AN ARTIFICIAL POROUS MEDIA EXPERIMENT FOR THE STUDY OF OIL RECOVERY EFFICIENCY

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Abstract. *Petroleum is an energy source of growing demand. This fact has attracted attention of oil industries to fields which were not massively explored before, like heavy oil fields (of hight viscosity), wich are predominant in Brazil. Studies of flow in porous media allow the development of new technologies for a more afficient oil recovery and/or recovery in fielss which were not economically feasible. Gravity drainage is capable of high recovery of heavy oil and can work together with enhanced oil recovery. Scale studies are cheaper and have a better control over the process variables. Experimental studies are more reliable than numerical ones for this complexity level. Therefore, an experimental apparatus was constructed for gravity drainage in a diverse of settings. A water injection system, as enhanced recovery method, was chosen, since it is one of the most used methods in oil industry. The experimental apparatus was validated by comparing the results obtained to the ones presented in the literature with a good qualitative agreement, since it is impossible to mach every condition of the cases compared.*

Keywords*: oil recovery, gravity drainage, porous media*

1. INTRODUCTION

Near future previsions project a continuous big role of petroleum in the world energetic matrix, altogether with the demand of petroleum as raw material for industries, such as plastic industry. The demand for petroleum is growing, however in a slower rate than its offer, which reflects on prices, table 1. This conjecture leads to a good economical situation for oil companies and a worry about future availability of this commodity. Because of this, those companies are turning its attention to under explored oil sources, such as tar sands and heavy oil fields, and oil recovery process that provides higher efficiency and total recovery potential.

Table 1 – Crude oil market indicators.

Year	2000	2001	2002	2003	2004	2005	2006**
Price* (US$/barrel)	27,60	23,12	24,36	28,10	36,05	50,64	62,75
World Demand (Mbarrels/day)	75,8	76,3	77,0	79,5	82,1	83,2	84,6

Source: OPEC
* - Average price for internacional market
** - First trimester 2006

In Brazil there is a predominance of heavy oil fields. From January to August 2006, Brazil has a deficit of 2.2 billions dollars in crude oil negotiations, due to the necessity to import light oil for the national refineries. As there are already in place politics to increase the number of national heavy oil refineries, the increase of heavy oil productions attends the national demands of the refineries and to reduce the trade deficit.

1.1. Oil recovery techniques

There are three principal primary recovery drive mechanisms: water drive, gas drive and gravity drainage. Water drive utilizes the pressure exerted by the water below the oil and gas in the reservoir formation to force the hydrocarbons into the production well. The reservoir pressure increases with its depth. The water pressure remains high as along as the fluid volume inside the formations remains constant, usually done injecting water. Eventually, the water level rises to a point where the well is producing mostly water. It is said that water drive is the most efficient natural drive and can produce around 50 % of reservoir oil.

The gas drive is sub-divided in two mechanisms, dissolved gas drive and gas-cap drive. Both use the pressure of the gas in the reservoir to force the oil out. In a dissolved gas drive, there are light hydrocarbons in the oil that becomes gas when reservoir pressure drops, e.g. caused by a well perforation, and pushes the oil out the formation. This process is similar to the bubble formation in soft drinks when they are opened. One can say that the amount of oil recovered by this process varies from 5 to 30 %.

Some reservoirs may present gas in the top of the oil. This expansion of the compressed gas cap pushes the oil out of the formation, towards the well. The more oil is removed, the more space is to the oil expands. This mechanism depletes slower than dissolved gas and can recover between 20 to 40 % of reservoir oil before the gas cap drive fails.

Gravity drainage uses the gravitational force to conduct the oil out of the porous media. This mechanism has the slowest recovery, however in long terms is capable of the greatest oil recovery and with a good efficiency. In Lakeview Poll, a Midway Sunset field, in USA, over forty years of production there was recovered 64 % of field's oil volume.

The oil production can be enhanced to increase the oil flow or ultimate recovery rate. Several techniques were developed to enhance production, primary forcing the oil out the formation or reducing its viscosity, thru heating or chemical means. A very common method is the injection. In this technique a fluid, usually water or natural gas, is injected in the reservoir forcing the oil into the production well.

1.2. Experiment selection

It's known that petroleum properties changes significantly from reservoir to reservoir. Therefore, the first step was to identify a Brazilian petroleum. Viscosity was identified, along chemical composition, as the main identifier of petroleum. The viscosity of a Brazilian petroleum and its emulsion in water was measured by Oliveira and de Carvalho (1998) and presented a high value. The present work has considered it as the Brazilian petroleum.

Gravity drainage is presented as a very efficient oil recovery method for high viscosity petroleum. A diversity of papers presents enhanced techniques applied along side this driving mechanism. Recent woks, Grattoni, Jing and Dawe (2000), Nabipour *et. al.* (2006) and Akin and Bagci (2001), presents a ultimate oil recovery over 60 % considering gravity drainage, while steam and carbon dioxide injection presents a ultimate recovery rate of 50 %, Gümrah and Bagci (1997).

Gravity drainage can have even better recovery rates utilizing enhanced recovery techniques, Nabipour *et. al.* (2006), and can have accentuated initial recovery, Akin and Bagci (2001). The effect of gravity driven flow is also important in some enhanced recovery techniques, even in non gravity drainage driven recoveries. Fayers and Zhou (1995) had shown the importance of gravity effects in vertical gas driven flows in the occurrence of gas fingers.

Recent works, Li and Horne (2003) and Donato *et. al.* (2006), has shown promising mathematical and numerical models to predict gravity drainage oil recovery. However there still are few models to predict oil recovery by enhanced gravity drainage.

Also porous media wettability, Shahidzadeh-Bonn *et. al.* (2003), Tweheyo *et. al.* (1999) and Zhou (1998), can have a high influence in oil recovery.

Therefore gravity drainage was identified as the most adequate recovery method for Brazilian petroleum and an experimental apparatus for its study is proposed. The apparatus was designed to allow a reduced scale study of gravity drainage considering diverse porous media and enhance techniques. Water injection was selected as the first enhance method utilized with the apparatus. It was validated with other experimental data in the literature.

2. EXPERIMENTAL APPARATUS

The experimental apparatus was developed for the heavy oil gravity drainage study in a manner that an injection system could be attached. A sketch of the experimental setting is shown in fig. 1. The main component is the porous media. It is assembled in a transparent acrylic recipient, 200 mm tall, 100 mm wide and 6 mm depth, in 2 mm plates. In line with Grattoni, Jing and Dawe (2000), which used a similar porous media recipient, no significant edge effect was found. The top remains opened to allow the change in particles that composes the porous media. This way the size and shapes of particles, porosity, permeability and wettability of porous media could be switched. A small hole, 1.6 mm in diameter, is located in the center of bottom face, for oil recovery. A topping is provided when the injection system is used.

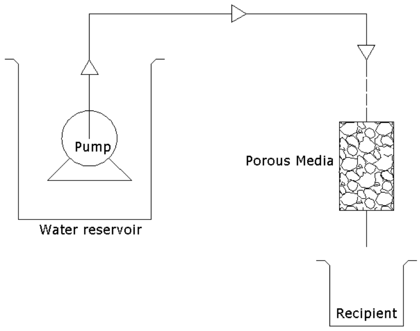

Figure 1 – Experimental setup

The injection system consists in a small centrifugal pump, which can have the flow rate adjusted, a topping for the porous media, with a 2 mm hole as injection point. The pump exit is 16 mm in diameter, so an abrupt reduction, from 16 mm to 2 mm in diameter, was utilized. The pump transferred colored tap water from a reservoir to the porous media. Green color was added to water to facilitate its visualization.

The recovered fluid dropped from the bottom opening in the porous media to a graduated recipient, so recovered fluid could be measured. As a high viscosity oil is utilized, the recipient was positioned in a way that dropped fluid did not had any contact to recipient walls, so recovered volume reading was more precise. For convenience, a water-oil separator was not utilized and total volume was utilized in the analysis, as water concentration in porous media was just residual.

3. FLUID PROPERTIES

The fluids utilized in porous media were selected to be similar to the ones utilized in similar experiments, Grattoni, Jing and Dawe (2000) and Nabipour *et. al.* (2006), allowing a more direct results comparison. Therefore, connate water saturation in porous media was utilized. Distillated water and high viscosity oil was utilized. The utilized oil have a similar viscosity to the one presented by de Oliveira and de Carvalho (1998). SAE 50 oil was utilized. During gravity drainage experiments without water injection air is also involved.

All fluid properties were measured, with exception to gas properties and water interfacial tension. L200 densimeter was utilized along with Cannon-Finke viscosimeter, for water, Preston's Universal Saybolt viscosimeter, for oil, and a Krüss tensiometer. Fluid properties are presented in table 2.

Table 2 – Fluids properties @ 20 °C

Water density	0.998 g/cm_ (998 kg/m_)
Water viscosity	1,007 mPa.s
Water interfacial tension	0,072 N/m
Oil density	0,976 g/cm_ (976 kg/m_)
Oil viscosity	5078,3 SSU (1,07 Pa.s)
Oil interfacial tension	0,03072 N/m
Air density	1,200 kg/m_
Air viscosity	1,080 E-05 Pas.s

4. POROUS MEDIA

The porous media can be assembled in side the acrylic recipient. The conducted experiments utilized three different kinds of particles to compose the porous media. Each porous media was assembled by a random distribution of one kind of particles. The particles were selected by its size and roundish form. Their dimensions were measured in a profile projector. Average diameter for each particle kind, or group, is presented in table 3.

Table 3 – Particle groups utilized

Group	Material	Average Diameter	Standard deviation
I	Low density Polyethylene	4,228 mm	8,88 %
II	Glass beads	2,062 mm	4,08 %
III	Fine beach sand	0,442 mm	28,34 %

The groups I and II presented a spherical shape, while the beach sand presented a random shape. Even though the group III wasn't spherical a spherical particles bed model was utilized to calculate the porous media permeability.

The porosity for each porous media was determinated by the weight difference for the media filled with air and destilated water. The permeability was determinated by the Blake-Kozeny formulation, with constant taken as 25/12. The porosity and permeability for the porous media utilized in each experiment is presented in table 4. The properties differences in porous media made with the same particle group are caused by the random distribution of particles.

Table 4 – Porosity and permeability in utilized porous media

Experiment	Particles	Porosity	Permeability
A	Group I	47 %	4,36E-08 m_
B	Group II	36 %	3,11E-09 m_
C	Group III	39 %	2,02E-10 m_
D	Group I	45 %	3,59E-08 m_
E	Group I	45 %	3,41E-08 m_
F	Group I	44 %	3,38E-08 m_
G	Group I	39 %	1,8543E-08 m_

5. EXPERIMENTAL PROCEDURE

The experimental procedure involved the following steps:

1) The acrylic recipient was filled with the selected particle group in a homogeneous way, without compact it. After that the porous media was weighted.
2) The porous media was filled with distillated water. The 100 % water saturated porous media was weighted. The water volume utilized was measured.
3) To reach the connate water three porous volumes of oil was injected from the top of the porous media. The water saturation for this condition was determinated volumetrically. The oil saturated porous media was weighted.
4) If required the injection system was connected to the porous media.
5) The porous media bottom exit is cleared and oil starts to flow. The injection system was turned on in the appropriated time.

The experiments were conducted in room temperature, kept close to 20 ºC.

6. EXPERIMENTAL RESULTS

A set of eight experiments were conducted. Four were gravity drainage without water injection, one for each particle group and one to check the repeatability of the experiment. Other three were conduced to analyze the oil recovery with the water injection turned on in three distinct moments. Also one qualitative experiment was conducted to verify the gravity drainage with lighter oil.

6.1. Experiment A

The porous media utilized in this experiment comprised only of group I particles. The initial oil column height was 180 mm. In the beginning the oil flow was constant, however it rapidly decayed. At 54 mm column height, with thirty minutes of oil flow, the flow was considerably slower then the initial. At 16 mm column height, after one hour flow, the oil flow practically ceased.

The initial water saturation was 1 % in volume. No water was noticed in the oil collecting recipient. This was attributed to the small initial water saturation, the high oil viscosity and similar densities of both fluids, that didn't allowed a visible separation of water and oil.

6.2. Experiment B

The porous media utilized in this experiment comprised only of group II particles. The initial oil column height was 191 mm. It was noticed that in this experiment almost no oil was kept trapped, indicating a high recovery efficiency. Initial water saturation was 4 %.

After three hours of oil flow, the recuperation became really slow, around 1 ml each half hour. At 30 mm column height, after five hours flow, the oil flow practically ceased. After ten hours the oil column is 27 mm high and experiment is considered over. Figure 2 shows the porous media near the beginning and near the end of the experiment.

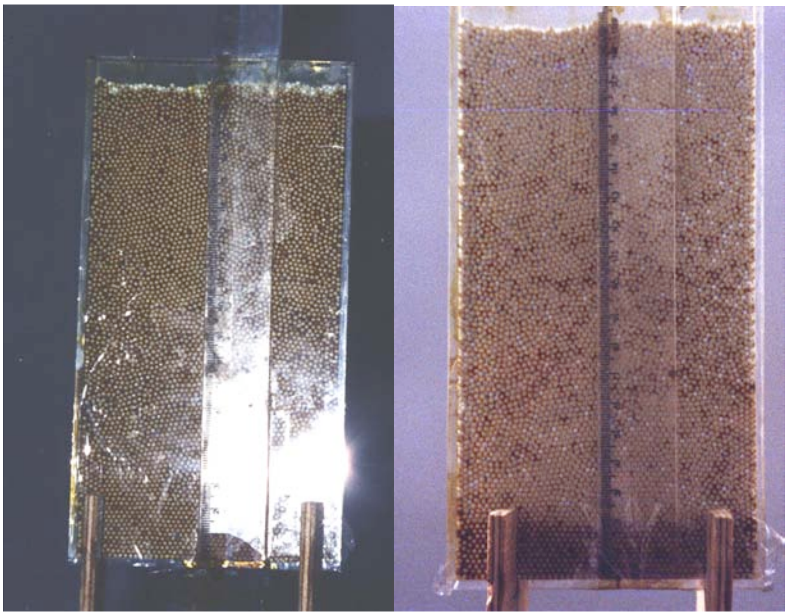

Figure 2 – Porous media in the beginning (left) and end (right) of the experiment B.

6.3. Experiment C

The porous media utilized in this experiment comprised only of group III particles. The initial water saturation process caused a compactation of the media, noticed as a 2 mm decrease in sand level. The media porosity considered the compacted porous media. However tortuosity alterations could not be estimated.

This experiment preparation and experiment itself were much slower than the predicted. The water saturation took days and after ninety one hours there here only a 16 mm reduction in oil column. Due to time constrains it was not possible to determinate the oil recovery curve for this experiment.

6.4. Experiment D

This experiment was a reproduction of experiment A and no different behavior was noticed. It also had 1% water initial saturation.

6.5. Experiment E

This was the first water injection experiment. This and all others water injection experiments utilized porous media comprised only of group I particles. The initial water saturation in this experiment was 1 %. In this experiment the water injection started in the beginning of oil recovery.

Within two minutes the injected water achieved the porous media exit, creating a direct water connection between the injection point and the exit point, fig. 3. This caused the recovered water to be much larger then the recovered oil. Total fluid, water plus oil, was recovered fast from the porous media. After water injection ended most of injection water was removed using the way it has created through the oil. Oil recovery after six minutes was estimated.

Figure 3 – Water injected through the porous media.

6.6. Experiment F

In this experiment the porous media topping and abrupt reduction were connected to the porous media before the start of the experiment. It was intended to turn water injection on after most of the oil was recovered, one and a half hour, according to experiments A and D. However the flow was considerably slower then in experiments A and D. It was attributed to the reduction in area exposed to atmosphere.

6.7. Experiment G

In this experiment the porous media topping and other parts of injection system were connected to the porous media only before the start of the water injection. The injection started after the oil production ceased. The water accumulated in the porous media, building up pressure. After a while it reached the exit, pushing the oil toward the laterals, diminishing the accumulated water and being disconnected from the exit by the oil. After a while the cycle restarted. Two cycles were observed before the end of experiment.

6.8. Experiment H

Soy oil, seventeen times less viscous than SAE 50 oil, was utilized table 5. This experiment was conducted as a time comparison of gravity drainage considering different viscosities. It used group I and group II porous media compared with experiment A and B. Experiments A and B lasted two and a half hours and 10 hours, respectively, while soy oil experiments three and fifteen minutes. The oil viscosity was decreased seventeen times and flow times decreased around forty five times, 2.5 times more then the viscosity reduction.

Table 5 – Comparison between utilized oils, @ 20°C.

Oil	SAE 50	Soy
Density	975,6 kg/m_	913,1 kg/m_
Viscosity	1,07 Pa.s	0,061 Pa.s

7. RESULTS COMPARISON

7.1. Repetability

The experiments A, D and G, before the water injection, were all done in the same conditions. Figure 4 shows oil recovery for the three experiments. It can be noticed a similar time evolution of oil recovery and similar ultimate oil recovery, although for a same time the recovery difference is large. This demonstrates the high influence of uncontrolled parameters, such as porous media tortuosity, in quantitative results during the recovery and a small influence in ultimate oil recovery and qualitative results.

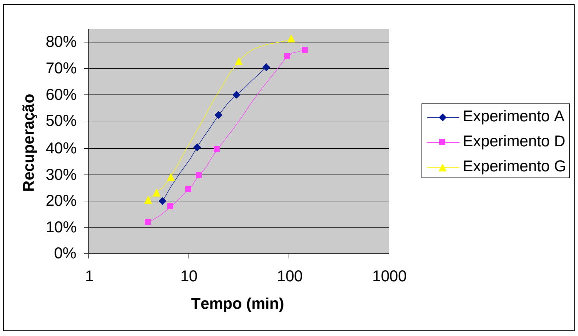

Figure 4 – Oil recovery in experiments A, D and G.

7.2. Comparison with literature

The experiments A, B and D were compared with similar experiments in literature. As no recovery curve was obtained for experiment C, it is not shown in this section.

Figures 5 to 8 presents the experimental results along with results presented in the literature. Oil recovery from experiments appears as a function of diverse parameters. The capillarity and Bond numbers were modified to be dynamic parameters, according to Grattoni, Jing and Dawe (2000). The dimensionless time is according Nabipour *et. al.* (2006).

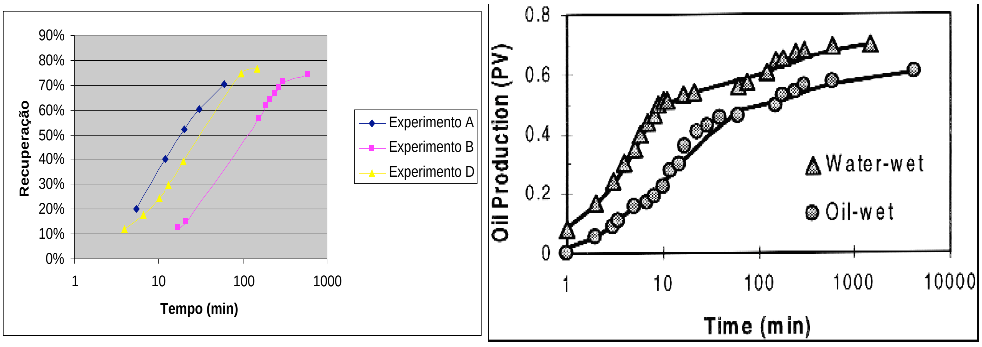

Figure 5 – Oil recovery as time function, experimental results (left) and literature (right)

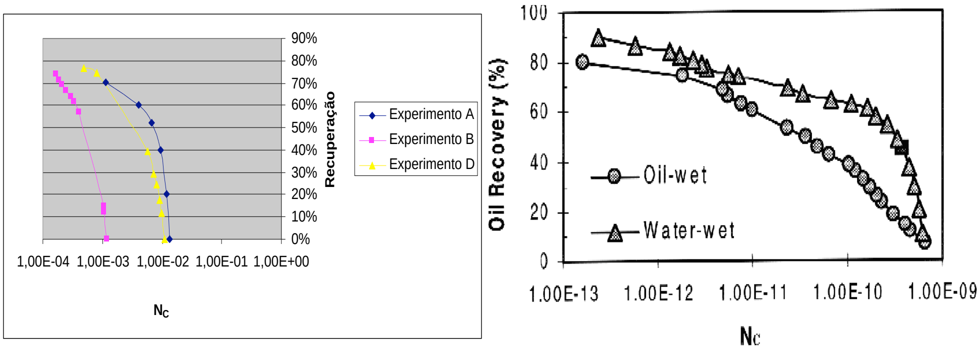

Figure 6 – Oil recovery as capillarity number function, experimental results (left) and literature (right)

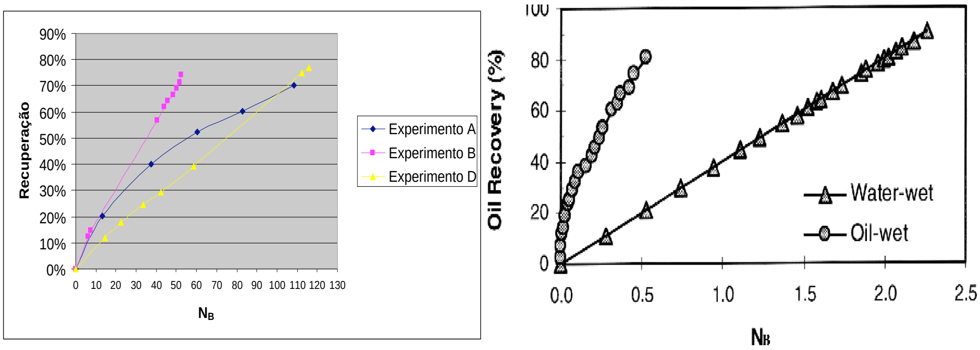

Figure 7 – Oil recovery as Bond number function, experimental results (left) and literature (right)

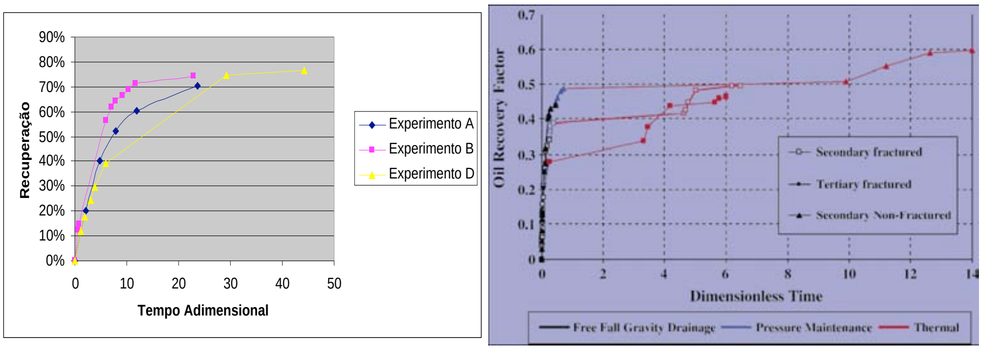

Figure 8 – Oil recovery as dimensionless time function, experimental results (left) and literature (right)

One can notice in figures 5 to 7 that experiments are concordant with theirself and literature in the way recovery happens differentiating in abysses axis as every experiment has its own particularities, as porous media and oil utilized. The one exception is experiment A that presented air bobbles trapped in the oil, as shown in Bond number curve, fig. 7.

Although the recovery is just slid the right in time, fig. 5 and fig. 8, as porous media becomes less permeable, in dimensionless time the recovery behavior is modified. Thus dimensionless time is more adequate to comparate experiments that utilize the same porous media, as the result extracted from the literature.

7.3. injection system

Figure 9 shows the total fluid recovery in three distinct cases, experiments D, E and G.

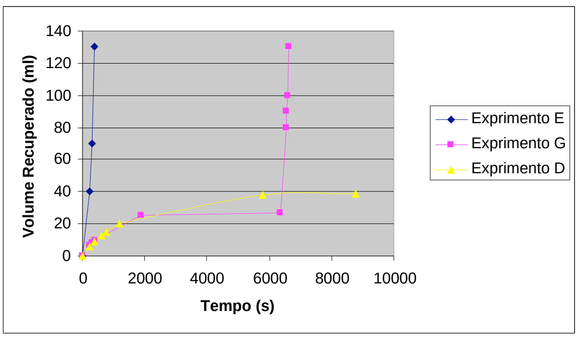

Figure 9 – Volumetric recovery in experiments D, E and G.

One can notice that when water is injected, fluid recovery increases much and suddenly. This happens because the grater mobility of water. However this higher mobility also makes that much more water is recovered than oil, once a water connection thru injection and exit points is established.

It was noticed that experiment G had a higher ultimate oil recovery than experiment D. It was also noticed that in the same time experiment E has recovered more oil than experiment D, however before water could reach the exit in experiment E the oil flow was grater.

8. CONCLUSIONS

The experimental apparatus proposed was able to conduct gravity drainage with and without water injection for diverse fluids and porous media and with repeatability. The experiments conducted in the apparatus have shown agreement with the literature. Quantitative differences are attributed to difference in specific components of the experiment.

Water injection was capable to increase oil production and ultimate recovery, although water mobility prevented better results. Those findings are also in agreement with literature.

Uncontrolled factors of a more random nature, as tortuosity, can have a high influence in quantitative results. Also the size of air entrance can have a major role in gravity drainage without water injection.

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