EXPERIMENTAL AND NUMERIC INVESTIGATION OF STEAM INJECTION IN HEAVY OIL RECOVERY FROM ESPIRITO SANTO BASIN

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Abstract. *Experimental and numerical simulations of steamflooding were carried out to determine the technical feasibility of applying this process to heavy oil recovery from onshore Espírito Santo basin (15.7 °API). In the present work, the studies were developed to better understand how the modification of some parameters contributes to the recovery mechanism. The parameter involved are: injection pressure ,injection temperature, initial oil saturation; which were varied between 50% and 70% and the production pressure that was kept constant and regulated in each experiment varied between 100 kPa and 500 kPa . The injection cell (0.62 m long and ID of 0.069 m) is made of stainless steel and placed in a vacuum jacket maintained at a reservoir temperature, 324 K. In the experiments, steam at 423 K was injected at flow rates between 4 and 5 ml/min. (cold-water equivalent). The study aimed at influences of different parameters on oil recovery. The experimental results show steam fronts in agreement to the ones encountered in the literature. The contribution of backpressure to the additional recovery is significant, basically due to the fact that high pressures sustain high temperatures inside the cell. The volumes recovered and analysis of the remaining rock indicates recovery factors exceeding 40%. On the numerical studies, the results simulated with the model of the injection cell show behavior in agreement to those observed experimentally.*

Keywords*: steamflooding; numeric simulation; thermal recovery, heavy oil recovery.*

1. INTRODUCTION

Thermal methods of recovery, especially steam injection, are at the forefront of most onshore projects of heavy oil recovery. The continuous injection and more recently the steam assisted gravity drainage allows high recoveries. Considerable attention has been given to thermal laboratory techniques for stimulating production of heavy oil. The special methods of recovering oil, especially thermal steamflooding is the most important method used in the world. Since the first commercial project in 1952, steam injection processes have been successfully to heavy and extra-heavy crude oil where the main production mechanisms are associated with viscosity reduction, changes in rock wettability, and thus making its displacement easier (Prats, 1982) and (Boberg, 1988).

A number of investigators “Willman *et al*, (1961)”, (Wu and Brown, 1975) have measured many parameters on experimental and numeric simulation to improve this process. The steam distillation yields are mainly dependent on the oil composition and may not correlate with crude API gravity. Thermal expansion and distillation of light hydrocarbons are the most important production mechanisms for medium/light oil. Change in steam injection pressure and temperature has insignificant effect on the yields; however, superheated steam significantly increases the yields for some crude oils. In Brazil, the small quantities of light fraction show that the most significant mechanism is the viscosity reduction.

2. DESCRIPTION OF EQUIPMENT AND EXPERIMENTAL PROCEDURE

The purpose of the laboratory test is to examine under controlled lab conditions, how much oil may be recovered by a steamflood process. To fill the tube, specific sand grain size (60-80 mesh), oil and distilled water were used for saturation of the mixture. The concept of the apparatus used in experiments is shown in Fig. 1. In this study, the experimental apparatus is similar to the models found in literature, as described by (Nesse, 2004) and (Simangunsong, 2005). It is observed in Fig. 1 that the injection system is represented by the blue line, the system of production by the green line and the data acquisition system by the red line. For the injection system, two different fluids such as water and gas may be used. Superheated steam to flow between 4 to 5 ml / min. to 423 K is generated and made available to the mixer through the injection valve.

For system security, a pressure control valve set at 1000 kPa is used on the generate steam. The production system consists of one gas-liquid separator, a balance, a gas meter, and chiller unit. The fluid produced in the injection tube through the stage of separation where the gas is routed to the condenser connected to the system of cooling to 20 ° C. Subsequently, the condensate is added to the production and the gases pass through the gas meter where the flow is measured. Water and then oil go to the pipe production, where the production valve located after the separator controls the flow. The data acquisition system, the type Ellipse Scada is used to control the heating resistance, readings of pressure and temperature transducers in the steam generator and in the mixer, a pressure transducer in the system of production and temperature transducers readings every 30 seconds.

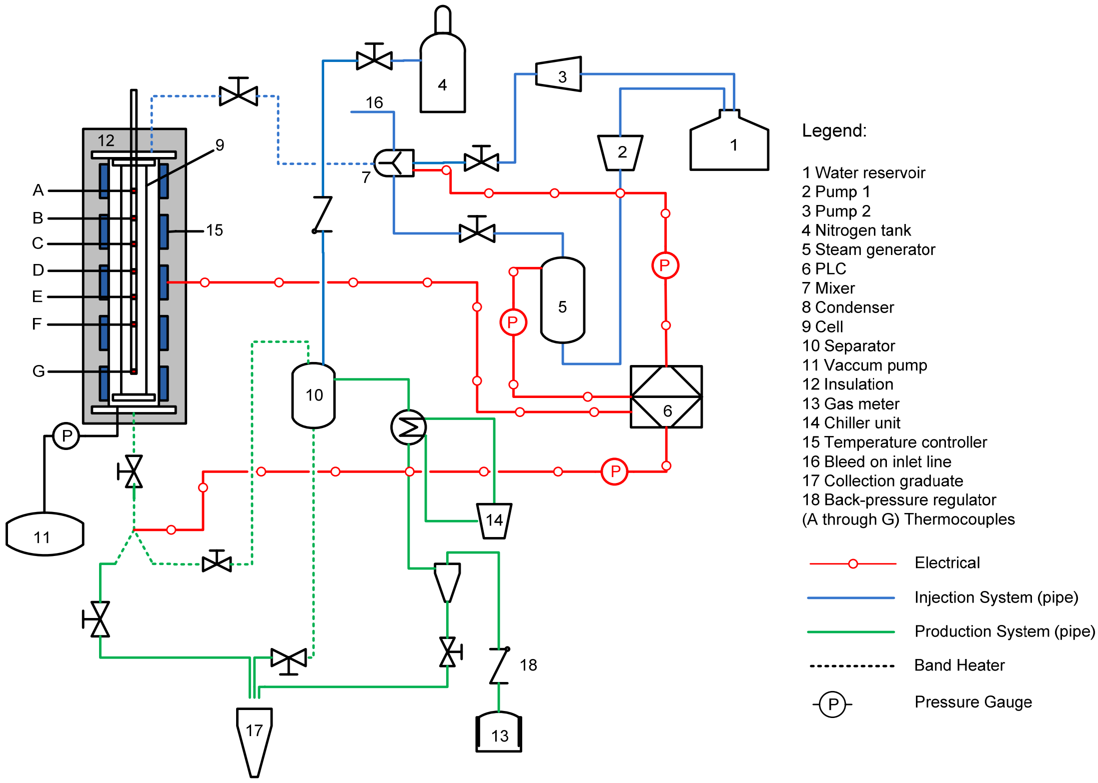

Figure1. Schematic diagram of the apparatus experimental

The injection cell, designed and built in stainless steel 316, has 0.62 m length and 0.069 m internal diameter. Placed inside the cell is a thermowell holding thermocouples. The thermocouples are spaced at different intervals to monitor temperature through the experiment. The intervals are: "A" to 0.06 m, "B" to 0.175 m, "C" to 0.25 m, "D" to 0.335 m, "E" to 0.41 m, "F" to 0.48 m and "G" to 0.615 m. The cell is placed inside a larger diameter heating jacket, creating an annulus between the two. The resistors are arranged around the vacuum jacket to take the temperature inside the tube to the reservoir temperature and heat according to the advance of the steam fronts. The compositions of mixtures and the experimental conditions of all experiments used to fill the cell are shown in Tab. 1.

Table 1 – Sand mix properties and experimental conditions and for runs 1-3

Run	1	2	3
Porosity, %	46.59	47.95	46.08
Pore volume, cm^3	992.89	1021.90	982.21
Water volume in cell, cm^3	182.84	200.00	222.92
Oil volume in cell (OOIP), cm^3	495.63	715.40	493.21
Initial water saturation, %	18.41	19.58	22.70
Initial oil saturation, %	49.92	70.00	50.21
Initial air saturation, %	31.67	10.42	27.09
Injection temperature, K	423	423	423
Injection Pressure, kPa	400	500	600
Steam injection rate, cm^3/min	5	5	4.5
Water control rate, cm^3/min	0.81	-	-
Steam quality, %	80	100	100
Outlet pressure, kPa	100	320	450
Vacuum jacket pressure, kpa	0.6	0.8	0.8
Initial cell temperature, K	324	324	324

From the composition of the crude oil from Espírito Santo basin, the experimental data and using the program WINPROP-CMG, was held proper characterization of the oil. This procedure is, in its first data, supplied by Petrobras. Three experimental points of viscosity, with the first point on the reservoir temperature (324 K), and two at 348 K and 373 K. The viscometer used is a rolling-ball and the viscosity is measured as the time to drop a steel ball through a cylinder occupied by the fluid, based on an equation of the calibration equipment. The viscosity was adjusted from the correlation of Fredenslund and Pedersen (1987). In addition to the three data properly adjusted, another experiment was conducted to adjust the viscosity to a 443 K. The other experiment was conducted in laboratory methods of thermal at State University of Campinas. The equipment used was the Cambridge viscometer measured in electromagnetic force, through the drag of a sensor inside a cell containing a sample of oil. Since the characterization of heavy oil in the thermal simulation is obtained from correlations of light oils, it is necessary to take particular care in setting the parameters for a consistent approximation of the PVT data of the oil. In literature, several experiments using the division of oil in a number from 3 to 5 pseudo-components to investigate the possible transfer of mass between the components due to vaporization of intermediate fractions. As crude oil and through WINPROP-CMG, only 573 K has a small steam distillation of oil. The final adjustment resulted in only one component. For this reason and adopted by choice, Fig. 2 shows only the total viscosity of the liquid and correlation obtained by modeling the fluid.

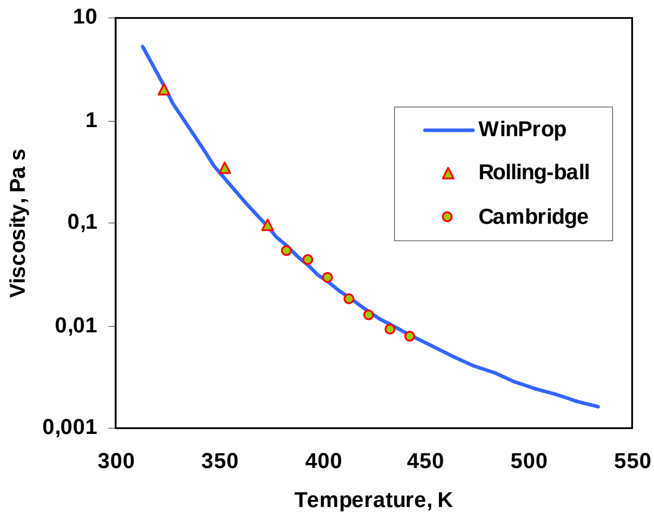

Figure 2. Temperature – viscosity relationship for the crude oil used in the experiments

To complete the injection cell appropriated clean and dry industrial sand with size between 60-80 mesh from mining Jundu Company Ltda was used. After the sand after was washed and dried it could be mixed with other components. The procedure for composing the mixture is determined by the mass of each component in pre determined quantities. Sand, between 20-35 mesh, is placed in the first segment of 0.03 m in the injection cell positioned in reverse and was filled from the top to the bottom. Sand and water are mixed, and oil was added later. With a mixture of complete and homogeneous appearance, is held to fill the injection cell. When filled, the remaining mass is accounted for the real knowledge of the mixture inside the tube. At the end of filling, a length of 0.02 m of the tube is again filled with sand. These segments of sand are used to provide a homogenous distribution of the flow at the base and the top of the cell. After filled, the region of the sealing flanges is cleaned to remove grains of sand, allowing for closure of the cell. The cell is then positioned within the vacuum jacket, is the proper connection of the injection system and the thermocouples inside the guide. With the tube positioned, nitrogen is injected through the separator until it is reached the pressure of work. Tests are performed in the pressure injection systems, production and injection tube to ensure no leaks. Satisfied with this assurance, the resistances of pre heating are related to alternative ways of getting the tube to the reservoir temperature. Stabilized the temperature inside the injection tube, a vacuum pump is activated to ensure minimum heat transfer to the outside of the tube. The data of temperature, pressure and mass are acquired through the Ellipse Scada. During the test, the fluids produced are collected by test tubes arranged on the balance. At the end of the test, the moisture content of the oil phase is analyzed by Karl Fisher Volumetric Holder Tritos 841, coupled with a model 832 KF oven ThermoPrep (Metrohm).

3. EXPERIMENTAL RESULTS AND DISCUSSIONS

In this first test, the saturation and experimental conditions are presented in Tab. 1. Through the profile of temperature along the tube in Fig. 3, it is possible to observe that at the start of injection there is sharp drop in temperature of injection. This drop in temperature can be explained by the large expansion of the steam after leaving the injection nozzle and the fact that the back pressure within the tube to atmospheric pressure. A low back pressure means that initially the tube is pressurized, thus reducing the pressure of the mixer. As a result of reduced pressure in the mixer, its temperature also decreases, influencing the advancement of steam fronts inside the tube.

There is the rapid advance of the behavior of steam fronts until the last thermocouple, at 2820 seconds. This is explained by the high initial saturation of air, resulting in a high absolute permeability of the media. At the beginning of the experiment there was considerable condensation of steam until the pressure and temperature of the system up to 270 kPa and 402 K respectively. So after 5400 seconds, the steam injection in the cell happens. With the production pipe without heating, the oil produced still in contact with the cooled pipe, and then the oil gain viscosity and inducing the increase of pressure. The level of pressure increases enough to break the retention. In the last thermocouple at 6180 seconds, the temperature decreases in a moment, noting an interruption of the flow of oil. With this interruption, greater mass of fluid accumulates in the production line and the pressure tends to increase as shown in the Fig. 6. When the system starts flowing again, the last thermocouple receive steam and there is a decrease in pressure due to the decrease of resistance in the flow. The valve output is always opened and under control, as the recovery factor reaches 40.15%.

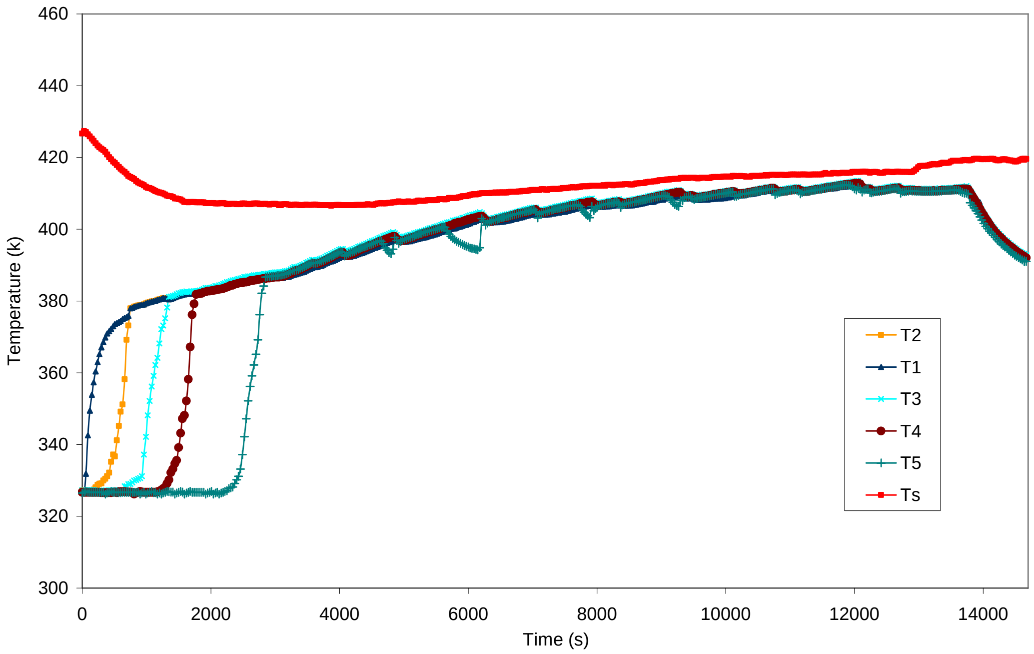

Figure 3. Temperature profiles for run 1

In the second test, the initial saturation and the experimental conditions were changed, as shown in Tab. 1. Repeat itself throughout the routine preparation of the tube, the porous medium containing a mixture of oil, water and air, pressurization system, pre-heating, leak tests and establishment of a vacuum. Fig. 4 shows the behavior of temperature profiles along the cell. A new enhancement is adopted to ensure the stability of the pressure upstream. To ensure that there is not loss of pressure in the system at critical moments, such as steam breakthrough, it was introduced a valve connecting the separator to a tank of nitrogen. As the pressure of 320 kPa is regulated, the opening of this valve maintains the pressure and thus the temperature inside the injection cell. The stage of establishing and operating system in previous cases, this run is that the temperature and pressure are controlled in the mixer to 423 K and 500 kPa surrounded by a resistance on the line of injection and 328 K on the line of production. After observing that the thermocouples inside the cell are stable in the temperature of reservoir, the valve to access the cell is opened and starts the injection. It is observed that the temperature rise in the first two thermocouples such as to the value of 375 K. When steam is injected, there is a progress of the steam passing through the clean sand with a high size until it finds the porous mixture. To find the porous medium itself, there is increased resistance to flow and it expands laterally. Thus, the temperature profiles of the two thermocouples are maintained at about 373 K until more vapor into the cell. The fact that can be seen when the steam temperature of 433 K reaches the third thermocouple. As well as the head of steam through the tube containing a mixture of liquid and gas, the pressure remains constant until the mass of condensate and oil with low viscosity reaches the last thermocouple. Before the temperature range of 433 K begins the peak of oil production. As there is a sharp decrease in resistance to flow, the difference in pressure also decreases. What leads to a simultaneous decrease in pressure and temperature of the entire system to 500 kPa and 428 K respectively. Note that the abrupt production of oil and water is also made with the eruption of steam, which reduces much of the pressure support system. To maintain the pressure and temperature of the system is triggered the entry of nitrogen in the separator. The recovery factor achieved was 86.03%.

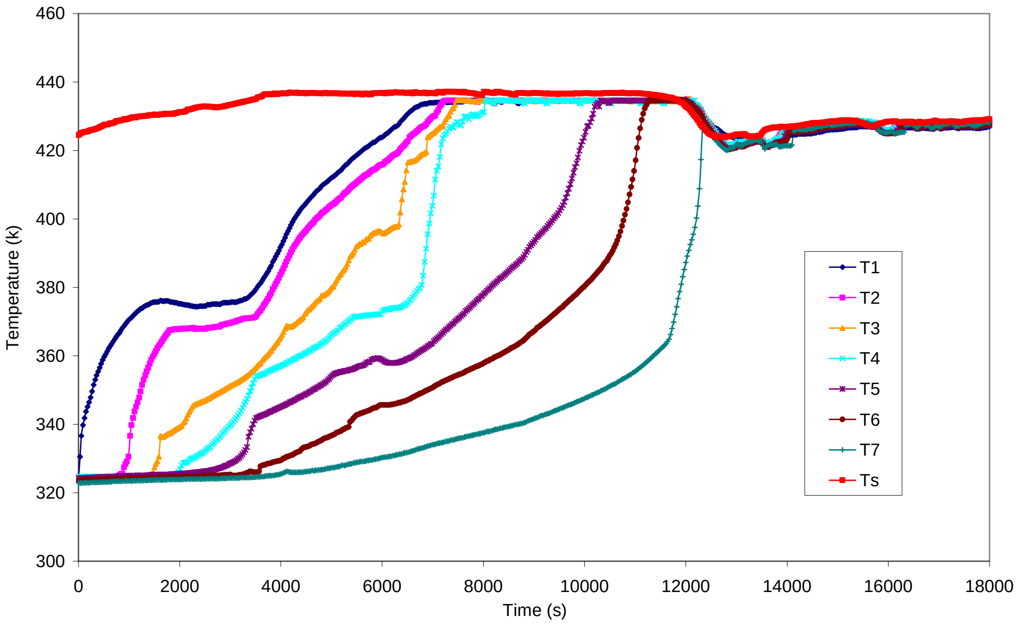

Figure 4. Temperature profiles for run 2

In the last test, remained approximately the same saturation and the initial experimental conditions of the second test, as indicated in the Guide. 1. The whole process before the experiment follows the same path of previous tests. Figure 4 shows the behavior of the temperature profiles along the cell. The behavior of vapor front is like the second test, but at the peak of oil production there is no sharp drop in temperature, pressure and injection system. The main change in the production system is the constant opening systematically of the back-pressure valve to inject nitrogen, keeping the pressure of producing around 450 kPa. So, when greater flow of oil and where the resistance decreases as a direct consequence reduce the pressure and temperature inside the cell, the pressure remains constant, providing good flow conditions. The recovery factor of 69.3% was achieved.

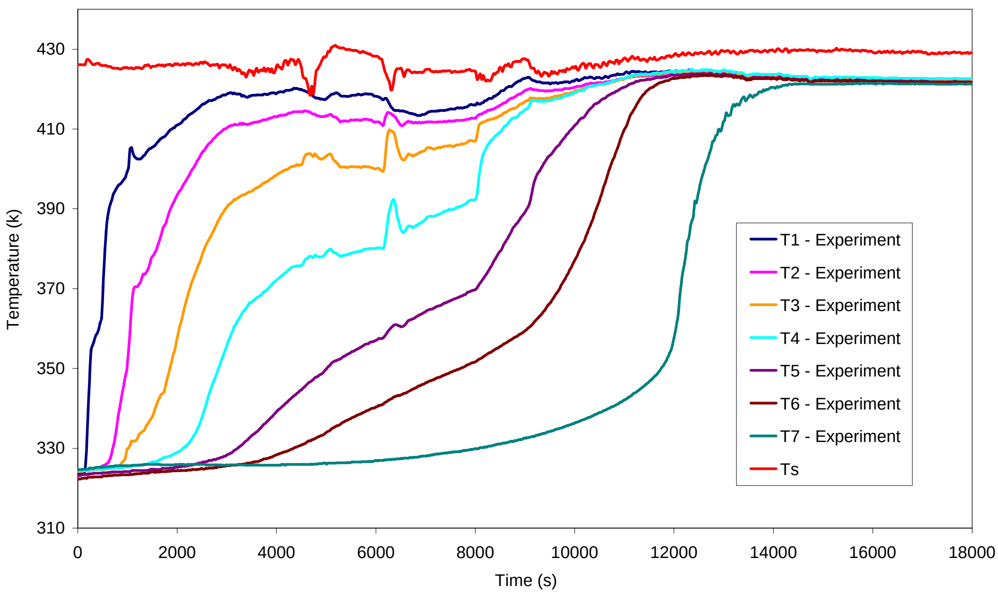

Figure 5. Temperature profiles for run 3

The Fig. 6 shows the behavior of the pressure of injection and production over time. The low back pressure in the first experiment even this does not have a heating system of the line of injection, interferes directly in the recovery of oil. As noted in the second experiment, increasing the back pressure along with increasing oil saturation shows good contribution in the recovery process and the back pressure was the main factor. Because of the excellent recovery, the third experiment, the same initial conditions of saturation of the first, but with the back pressure around 470 kPa shows satisfactory recovery.

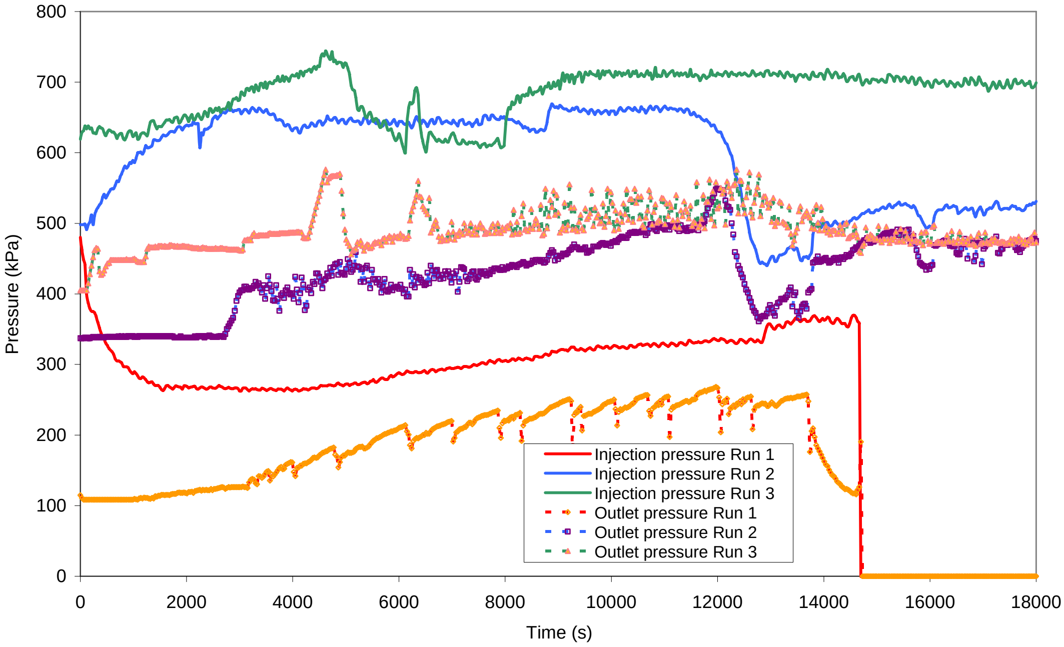

Figure 6. Cell pressure versus time for all runs

The Fig. 7 shows the combined production of oil and water for the last two experiments. Observe that the second experiment the production of liquid is anticipated due to the greater flow of cold water equivalent transformed into vapor compared to the third experiment. In the second experiment, there is the production of water after a steam breakthrough due to condensation and the efficiency of vertical displacement indicated by the formation of a bank of condensate and oil.

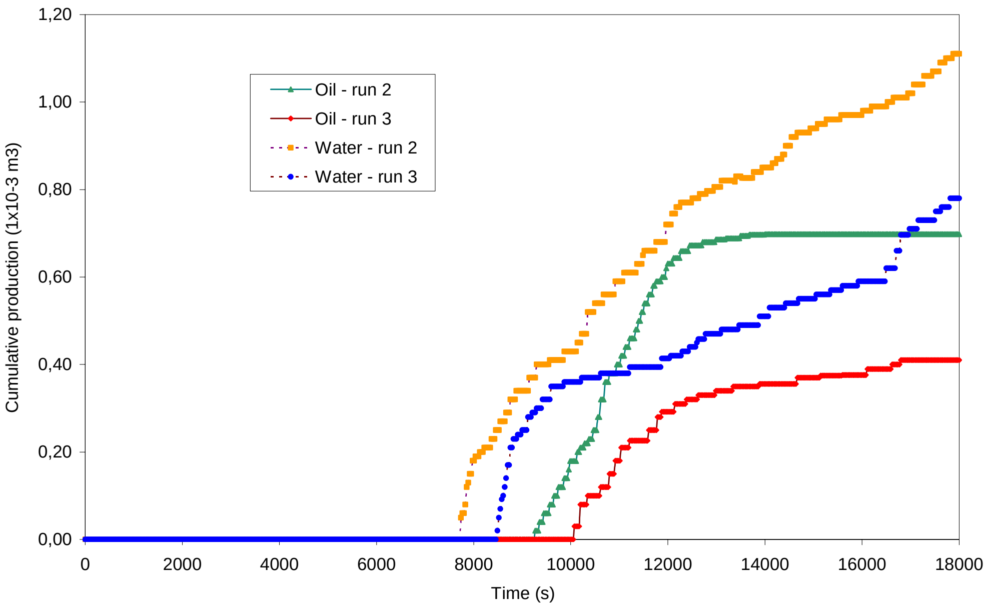

Figure 7. Cumulative oil and water production versus time for runs 2 and 3

Numerical history matching of the lab experimental results was conducted. CMG's STARS simulator was used in the simulation. A radial grid block system of (7×0.01×0.62) m was used. Because of the high value of the permeability, 13 Darcies, close to straight-line relative permeability curves were used. For the same reason, capillary pressure was neglected. Although the cell was insulated inside the pressure vessel, heat loss through the surfaces was still inevitable however is not include in this study. The means parameters used to be tuning during the history matching was the permeability and back pressure. The history matching was conducted using injection rate and production pressure of the third experiment. The simulation resulted in history matching of the bottom hole pressure at the injection well, as show in Fig. 8.

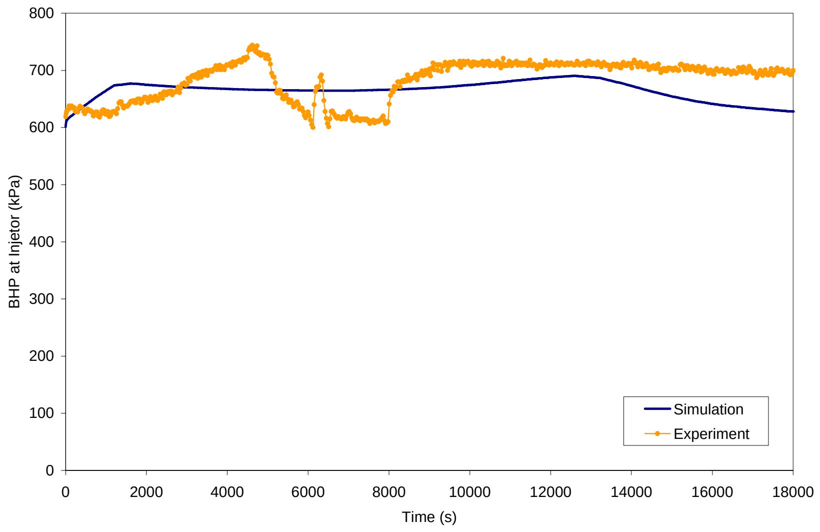

Figure 8. Comparison of the bottom hole pressure measured at the injection well in the experiment with the prediction of the numerical simulation

Although excellent match of the oil production was obtained, it is more important to match temperature profiles, which are a better indication that the simulation indeed captured the main features. Figure 9 shows comparison of temperature profiles during steamflood operation. The profiles from measurement and simulation are very close and our assumptions used in the simulation seem to be reasonable.

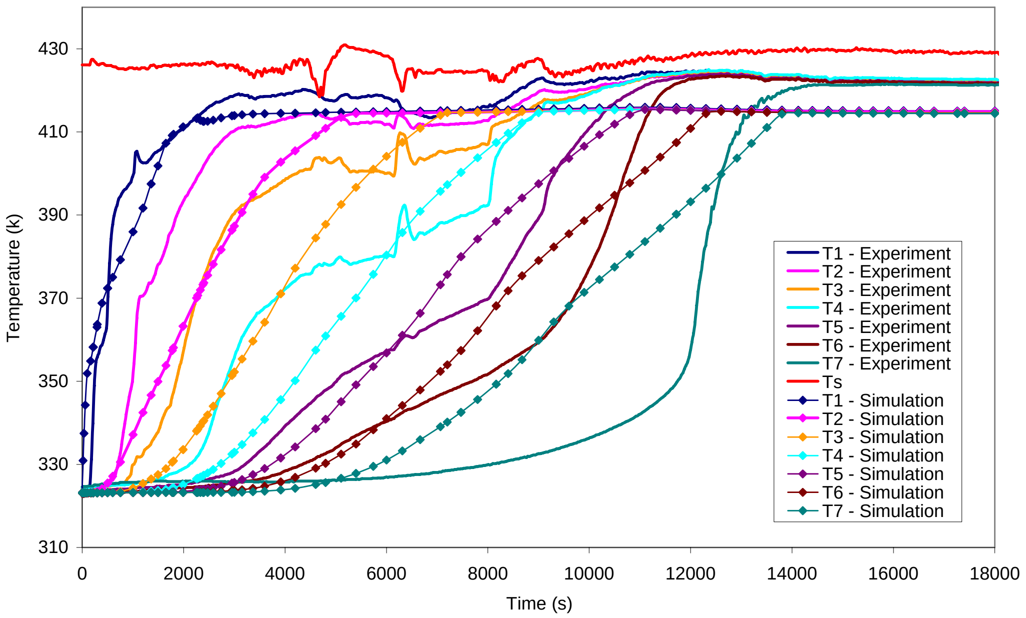

Figure 9 Comparison of simulated and measured of the temperature profiles

Lab experiment and corresponding numerical simulations were carried out to study a steamflood process. The experimental modifications of some parameters are extremely important to the performance on steamflood process. Conclusions about this performance are presented here:

- Appropriate initial conditions of pressure inside the cell can be observed in the second and third test. A back-pressure value at around 400 kPa does not decrease in injection pressure and consequently better conditions of temperature and pressure of steam injected.
- High-pressure and temperature steam is more effective at recovery oil than low-pressure steam comparing the first and third experiments with almost the same initial conditions.
- The initial saturation also has an important role when linked to the speed of the front of steam. As can be seen in the first test, high gas saturation and a low production pressure to provide a decrease in pressure filling the cell faster until it reaches work pressure.
- Ensuring the continuous flow responsible for the use of back-pressure valve operating with an input of nitrogen in the separator provides a continuous production even when presented with the eruption of steam, avoiding a decrease of pressure and temperature injection.
- The temperature profiles of steam front were successfully history matched using CMG's STARS reservoir simulation.

3. ACKNOWLEDGEMENTS

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