OIL RECOVERY PROCESS FROM AN ARTIFICIAL POROUS MEDIUM BY N2 INJECTION: AN EXPERIMENTAL APPROACH

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Abstract. *The liquid displacement in a porous medium by injection of some kind of fluid is a technique used in several industrial processes as the cleanliness of contaminated soils and enhanced petroleum recovery in a porous medium. Such kinds of problems are strongly dependent of the capillarity number characterized by the ratio of viscous forces and superficial ones.*
In this work was investigated the effect of capillarity number and the mean diameter on fraction of mass, mp, that is left behind. To achieve the aims, a glass spheres-packed column experiment was developed to study the viscous liquids recovery process in porous medium. The test fluid was obtained dissolving poly-ethylene-glycol (PEG) in water. Nitrogen was used for the gas- displacement.
The main results are presented in terms of the effect of capillary number during the breakthrough time, and compared with that by (Taylor, 1960) in his study of gas-liquid displacement in capillary tube. This comparison is performed in order to find out the relationship between the gas-displacement in a capillary tube and the gas-displacement in a realistic porous medium for oil recovery process. Thus, one can show evidences that the capillary number is, in fact, the physical parameter that governs the proposed problem. Furthermore, the influence of capillary number is restricted to a rather small value of this parameter.

Keywords*: Taylor capillarity number; porous medium; oil displacement; EOR.*

1. INTRODUCTION

The global energy community is currently engaged in debate about the extent of the world's remaining oil reserves. Because of this incertitude new methods are required to improve the recovery rates of oil fields and to recover oil found in pores between rock particles. For this reason Enhanced Oil Recovery (EOR) processes are being a focus of a considerably number of investigation [Taber and Martin (1983), Lake et al (1992), Chierici (1994), Littmann (1997), Laherrere (2001), Williams (2003), Felber (2004), Ramlal (2004), Friedman et.al (2004), Zhang et al (2004), Yeten (2004), Moritis (2004)].

According to NPC (report 2007), of the total barrels of oil in place in discovered fields, 36% of barrels already have been produced or proved, leaving behind 64% of barrels. A significant portion of these 64% of barrels is immobile or residual oil left behind (stranded) after application of conventional (primary and secondary) oil-recovery technology. With appropriate EOR technologies, 29.5% of barrels of this stranded resource from already discovered fields may become technically recoverable.

About the methods of oil recovery, the production of a petroleum reservoir may be divided into three different production methods. The first one is the initial approach to produce oil and it includes primary recovery process. The average primary recovery rate is around 5-15 % of the original oil in place, Hammershaimb et al (1983) and Tzimas et al (2005), depending on the oil and rock properties as well as the drive mechanism. The second production method, called, secondary recovery process includes fluid injection such as gas reinjection or water flooding into the reservoir to improve oil recovery. The most common method involves flooding the reservoir with water. According to Tzimas et al (2005) by employing this method the recovery factor can be increased from 30 to 50 %. This work is focused in the third method called tertiary method or EOR methods. The oil left in the reservoir after the primary and secondary methods is the potential target of this method.

The physical and geological effects are the causes of the poor recovery of the first two production methods. The main physical reason is the existence of interfacial tension forces and the difference between rheological properties of oil and water resulting in the entrapment of immobile residual oil saturation in the formation, Lake et al (1992) and Moritis (2004). The EOR-methods involves techniques to overcome or to minimize theses effects. Some theses techniques according to Lake et al. (1992), Littmann (1997) and Williams (2003) are listed:

- Reduce the interfacial tensions between oil and water and therefore a reduction of capillary pressure;
- Decreasing oil viscosity or increasing water viscosity.

The EOR can be classified as Thermal and Non-thermal method. Thermal methods are primarily projected for heavy oils and tar sands although they are applicable to light oils in special cases. Thermal methods have been tested since

1950's and they are the most advanced among EOR methods, as far as field experience and technology are concerned. Among these methods are: Cyclic Steam Stimulation (CSS) [Owens and Suter (1965)]; Steamflooding [Stokes and Doscher (1974) and Farouq (1979, 1982)]; Steam Assisted Gravity Drainage (SAGD) [Butler (1985)] and In Situ Combustion [Cheih (1977, 1982) and Martins (2008)]. The major mechanisms include: - a large reduction in viscosity and hence mobility ratio; - rock and fluid expansion; - and steam distillation. Thermal methods have been highly successful in Canada, USA and Venezuela.

In relation to non-thermal methods, they are best appropriate for light oils. In a few cases, they are applicable to moderately viscous oils, which are unsuitable for thermal methods. The three major classes under non-thermal methods are miscible [Stalkup (1992)], chemical [Thomas and Farouq (1993, 1999)] and immiscible gas injection methods [Nguyen (1988)]. Among immiscible gas drive method, CO_2 immiscible injection has been more successful than others. The immiscible gas injection method was used in this work. The two major objectives in non-thermal methods are lowering the interfacial tension and improving the mobility ratio. These two last factors are linked to the degree of trapped oil, in other words, the viability of the oil recovery process depends on these factors.

The mobility ratio accounts the macroscopic displacement effect, i.e., the volumetric displacement efficiency, given by:

$$M = \frac{k_{r,ing}}{k_{r,ed}} \frac{\mu_{ed}}{\mu_{ing}} \tag{1}$$

where k is the effective permeability ratio of the rock-displacing fluid (e.g. water) to rock-displaced fluid (oil), and μ is the viscosity of the fluid concerned. A value of $M > 1$ is considered unfavorable, because it indicates that the displacing fluid flows more readily than the displaced fluid (oil), and it can cause channeling of the displacing fluid, and as a result, bypassing of some of the residual oil.

Another factor to determine the trapped oil degree, it is known as the capillary number, which correlates by means of viscous forces and capillary forces, the microscopic displacement phenomena. Thus, the main goals of any EOR method are increasing the capillary number and providing 'favorable' ($M < 1.0$) mobility ratios.

Developing capillary number theory, it has been widely used to represent the relative importance of viscous and capillary forces in experiments with immiscible fluids involving capillary system. Numerous different forms have been used for the capillary number, some of them are:

- Taber (1983)

$$Ca = \frac{k\Delta P}{L\sigma} \tag{2}$$

where k is the permeability, $\Delta P/L$ is the pressure gradient along the capillary and σ is the interfacial tension.

- Dullien (1988, 1992)

$$Ca = \frac{4\mu v}{\sigma \cos\theta} \frac{L}{R} \tag{3}$$

Dong et al (1998) in line with the previous work made by Dullien (1988) conduced meticulously discussion about the capillary number and pointed out some precautious when work about it. In all of the different forms of Ca lack length scales of the system under study. Most of them are also without a measure of wettability. As viscous forces are known to be proportional to a length scale L in the direction of flow, and capillary forces are proportional to a characteristic pore size scale R_{eq} and to $cos\theta$, where θ is the advancing contact angle measured through water. Ca represents the ratio of viscous to capillary forces only if $L = R_{eq}$ and $cos\theta = 1$.

As the condition $L = R_{eq}$ usually does not apply, the numerical values of Ca published does not permit comparison to be made, only if the experiments or simulations has the same values of L, R_{eq}.

For these reasons the present work proposes another approach. Moving the view to capillary tubes approach introduced by Fairbrother and Stubbs (1935) and improved by Taylor (1960): "when air is blown into one end of a tube containing a viscous fluid it forms a round-ended column which travels down the tube forcing some of the liquid out at the far end and leaving a fraction m in the form of a layer covering the wall". In their studies of gas-liquid displacement in capillary tube the objective of their work was to quantify the mass fraction lost, m_l, in the tube wall during the passage of gas, Eq (4).

$$m_l = \frac{U - \overline{u}}{U} \tag{4}$$

where U is the displacement velocity of the gas-liquid interface proposed by Taylor, and $\overline{u}$ is the fluid flow average velocity. Thus, the Capillary number according to Taylor is defined as Eq. (5):

$$Ca_T = \frac{\mu U}{\sigma} \tag{5}$$

where μ is the displacing fluid viscosity and σ is the interfacial tension of recovered fluid.

In Taylor's work is important to emphasize the way which is characterized the capillary number, Eq. 5, It is according to the displacement velocity of the gas-liquid interface, U. This velocity consists of the balance of normal forces at the gas-liquid interface of displacement, measure directly because the interface displacement is visible, characteristic of flow in capillaries tubes.

For the present work gas-liquid interface velocity is obtained indirectly, from the measurement of the average velocity of the fluid, $\overline{u}$ and measuring the mass fraction lost m_l, Eq. 4. Thus, a relationship between the gas-displacement in a capillary tube and the gas-displacement in a realistic porous medium can be proposed, Fig.1.

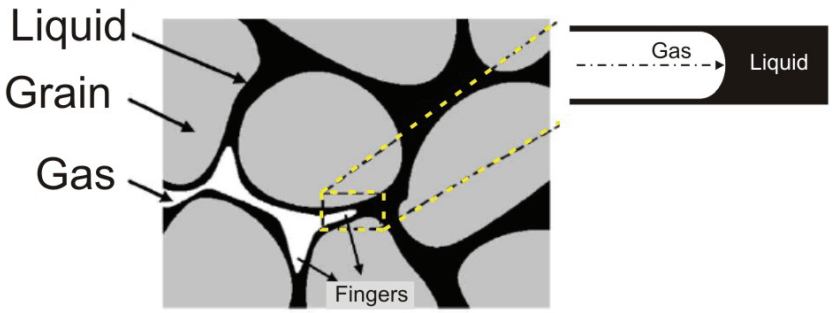

Figure 1. Representation of relationship between capillary tube and porous medium approach.

Considering this approach the following aims were determined for this work:

- To develop glass spheres-packed column experiment;
- To investigate the effect of Capillary number of Taylor (Ca_T) and Mean diameter on mass fraction lost;
- To establish a comparison between the main results in terms of the effect of capillarity number and compared with that by (Taylor, 1960).

2. EXPERIMENTAL SETUP

For this set of experiments, the cylinder containing the porous medium is long enough to allow the development and stability of the gas fronts and to minimize the measurement uncertainty, and it is small enough to allow for a time-efficient exploration of the phenomena.

2.1. Porous medium characterization

As porous medium material a glass spheres were used and characterized as described below. This material is chosen because is known that glass is extremely water-wet and only for gas-liquid systems one can safely assume that gas is always the non-wetting phase.

For this work the particles size ranges were 500-900 μm, 1000-1400 μm and 1400-2000 μm. The size-frequency distribution for each range was established by an image processing method. This method consists on random particles samples collection, after the particles are fixed in a card, photos are taken and then the images are processed using an image editor, making it possible to determine some geometry properties as perimeter, hydraulic radius and circularity factor. The average particle diameter for each range was respectively 0.81 *mm*, 1.17 *mm* and 1.65 *mm*.

Figure 2 presents the results of size-frequency distribution for each particle range. The abscise axis indicates the particles diameter in *mm* and the ordinate corresponds to the diameter frequency distribution. Figures 2a and 2b show a symmetrical distribution of particles diameters, whereas in the Figure 2c the diameter distribution for the range 1400-2000 μm is conspicuously skewed, they tend to cluster toward the lower end of the range.

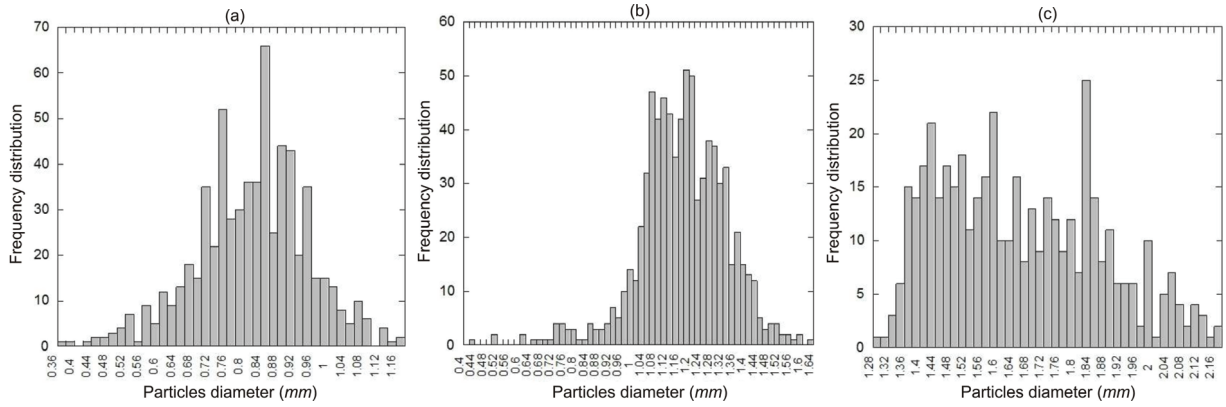

Figure 2. Size-frequency distribution for the ranges: (a) Particles range 500-900 μm, (b) 1000-1400 μm and (c) 1400-2000 μm.

Another practical property of the porous medium was also determined for each particles size range, the porosity. This property was defined by the ratio $\varphi = V_v / V_T$ by measurements on the volume of void-space, V_v (such as fluids) and the total or bulk volume of material, V_T . The average packed porosity for these three ranges was quite similar to 0.38.

2.2. Fluid preparation and characterization

The fluid was obtained dissolving poly-ethylene-glycol (PEG) of 600 $kg\ m^{-3}$ density in water. Before beginning the characterization, the solution PEG/water was mixed until an apparent homogenization. After fluid preparation three physical properties were measured, are they: density, kinematic viscosity and surface tension.

The density of the fluid was measured by weighting fluid sample mass contained in a given reservoir volume. The average fluid density measured was 1057 $kg\ m^{-3}$.

The kinematic viscosity of the solution was determined by using a glass tube viscometer immersed in a thermostat water bath to control fluid temperature. In Figure 3 is plotted the temperature influence on the viscosity for the PEG mass concentration in the range 9 to 33 *%*. As can be shown in the figure a high PEG concentration in water indicates a greater drop in viscosity with increasing temperature. For the present work the PEG concentration adopted was 33 *%*. For this concentration the average kinematic viscosity at 25 *°C* was 39 *cSt*.

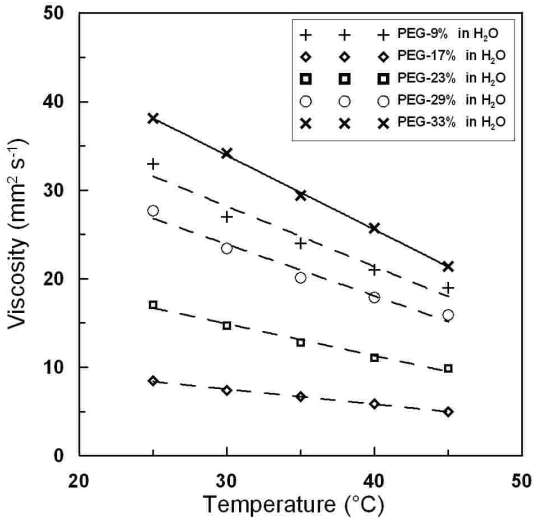

Figure 3. Behavior of kinematic viscosity increasing fluid temperature.

Finally to closure the fluid characterization the surface tension was determined by using a KSV Sigma 702 tensiometer allowing a precision of measurement of about $10^{-3}\ mN\ m^{-1}$. The surface tension at 25 *°C* was 57.00 $mN\ m^{-1}$.

2.3. Experimental protocol

The vertical column is an acrylic cylindrical tube 74mm in internal diameter and 903mm in height. This tube is surrounding by a 110mm square cross section x 903mm length acrylic tube. The free space between both tubes is filled

with water or glycerin to minimize the diffraction effects of light and to allow a better visualization of the front displacement. Into the top end of the cylinder a gas homogenization chamber is placed and sealing using an o-ring, and at the bottom a stainless steel grating is placed to support the particle bed. To ensure the sealing of the closure at the top and bottom, the two tubes are fitted into an interference fit made on acrylic plate cover. After assembled the parts the flanges localized at the top and the bottom of the external tube are fixed on the cover by means of screws.

An inert gas was used as displacement fluid, the nitrogen, from a gas cylinder attached to the experiment by means of hoses and control valve, Figure 4. To control and verify the nitrogen flow rate influence on the capillary number two rotameters were used. One having a flow rate range of 15 to 250 *ml min*$^{-1}$ and a second one between 200 and 1750 *ml min*$^{-1}$.

First of all the vertical column received the glass-spheres packed bed. For all experiments the bed was filled in the same way. At this stage the porous medium is ready to be soaked by the fluid prepared previously. With the valve (V5) opened the fluid is added to the smooth and gradual manner, soaking the porous medium until the fluid reach a level greater than that of the spheres, then the valve (V5) is closed. This residual volume added ensures the complete soaking of the medium, as well as to fill the hose that connects the outlet (o) to the collector container (C). Finished the porous medium soaking, the gas homogenization chamber is placed into the top end of the cylinder and sealing using an o-ring, then glycerin is put into the free space between both tubes and after that the top cover is fitted together.

The following step was to connect the gas circuit (nitrogen cylinder, valves, manometers, rotameter) in the column inlet and to place the scale with a container to receive the recovered fluid, Figure 4.

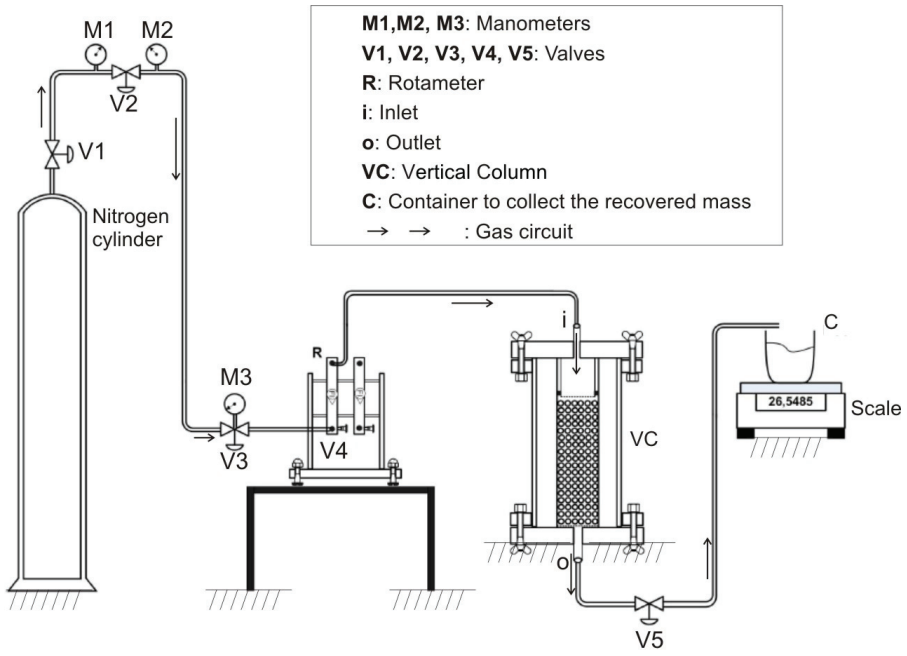

Figure 4. Experimental setup

With V2, V3, V4 and V5 valves closed the circuit is put under pressure opening the V1 valve, thus the M1 manometer indicate the nitrogen cylinder pressure. The V2 valve is progressively opened until the M2 manometer indicates 5.0 *bar* in the gas circuit. This pressure is the maximum work pressure. After that V3 valve is also progressively opened until to obtain 2.0 *bar* of indication in M3 manometer. This pressure is necessary to make work the rotameter (R). Thus all the testing data are obtained with the M3 manometer at 2.0 *bar*. In this moment the V4 rotameter valve is opened up to the nitrogen flowrate wanted.

Once all gas circuit under pressure the V5 valve is opened and the fluid starts to be displaced up to the fluid reach the top surface of the glass-sphere bed where V5 valve is closed again. The residual mass recovered is weighed and subtracted of total mass (m_T) used to soak the bed. Now the experience can be started.

The first measured made is the time required to the gas pass through the glass-sphere bed, commonly called the "Breakthrough Time". The trial is started reopening V5 valve, in the same time the chronometer is also started. At the moment (visual observation) when the first gas bubble reaches the inlet (o) the chronometer is stopped and the breakthrough time *t* is done. The following date could be obtained:

- the mass recovered (m_r) of the fluid is measured;
- the mass fraction lost (m_l) is calculated by relation $m_l = m_T - m_r / m_T$;

- the mass flow rate of recovered fluid is given by $\dot{m} = m_r / t$;

Recalling the Taylor capillary tube theory one has:

- the fluid average velocity u is given by $u = \left(\dot{m} / \rho_{fluid}\right) / A\varphi$, where A is the acrylic cylinder cross section area and φ is the bed porosity;
- the displacement velocity of the gas-liquid interface U proposed by Taylor, $U = u / 1 - m_l$;
- finally, as shown in Eq. (5) the capillary number is given by $Ca_T = \mu U / \sigma$ and knowing fluid properties, one can plot (m_l *x* Ca_T).

After the end of the trial the vertical column is disassembled, glass-spheres were washing and then the procedure is repeated until the number of points (m_l *x* Ca_T) wanted.

3. RESULTS

In Figure 5 is shown the main results obtained by using experimental setup developed. In this Figure are plotted the mass fraction lost versus capillary number for the three particles ranges adopted: 500-900 μm, 1000-1400 μm and 1400-2000 μm. For these three ranges the curves (m_l *x* Ca_T) show an asymptotic behavior increasing capillary number.

One can see that for the range 500-900 μm mass fractions lost asymptotize to a value of about 0.92 when the capillary number tends to 0.014. For other two ranges mass fraction lost asymptotize to values of about 0.84 and 0.79 when the capillary number tends to 0.020 and 0.028 respectively.

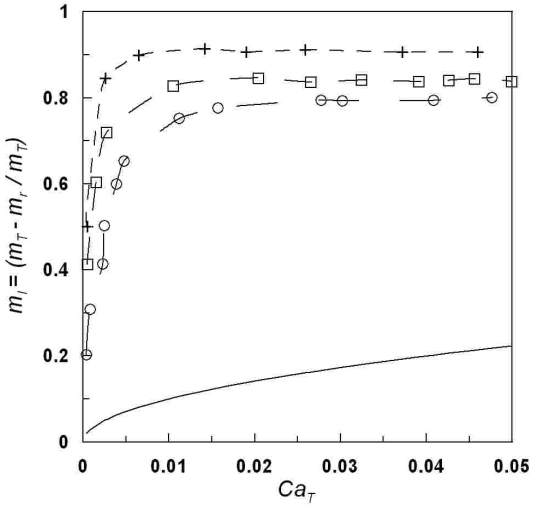

Figure 5. Mass lost versus Taylor Capillary number. Particles ranges: Dashed line with (+ +) is to 500-900 μm, with (□ □) is to 1000-1400 μm and with (○○) is to1400-2000 μm. The continuous line (—) is to show the Taylor curve reference.

One can also observe in the Figure that the higher mass fraction lost is obtained for the smaller average particles diameters. Thus, for a given capillary number the sweep efficiency increase with increasing average particles diameters.

Finally in the Fig. 5 the main results presented in terms of the capillarity number are compared with that by (Taylor, 1960) in his study of gas-liquid displacement in capillary tube. This comparison is performed to find out the relationship between the gas-displacement in a capillary tube and the gas-displacement in a realistic porous medium. The first remark is the asymptotic behavior in both works. Whereas in the present work the curves (m_l *x* Ca_T) tend to asymptotize quite quickly when compare with that Taylor. For a same capillary number the mass fraction recovered in the capillary tubes is higher than that by porous medium, this difference becomes evident by the particularly characteristic of the both types of oil displacements, i.e. in capillary tubes there is only one-way to accomplish the liquid displacement. While in the porous medium conditions is formed a preferential flow path between the particles grain having an influence in the sweep efficiency. In the capillary tube condition the mass fraction lost asymptotize to value of about 0.6 which is equivalent to the maximum recovery rate of 40%. For the case of this work, porous medium conditions, for the three ranges the mass fraction asymptotization point was 0.92, 0.84 and 0.79 respectively, which in terms of maximum recovery rate is around 20%, 40% and 52.5% for each particle range.

4. CONCLUSIONS

The preliminaries results using a vertical column apparatus that was designed, developed and operated with success were presented. Using this apparatus a new approach on gas-liquid displacement in porous medium was showed.

The main results were presented in terms of the 'actual' capillary number during the breakthrough time, and compared with that by (Taylor, 1960) in his study of gas-liquid displacement in capillary tube. This comparison was performed to find out the relationship between the gas-displacement in a capillary tube and the gas-displacement in a realistic porous medium for oil recovery process.

A fine characterization in both spheres particles and displaced fluid was performed. As porous medium glass spheres were used. Three particles range were considered and characterized, 500-900 μm, 1000-1400 μm and 1400-2000 μm. The displaced fluid was prepared using poly-ethylene-glycol/water and after characterized to obtain follows physical properties: density (1057 $kg\ m^{-3}$), kinematic viscosity and surface tension (39 cSt).

The trials allow remarking the asymptotic behavior in the (m_l x Ca_T) curves, similar to the behavior described in the Taylor's experiments. The evidences that the capillary number governs the oil displacement problem in a restrict range of Ca_T from 0 to 0.01 was established. Regarding to the maximum recovery rate that could be achieved using this gas injection method, it was about of 52.5 % for the higher particle range, confirming the influence of the average particle diameter in the oil recovery process.

5. ACKNOWLEDGEMENTS

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7. RESPONSIBILITY NOTICE

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