by using the valve located before the flash tank. Temperature of flash tank was maintained at 70ºC to ensure proper flashing of the gas. The flashed gas was diverted to the first water column. Wherein the water was displaced resulting in a rise of the water level in second water column. After some time (10-15 min) differential pressure reading approached zero with no more displacement in the second water column. The displaced volume of water determined the gas volume. The valve on the top of first column was opened to vent the gas, and net amount of dead oil was collected by opening the valve at the bottom of the flash tank. Knowing the amount of propane or butane (C_4H_{10}, or C_3H_8), dissolved in oil, the solvent gas-free oil (dead oil) weight, and the volume of the live oil, the solubility of gas was determined as well as the live oil density using the following formulas:

$$\omega = \frac{m_{\text{gas}}}{m_{\text{gas}} + m_{\text{oil}}} \tag{3}$$

$$\rho = \frac{m_{\text{gas}} + m_{\text{oil}}}{V_{\text{live oil}}} \tag{4}$$

where ω weight fraction of solvent gas, m_{gas} is weight of liberate solvent gas, m_{oil} is the weight of dead oil, ρ is the live oil density, and $V_{\text{live oil}}$ is the volume of live oil.

2.1.4 *Effect of pressure on live oil production rate*

The mass transfer is enhanced when solvent is injected close to its dew point pressure at injection temperature 21ºC. Slow mixing of the solvent with heavy oil and bitumen reserves results in a long start-up time and a low initial rate of heavy oil and bitumen recovery. The results obtained in the present study demonstrated that the temporal variation of solvent injection pressure had a significant effect on oil production rates and recoveries. The variations in the injection pressure can increase the live oil production by more than 30% in some cases. The effect of injection pressure variation on oil production rates is discussed below in detail.

- *Live oil production rate at different pressure close to dew point*

In order to study the effect of pressure on heavy oil recovery by VAPEX process, pure butane solvent at different injection pressures of 91.01, 97.90, 104.80, and 111.69 kPa was injected into the physical sample enclosure for 6 hours using heavy oil with viscosity of 14,500 mPa-s.

Figure 4 shows the cumulative live oil productions at varying pressures. It is clear from this figure that more oil was produced at higher pressures. Typically we found that by increasing the pressure from 91.01 kPa to 111.69 kPa, the production rate of oil increased from 0.25 g/min to 0.45 g/min. This was due to the increase in the solubility of the solvent in heavy oil with pressure. In other words, use of vaporized solvent near its saturation conditions resulted in more oil recovery. As a result, the recovery process efficiency increased as the pressure approached the saturation pressure. We also injected the solvent gas at very close to the dew point. There was a sudden pressure drop and solvent condensation, which resulted decrease in mass transfer due to liquid-liquid mass transfer and reduction of process efficiency. In our experiment, it was observed that at the pressure of 17.2 psi (118.58 kPa), the butane started to liquefy. As a result, a two-phase solvent-oil mixture formed inside the physical model and blocked the oil drainage, and decreased the oil production rate.

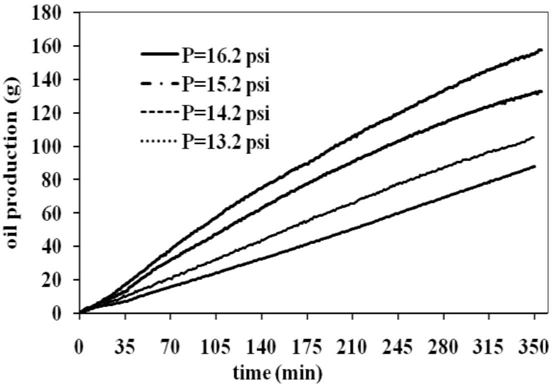

Figure 4: Cumulative live oil production versus time (204 D, H=25 cm, Butane, different pressure)

- *Effect of pressure variations*

In the next step, we varied solvent injection pressure with time. The model height and permeability were fixed at 25 cm and 204 Darcy, respectively. Solvent injection pressure was varied to generate a temporal variation in pressure (pressure pulsing). The pressure was varied by releasing the solvent gas at once to vent and re-injecting the gas again with a specified time interval. The oil production history at two different re-injection times was studied and was compared with the production history from a constant injection pressure.

Figure 5 presents the solvent injection pressure curves for two re-injection times. The solid black line shows the injection pressure curve when solvent was re-injected right after it vented out (short pulse). Re-injection of solvent with short pulse resulted in approximately three minute delay for the system to achieve the set injection pressure. The dotted black line shows the pressure when solvent was re-injected with a delay (long pulse). A delayed re-injection resulted in approximately 8 minutes delay for the system to achieve the set injection pressure.

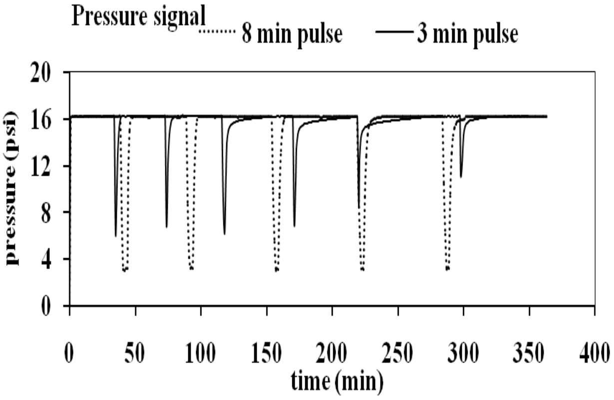

Figure 5: Two different variation pressure versus time

Figure 6 compares the cumulative oil production obtained from the constant pressure injection and pressure pulsing generated with short pulse. The pulse injection pressure is also presented on the same plot. Temporal variation in the injection pressure resulted in the recovery of ~193 grams of oil in 350 minutes as compared to 155 grams of oil recovery over the same period for a constant injection pressure. This outcome indicates that a variation in the injection pressure pulsing resulted in ~24% more recovery compared to constant injection pressure.

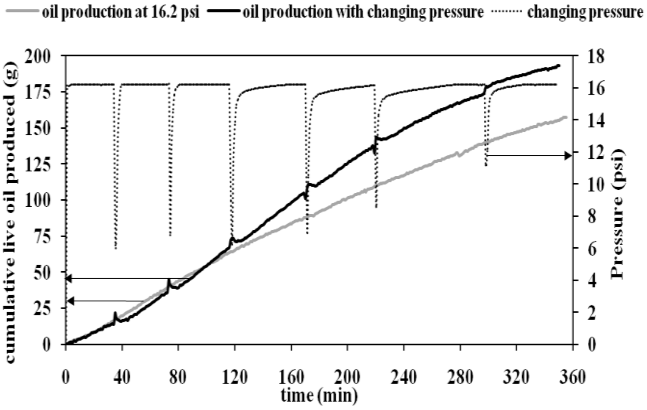

Figure 6: Cumulative live oil production versus time (204 D, H=25 cm, Butane, short pulse)

Figure 7 compares the cumulative oil production curves obtained from the constant pressure injection and pressure pulsing generated with long pulse. Similar to the previous case, temporal variation in injection pressure with long re-injection times resulted in ~19% more oil recovery compared to constant injection pressure.

However, a short pulse showed more promising recovery and oil production rate. Moreover, the results also showed that there was increased in production rate at the re-injection intervals, which indicates that some oil gets entrained long with solvent gas from the physical model

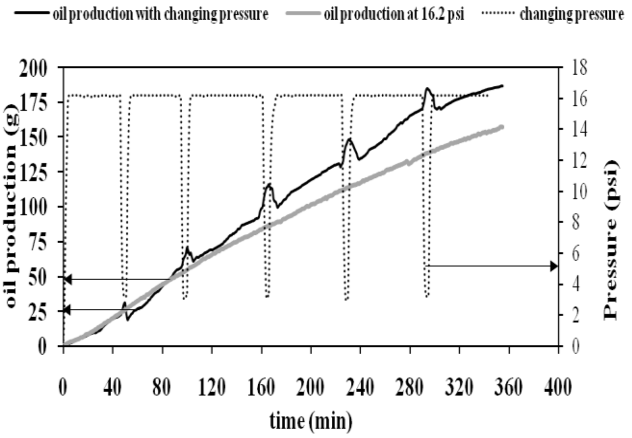

Figure 7: cumulative live oil production versus time (204 D, H=25 cm, Butane, long pulse)

2.2 Interfacial concentration setup

This setup was used to correlate the injection pressure of a solvent to its concentration at the solvent-oil interface during Vapex. This evaluation was required to map the optimal interfacial solvent concentration versus time obtained from the optimal control algorithm to solvent injection pressure versus time policy.

This experimental setup primarily comprised of a high-pressure vessel, syringe pump, water bath, data acquisition system, capillary tubes for oil sample collection and high accuracy scale. This experimental setup was designed to determine a functional relationship between the solvent injection pressure (P) and interfacial solvent concentration (ω_{int}) at the solvent-oil interface, i.e.

$$P = P\,(\omega_{\text{int}}) \qquad (5)$$

Experiments with different injection pressures were performed in the setup whose schematic is shown in Figure 8 and the maximum solvent concentration for each pressure was measured.

2.2.1 Experimental procedure

Figure 9 shows picture of the experimental setup, the pressure vessel was placed in a water bath held at a constant temperature, and was filled with about 25 grams of heavy oil. The top end of the vessel was connected to syringe pump and a capillary tube that was used to take the oil sample from the top most layers. Propane or butane gas was injected to the vessel through the syringe pump at a constant pressure for at least 24 hours at 21ºC. The concentration of solvent present in the surface was determined as follows.

Through capillary lines the diluted oil sample was taken from the top layer very close to the heavy oil surface (about one millimeter) into a sealed collection tube (see

Figure 8). The sealed sample tube was weighed for oil with solvent. Then this tube was open to atmosphere and warmed around 60°C to release the dissolved and residual propane in the oil. After flushing the solvent gas out the tube with oil (only) was weighed. From the mass balance, gas mass fraction in the oil was calculated. The experiments were performed at different injection pressures. The solvent concentration thus obtained is the interfacial concentration used in this study. Table 2 shows the interfacial concentration of propane and butane at different pressures.

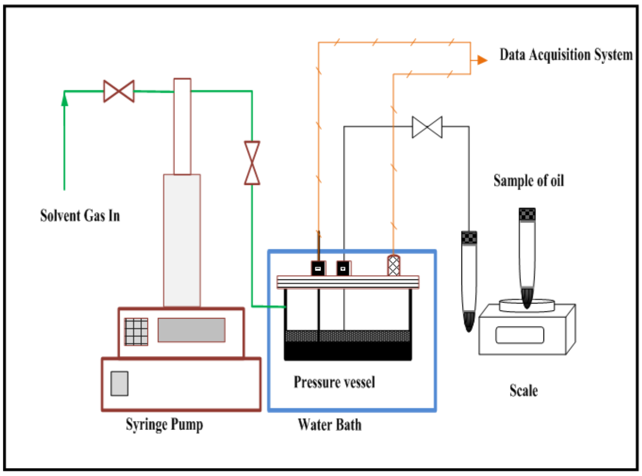

Figure 8: Schematic of solvent–heavy oil system for the measurement of interfacial solvent concentration

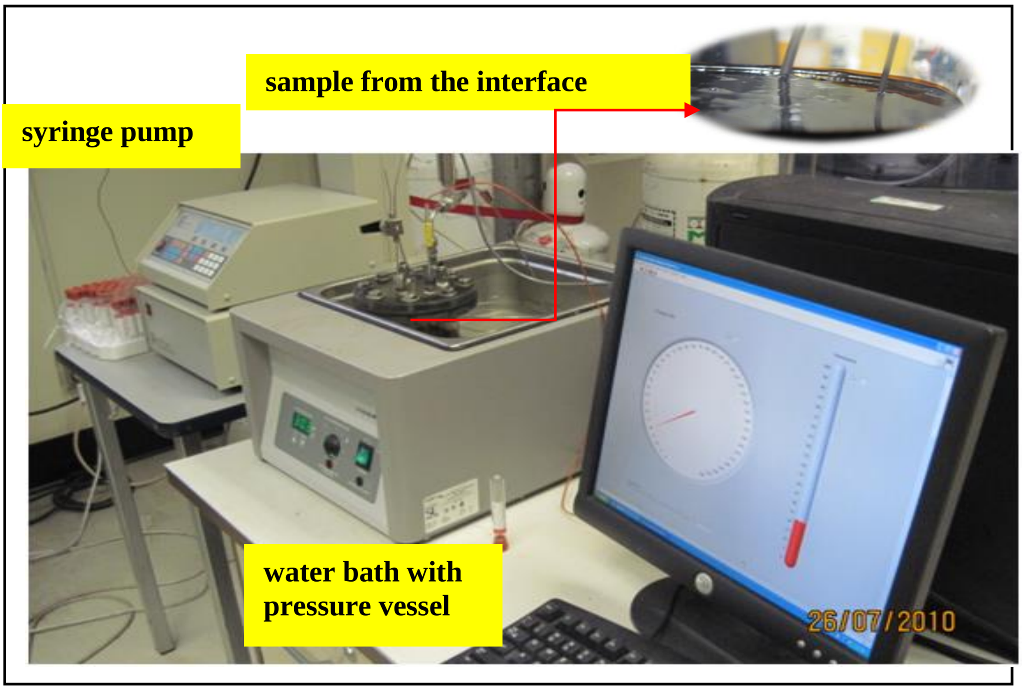

Figure 9: Picture of solvent–heavy oil system for the measurement of interfacial solvent concentration

Table 2: Pressure versus interfacial concentration for propane and butane

Propane mass fraction (ω_{int})	0.26	0.45	0.54	0.68	0.77
Pressure (kPa)	413.7	482.6	551.6	620.5	689.5
Butane mass fraction (ω_{int})	0.22	0.34	0.37	0.49	0.61
Pressure (kPa)	91.01	97.9	101.3	104.8	111.69

2.2.2 Solvent concentration at the solvent-oil interface

Experiments were performed to evaluate a functional relationship between injection pressure and solvent concentration at the interface which was used in the model development. Experiments with different injection pressures were conducted in the setup whose schematic is shown in Figure 8 and the maximum solvent concentration for each pressure was measured.

Figure 10 presents the results obtained from this experimental study. According to the figure, the relationship between injection pressure and solvent concentration at the interface can be approximated with a power function with an r^2 value of 0.998. This relationship describe the injection pressure as function of the solvent mass fraction in the Vapex process.

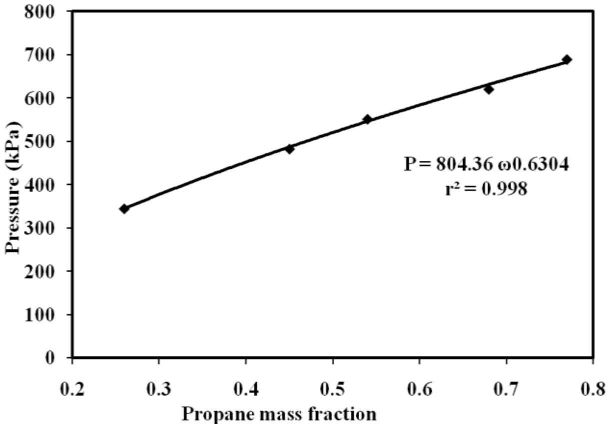

Figure 10: Variation of propane mass fraction with different constant pressure.

3 Results and discussions

The above experimental results demonstrate that the solvent injection pressure is an important parameter that has significant effect on oil production rates and recoveries in a VAPEX process. Maneuvering the injection pressure can improve the overall oil recovery significantly. The results show that injection pressure parameter is directly related to the physical properties of the reservoir.

A possible explanation of such a beneficial effect of pressure pulsing associated with model physical properties is as follows. The efficiency of VAPEX depends upon the solvent mass transfer rate into the in-place oil. The solvent dissolves into the oil reduces its viscosity and the reduced viscosity oil drains out of the model or reservoir by gravity. The reduction in oil viscosity depends upon the amount of dissolved gas present in it and the rate of viscosity reduction depends upon the rate at which solvent gas dissolves into it. A higher solvent mass transfer rate will result in higher oil viscosity reduction rate.

The extent of viscosity reduction depends upon the solubility of the solvent gas in oil. This indicates that performance of VAPEX process can improve by increasing the solvent mass transfer rate. When a pressure pulsing is introduced by releasing the system pressure and re-injecting the solvent, the dissolved solvent in the oil phase tends to leave the physical model.

Upon re-injecting the solvent the solvent mass transfer restarts with a lower viscosity oil to dilute in. This improves the overall oil recovery with pressure pulsing. A solvent release can also create more channels in the physical model, thereby providing larger areas for solvent mass transfer. The re-injected solvent that has maximum solvent concentration passes through these channels and transfers to the undiluted oil. In summary these variations result in enhance mixing that improves the process efficiency. The enhanced mixing occurs due to the gas moving opposite to the solvent to oil mass transfer direction in the event of pressure release.

4 Conclusions

In this work the effect of variation in solvent injection pressure was investigated on oil recovery during VAPEX process. A number of lab-scale experiments were designed and performed to investigate the effect of temporal variations in injection pressure (pulsing) as opposed to constant injection pressure on oil recovery. The permeability of 204 Darcy; heavy oils with viscosity of 14,500 mPa-s; and physical reservoir model height of 25 cm were considered. Normal butane with purity of 99.99% was used as a pure solvent. The effect of constant injection pressure was studied by injecting the solvent at four different injection pressures below the butane dew point. The temporal variation in injection pressure was generated by suddenly releasing the injected solvent and by re-injecting it. Effect of delay in re-injection time was also studied. Moreover, the experimental setup was used to find the injection pressure of a solvent with its concentration at the solvent-heavy oil interface. Propane and butane were used as pure solvents in Vapex at room temperature.

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