IN-SITU COMBUSTION PILOT BASIC DESIGN AND LABORATORY EXPERIMENTS

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When it must be decided to develop a field with an enhanced oil recovery method, first it is needed to have a reservoir characterization model of high quality. Then the choice of the best suited method has to be carried out. For any method, a preliminary study has to be performed in order to help to decide. In the case of an in-situ combustion field development, various patterns are considered; at the same time, duration for the combustion front to move from the injector to a producer is analyzed. Field examples of various patterns are presented.

The amount of air to inject in case of dry combustion and of air and water in case of wet combustion has to be determined in order to design air compressors and water pumps. The amount of air is a function of the volumetric sweep efficiency and of the oil and the matrix from the reservoir. Lab experiments must be performed in the reservoir matrix with the reservoir oil to determine the air requirement, which is the amount of air needed to burn a unit volume of reservoir. The amount of water is also determined by lab tests. Then the flows of air and of water are determined, which allows the design of compressors and pumps.

The amount of oil produced is calculated taking into account the sweep efficiency in the different zones in front of the combustion. Production of oil, water and gas and their compositions obtained at the lab scale are presented. A scheme of the production, treatment and storage for a pilot field test is shown.

In conclusion, a diagram shows the general guidelines for the preparation and implementation of field experiments using in-situ combustion.

Keywords: enhanced oil recovery, in-situ combustion, pilot, design, laboratory experiments
DOI: http://doi.org/10.18599/grs.19.1.1

For citation: Gadelle C. In-situ Combustion Pilot Basic Design and Laboratory Experiments. *Georesursy = Georesources*. 2017. V. 19. No. 1. Pp. 2-8. DOI: http://doi.org/10.18599/grs.19.1.1

Introduction

Due to the increase in the world population and to the increase in its welfare, more and more energy is needed. Renewable energies are not sufficient to answer the demand and fossil energies will remain for a long time the main resources. New fields are more and more difficult to find and more and more expensive to develop. The mean recovery factor of the developed fields is around 35 % of the oil in place. New methods – Enhanced Oil Recovery (EOR) – are the solution for increasing this recovery factor.

Different methods existing in EOR are classified in:

- Chemical methods: polymers, polymers-surfactants, alkali-surfactant-polymer;
- Miscible or partially miscible gas methods: hydrocarbons (lean or rich gas), carbon dioxide, nitrogen;
- Thermal methods: steam injection, in-situ combustion;
- Microbial methods.

Whatever the method, the first step to produce a reservoir is to perform its characterization in order to know the quantities of hydrocarbons in place and the complexity of the structure for the flow of fluids (Fig. 1) (Burger et al., 1985).

Thermal methods are the best EOR methods for heavy, extra-heavy oils and bitumen. In steam injection, heat is produced on the surface and injected into the reservoir through the vaporized water. In in-situ combustion, the heat is produced in the reservoir itself, meaning better energy efficiency than in the case of steam.

The principle of in-situ combustion is to burn with air or oxygen, some of the oil in place. The heat generated by the combustion is used to decrease the viscosity of the remaining oil and hence facilitates its production. Combustion is started by an artificial mean or by self-ignition, increasing the temperature up to a value where a combustion front is initiated and moves from the injection well to production wells. Only an oxidizing gas – dry combustion – is injected or air and water – wet combustion – are injected simultaneously or alternately. The aim of the water injection is to recover the heat stored in the reservoir behind the combustion front. In both cases, there is formation of a coke-like material, which will act as

GEOLOGICAL STUDY
- Lateral and vertical boundaries of the reservoir
- Characteristics of the overburden
- Number of layers and continuity (faults, impervious barriers...)
- Correlations between wells (depth and thickness of layers)
- Lithology and mineralogical composition of the rock (clays...)
- Mineral and organic geochemistry
- Matrix heterogeneities and fissuration

▼

STUDY OF THE SELECTED RESERVOIR
- Petrophysical properties (porosities, saturations, permeabilities)
- Interpretation of production data and of well tests
- Oil analysis (density, viscosity, distillation curves, pertinent standard tests, geochemical analysis)
- Analysis of reservoir water (salinity...)

Characteristics of the aquifer and the gas cap
- Tests of interference between wells, injectivity tests

▼

REALIZATION OF A RESERVOIR MODEL
- Geometry of the reservoir
- Amount of oil already produced and still to be produced
- Distribution of the saturations

Figure 1. Diagram of the Study of Reservoir Data Prior to an EOR Test

This paper was presented at the 1st International Workshop "Thermal Methods for Enhanced Oil Recovery: Laboratory Testing, Simulation and Oilfields Applications", ThEOR 2016, held in Kazan, Russia, June 28 – July 1, 2016.

the fuel for the combustion. This fuel is produced by cracking and pyrolysis of the oil in front of the combustion front. The amount of fuel is lower in the case of wet combustion due to the heat transfer from behind the front, allowing a better sweep efficiency in front of the combustion front.

Before implementing a field test for in-situ combustion, it is needed to check if the reservoir fulfills the screening criteria already known, to define the pattern on which ISC will be tested, to estimate the performances which can be reached, to determine through lab tests the main parameters governing the ISC process and to define the main equipment which will be used for performing the pilot test. Utilization of thermal numerical models like Stars or Eclipse will be very useful for optimization of the parameters involved in the combustion process, but analytical models like the one from Nelson and McNiel (Nelson, McNiel, 1961) give a better understanding of the ISC.

Screening criteria

Screening criteria (Gadelle, Clause, 2013) have been developed to select the best method of EOR for a given reservoir (Fig. 2). For an in-situ combustion field experiment, it is recommended that the reservoir depth is enough high for not having an overburden fracture when injecting air, the maximum depth is limited by the economics of the process (cost of air injection at high pressure). Sand or sandstone are better matrix than carbonates which being very often fissured or fractured, are not recommended for a gas injection such as air injection. Viscosity or specific gravity must be high.

Pattern size

Different patterns (Renard, 2011) with varying spacing between wells and numbers of wells (5, 7, 9 spots) can be used at the pilot level (Fig. 3). The case of the THAI process (combustion with horizontal and vertical wells is not considered here). The inverted 7-spot is the most regular with the same distance between injector and producers; the inverted 5-spot is also very regular but having fewer wells, its sweep efficiency will be lower. Generally the field is then developed with patterns identical to the one used for the pilot; in case of a dipping reservoir, line drive is preferred to usual patterns (Fig. 3). In the Suplacu de Barcau field in Romania (Gadelle et al., 1981), the combustion was ignited in a 5-spot pattern, which, after the good results obtained, was extended to a 9-spot pattern. Then the combustion was pursued in several patterns.

CRITERIA	THERMAL		MISCIBLE GAS	CHEMICAL FLOODING
	STEAM	IN SITU COMBUSTION		
LITHOLOGY	NC	SANDSTONE	NC	SANDSTONE
GAS CAP	SMALL	SMALL OR NIL	SMALL OR NIL	SMALL OR NIL
FRACTURING	NC	SMALL OR NIL	SMALL OR NIL	SMALL OR NIL
TRANSMISSIBILITY	> 30	> 5	NC	NC
MOBILITY	NC	NC	NC	> 25
VISCOSITY (cP)	NC	NC	< 10	< 40
DEPTH (m)	> 300 < 1500	NC	> 700	NC
SALINITY	NC	NC	NC	< 50
RECOVERY (% OIL IN THE GROUND)	30/60	25/60	20/40	15/35

Figure 2. Screening Criteria for Enhanced Oil Recovery Process

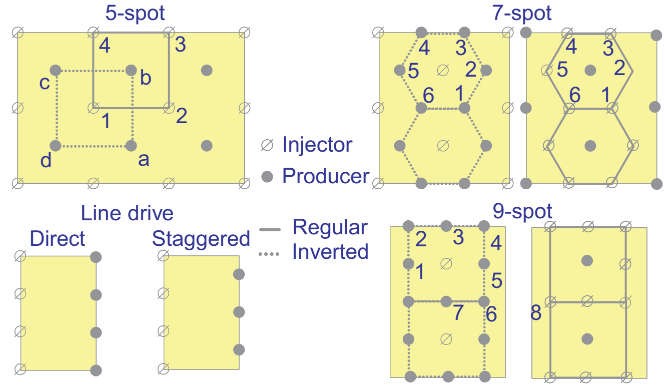


Figure 3. Various Patterns

After some years, instead of continuing to produce the field with patterns, it was decided to start a line drive for the combustion in order to benefit from gravity displacement due to the dip angle of the reservoir. The pattern size in case of 5-spot is described on Fig. 4. The rate of the combustion front is generally comprised between 5 and 10 cm/day; here a mean value of 7.5 cm/day for the rate of the combustion front is used; with such a value, the duration to sweep 1 ha (100 m*100 m) is 2.6 years. In the case of the Chichimene field in Colombia (Fig. 5), the first design was a distance between the injector and the producers of 450 m; duration for the front to arrive to a producer was 12 to 25 years with rate of the front of 10 and 5 cm/day. This delay was too long and it was decided to modify the pattern in order to have only 110 m between the injector and a producer, meaning a time of 3 to 6 years with the previous rates.

Amount of air and water to be injected

Amount of air

The amount of air to be injected to sweep the pattern is depending of the size of the pattern and of the thickness of the layer, of the areal and vertical sweep efficiencies and of the air requirement to burn a unit volume of reservoir which is the ratio between the air flux and the combustion front rate.

Sweep efficiency

The volumetric sweep efficiency by the air injected depends on the pattern used for the pilot test. For an inverted 5-spot, the areal sweep efficiency lies around 65 %. The vertical air sweep efficiency is depending on the thickness of the layer; due to segregation effects, it decreases with the

• Size of patterns	50*50 m^2	100*100 m^2	150*150 m^2
• Distance injector to producer	35 m	70 m	105 m
• Rate of the combustion front		# 7.5 cm/day	
• Duration to sweep the pattern	1.3 years	2.6 years	3.9 years

Figure 4. Pattern Size

- **First design**
- Distance between injector and producers: #450 m
- Rate of the combustion front: 5 to 10 cm/day
- Duration to sweep the pattern: 4500 to 9000 days, i.e. 12 to 25 years
- **New design**
- Distance between injector and producers: #110 m
- Rate of the combustion front: 5 to 10 cm/day
- Duration to sweep the pattern: 1100 to 2200 days, i.e. 3 to 6 years

Figure 5. Chichimene Pilot for ISC

thickness; it increases with the air flow rate. Up to a thickness of the layer of 5 m, a value of 1 can be considered for the vertical sweep efficiency; above this thickness, vertical sweep efficiency must be decreased.

Air requirement

The air requirement which is the ratio of the air flux to the rate of the combustion front represents the amount of air needed to burn a unit volume of porous medium. This value does not depend of the flow rate and the pressure; it is a characteristic of the reservoir and its oil. It cannot be extrapolated from other tests performed with different oils or matrix. This is shown in Fig. 6; the 2 oils considered have quite similar properties in terms of sp.gr., viscosity, asphaltene content and the matrix have amount of metals susceptible to act as catalyst for the combustion, of the same order of magnitude.

The air requirement is obtained through laboratory tests performed in combustion tubes. Figure 7 shows the equipment for combustion tube tests manufactured by Xytel Inc. (Gadelle, Clause, 2012). It can work up to pressure of 350 bar and temperature of 800 °C. It consists of a thin inner tube of 10 cm diameter and 200 cm length which can sustain a pressure of 10 bar and an outer shell which withstands very high pressure. Around the inner tube 33 heaters are used to prevent heat losses; temperatures are measured in the axis of the inner tube and at its wall at the level of each heater; wall temperature at each heating collar is maintained around 10 °C lower than the axis temperature in order to be sure to not inject heat. In the annulus between the inner tube and the outer shell, insulating material is placed for decreasing the heat losses, and it is under a nitrogen pressure. Air and water in case of wet combustion are injected through a specific manifold. At the outlet, the gases are measured and analyzed; the oil and water produced are also measured and analyzed.

OIL CHARACTERISTICS-AMOUNT OF COKE

CHARACTERISTICS	ROMANIA	INDIA
Specific gravity	0.96	0.94
Viscosity (20°C)	2,000 cP	6,000 cP
Conradson Carbon	7.2%	7.7%
Asphaltenes	1%	0.15%
Amount of Ni + V	15 ppm	200 ppm
COMBUSTION		
Ignition	Easy	Difficult
Coke deposit	25-30 kg/m^3 ~ 1.8 lb/ft^3	35-40 kg/m^3 ~ 2.3 lb/ft^3
Produced oil	Little modifications	Degraded

Figure 6. Influence of Oil Characteristics on Coke Deposit

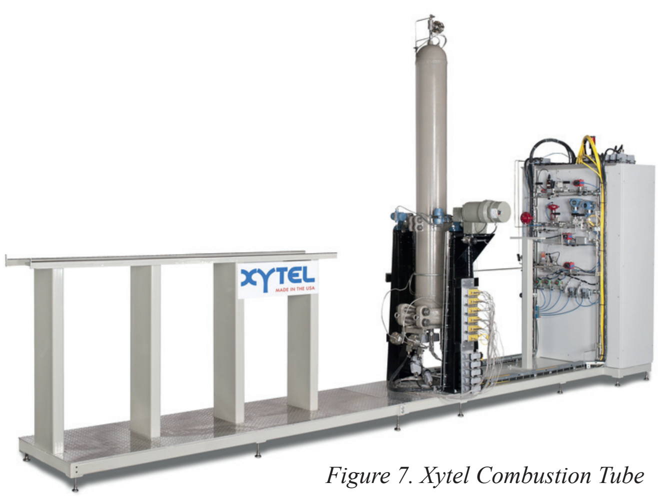


Figure 7. Xytel Combustion Tube

Figure 8 shows the position of the combustion fronts vs. time in an experiment (Gadelle et al., 1981) started in dry combustion and followed by wet combustion. The slope of the curve represents the rate of the combustion front. Knowing the air flow rate and the diameter of the combustion tube, it is easy to calculate the air flux. From the air flux and the rate of the combustion front, the air requirement is calculated.

As shown in Figure 9, it is needed to carry out several tests to determine the best conditions for propagating the combustion in dry or wet mode.

The experiments carried out in a combustion tube must be realized with the oil and the matrix from the reservoir as mentioned earlier. In many cases the availability of reservoir matrix is difficult and when it is consolidated, this material must be crushed and sieved before using. If there is not enough reservoir matrix, it could be necessary to find a sand and additives (such as clay) having the same properties regarding ISC as the initial matrix. Then the artificial sand will be used for quite all the experiments. Ramped Temperature Oxidation (RTO) can be used to find a substitute to the original matrix.

The equipment for RTO, manufactured by Xytel Inc., is shown in Fig. 10 (Gadelle, Clause, 2012). A sample containing oil and sand (or crushed core material) is heated from room temperature up to 500-600 °C. An oxygen containing gas or nitrogen is circulated through the sample. Thermal effects are observed with thermocouples and the reactions are followed through the oxygen consumption and the CO_2 and CO formation (Fig. 11). Two reactions appear, one at low

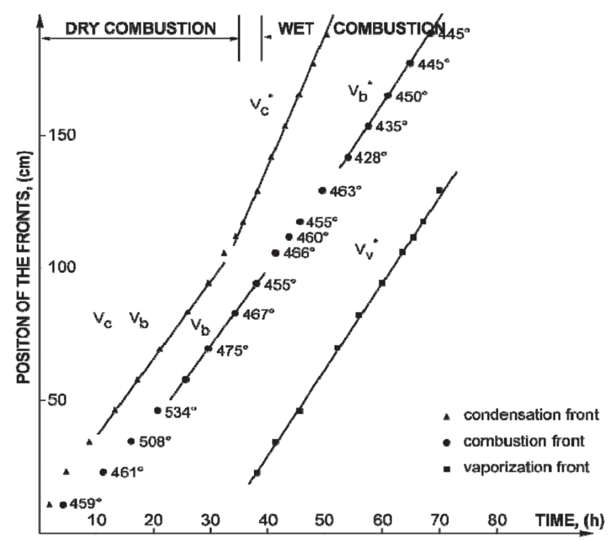


Figure 8. Positions of the Fronts in Dry and Wet Combustion

Dry or wet combustion

• Dry combustion tests: 2 at different air flow rates;
• Wet combustion tests: start in dry combustion, move to wet combustion;
• 2 or 3 tests at different water/air ratio with the best air flow rate determined before;
• Enough water to reach the combustion front;
• Not too much water to not extinguish the combustion.

Figure 9. Combustion Experiments to Perform for a Pilot Test

temperature which is the fixation of oxygen on hydrocarbon molecules (practically no formation of carbon oxides), the second at high temperature where all the oxygen consumed is transformed into carbon oxides. The first reaction is an oxidation reaction whereas the second is a combustion reaction. In some cases a third reaction peak is seen at very high temperature. It is attributed to insoluble organic material linked to the matrix (kerogen).

The second peak, corresponding to a combustion reaction, gives an order of magnitude of the amount of fuel which will be burned during the in-situ combustion. The first peak, corresponding to hydrocarbon oxidation, normally does not exist during in-situ combustion, because the operator wants that all the oxygen is consumed at the front and that there is no residual oxygen in front of the combustion front. The virgin oil is heated by a gas containing no oxygen or a very small amount, and is submitted to pyrolysis and cracking in an inert atmosphere. Results are shown on Figure 11.

This equipment is very useful not only for choosing a substitute to the original matrix or to compare the chemistry of different oils in different matrix, but also to check the influence of catalysts which can be injected during the ISC process.

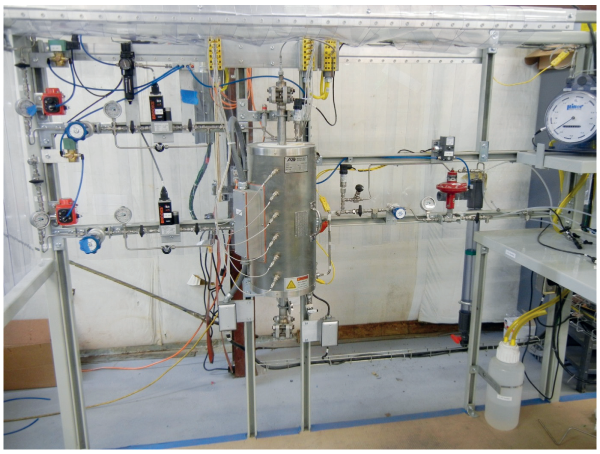


Figure 10. Xytel Ramped Temperature Oxidation Equipment

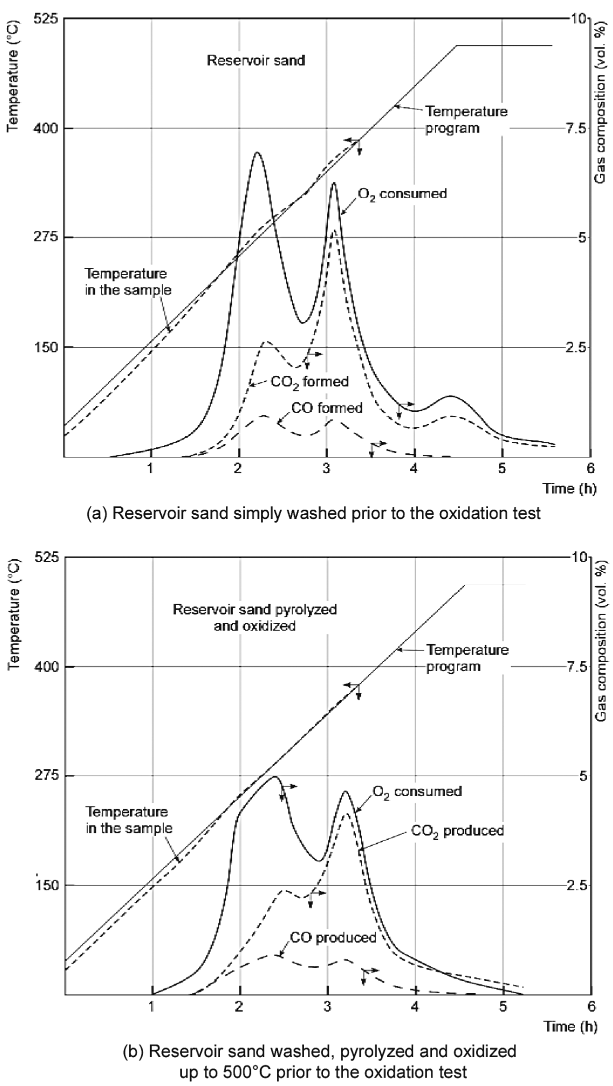


Figure 11. Ramped Temperature Oxidation – Effluent Gas Analysis

Amount of water to be injected

The combustion tube allows defining the best ratio between the flow rates of air and water in wet combustion. The amount of water to be injected during the operation is then calculated from the amount of air. The water can be injected simultaneously or sequentially with the air. Generally it is preferred to inject alternately the air and the water for minimizing the corrosion effect.

Air and water flow rates

The maximal injected air flow rate is generally reached at the end of the pilot test when the combustion is the largest; this value is depending on the vertical and horizontal efficiencies and on the area of the pattern and thickness of the layer. It is assumed that the rate of the combustion front is at its minimum value which is in the range of 4 cm/day.

The air injection schedule can be to use immediately the maximal flow rate of air or to increase the flow of air step by step until it reaches the maximal air flow rate. The second possibility is probably better because during the combustion displacement, it minimizes the air going through the front and so the possible detrimental low temperature oxidation.

If the water is injected slug by slug, it is necessary to take into account during the calculations the ratio of water/oil and the duration of the slugs of air and water.

Air and Water Facilities

From the amount of air and water to be injected and their respective flow rates, it is easy to determine the maximum injection pressure. Then the design of the compressors and pumps can be carried out. Fig. 12 shows such air and water facilities.

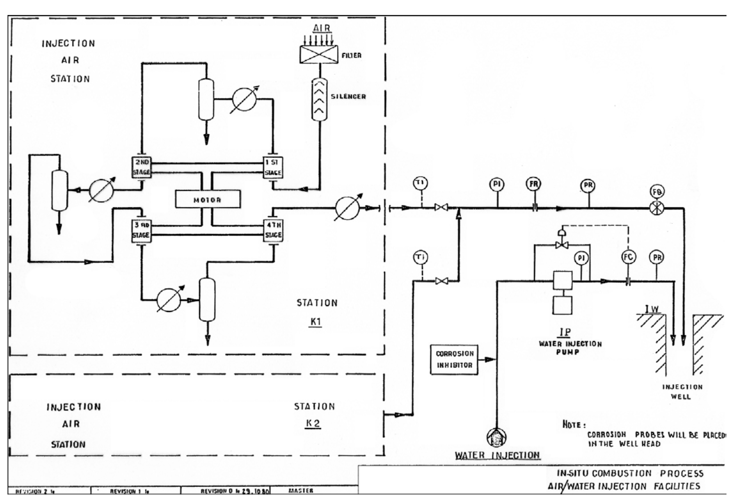


Figure 12. Air and Water Injection Facilities

Prediction of performances

Amount of oil

The volume of oil produced during the pilot test can be evaluated by considering the displacement phenomena in the various zones (Fig. 13) (Burger et al., 1985):

Zone 1: zone effectively burned from which the oil has been burned or displaced;

Zone 2: steam zone downstream the burned zone, where the oil saturation is quite the residual oil saturation after a steam displacement;

Zone 3: hot water zone downstream from the steam zone, where the oil saturation is the residual oil saturation after a hot water displacement;

Zone 4: hot water zone below the zones 1 and 2 with the same residual oil as in zone 3;

Zone 5: zone not affected by the combustion.

From the values of air injected and oil produced, it is possible to calculate the Air/Oil Ratio (AOR), which is a measure of the interest of the project.

Correlation between the volume burned and the volume of oil displaced in a specific field have also been proposed and can also be used to determine the amount of oil recovered (Gates, Ramey, 1980).

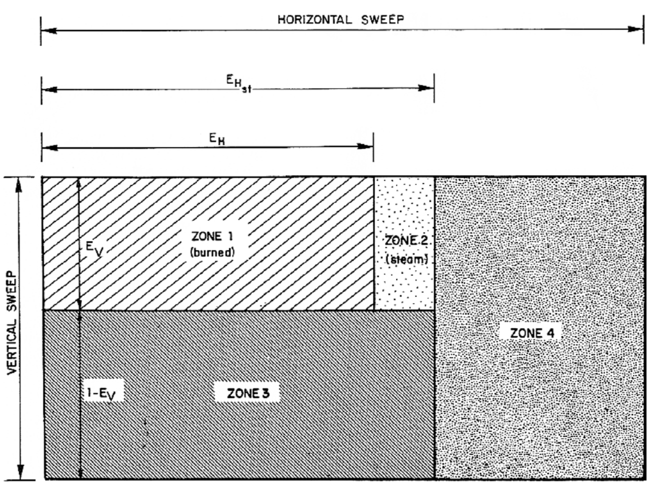


Figure 13. Sweep Efficiencies for In-situ Combustion

Amount of water

The water produced is the connate water and the water of combustion which is calculated from the stoechiometric equation of burning the coke material; in case of wet combustion, part of the water injected with air is produced.

Amount of gas

The gas produced is the nitrogen injected with the oxygen for the combustion, and the carbon oxides. The amount is not much different of the amount of air injected. When the oil contains some sulphur, hydrogen sulphide will be produced, and safety measures have to be taken.

Production facilities

Figure 14 shows facilities for a pilot test. First there is a gas – liquid separator, followed by separation between oil and water with the use of heater – treater for braking emulsions. All the gas is sent to a stack or today it is treated to eliminate through oxidation all the residual hydrocarbons, carbon monoxide. In case a specific treatment is designed for H_2S. The water after treatment is disposed of. The oil goes to storage.

Technology

Technology is a very important point when implementing a pilot. On this side, it is necessary to define the completion of the injection well and of the production wells taking in account the high temperature encountered during the combustion (high quality stainless steel for tubing and casing, thermal cement, thermal packers). Cooling of the wells by internal tubing is a requisite. All this part must be carried out by specialists of the different domains.

Only one point which is very important has to be considered here: the ignition. Ignition is the first operation to be realized when starting the pilot. A good ignition will generally allow a successful combustion, but a bad ignition means a failure. The different ways for starting the combustion are self ignition or artificial ignition.

Self ignition

If the oil in place is sufficiently oxidizable under bottom hole conditions, spontaneous ignition may occur near the

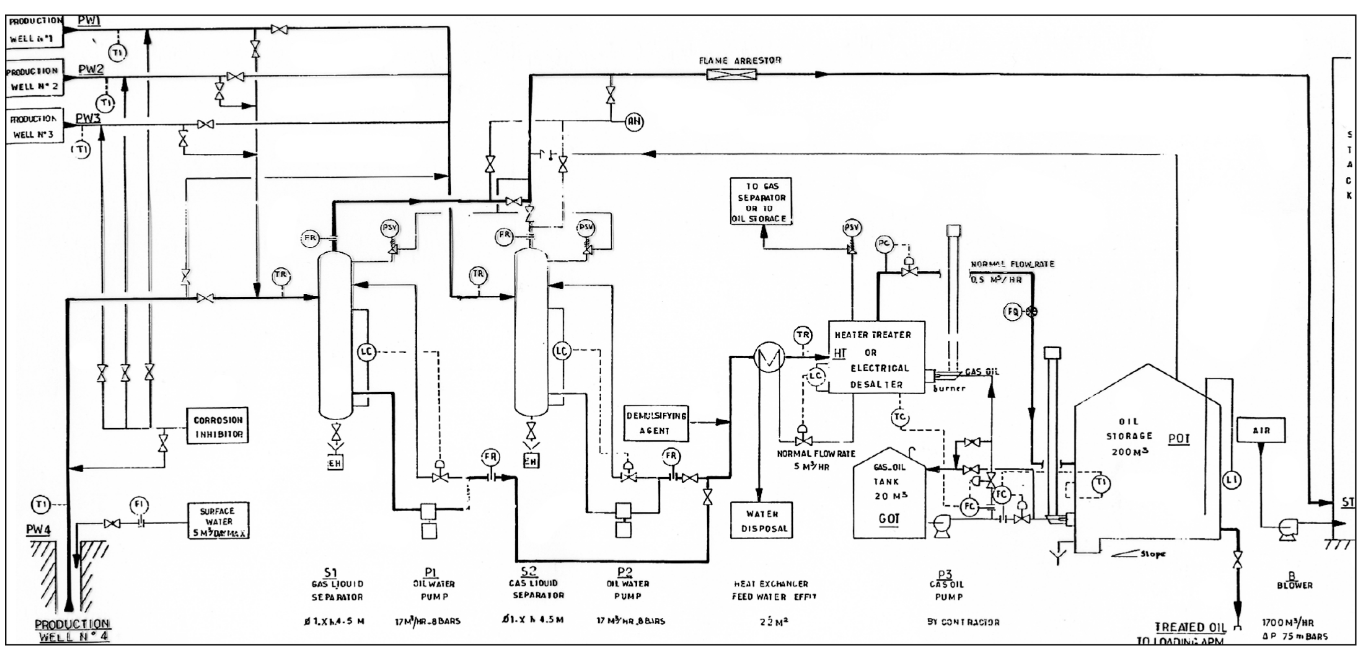
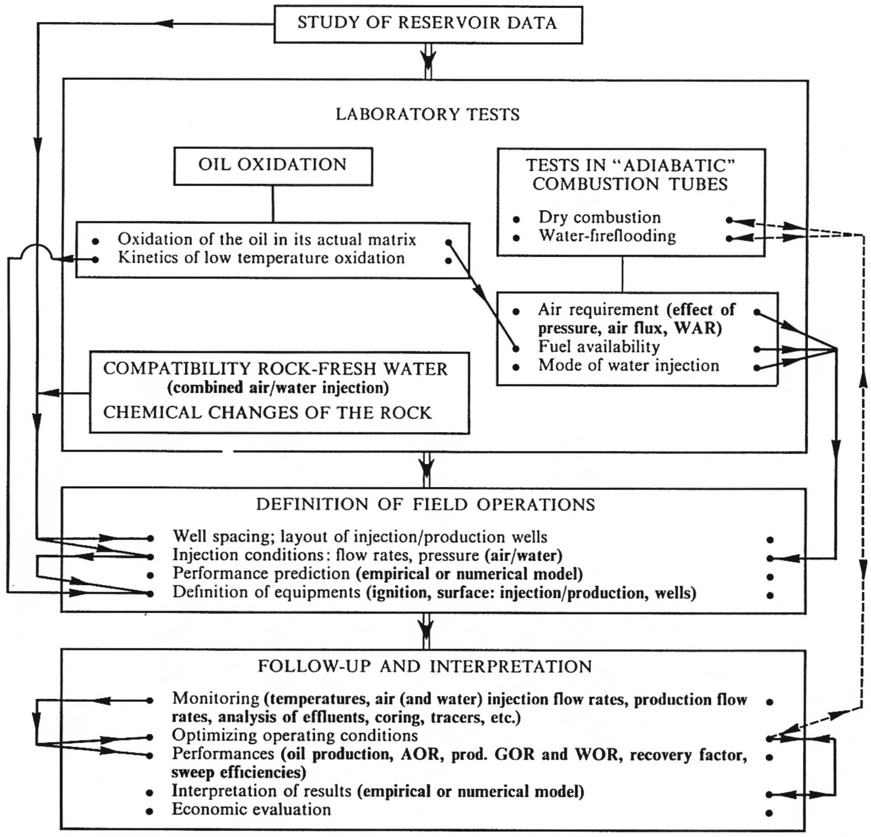


Figure 14. Production, Treatment and Storage Facilities

Figure 15. Isothermal Cell for Studying Kinetics of Oxidation

wellbore after a certain time of air injection; this time is called the ignition delay. It depends on the heat generated by the oxidation of the oil and on the heat losses to the surroundings. The heat from oxidation reaction is calculated taking into account the kinetic of reaction of the oil with oxygen. This kinetic law is determined in the laboratory with equipment such as the one, manufactured by Xytel Inc., in Fig. 15. Then by using analytical formula or simple numerical model, the ignition delay at reservoir conditions is estimated (Hernando Bottia-Ramirez et al., 2017).



(1) This diagram is valid for firef looding with oxygen-enriched air, with the oxygen content as an additional parameter.

Figure 16. Diagram of the Study of an In-situ Combustion Project

Artificial ignition

If spontaneous ignition is not possible at reservoir conditions, artificial means are necessary for igniting the formation. Gas burners, electrical igniters, steam or chemical additives have been successfully used in field operations. All of them have their own limitations.

Conclusions

In the past several field tests were unsuccessful due to a lack of knowledge of the main factors to take into account for designing such tests. One of the main reasons was the absence of good quality data regarding the behaviour of the oil in in-situ combustion. Today, there exists the possibility to carry out laboratory tests in perfectly designed equipment and to obtain the necessary data for designing a field test. Utilization of analytical models or numerical models allows knowing of the displacement of the combustion in the formation. Combined with the lab data, they permit a good design of a pilot field test. Figure 16 shows the general guidelines for the preparation and implementation of field experiment for in-situ combustion.

References

Burger J., Sourieau P., Combarnous M. Thermal Methods of Oil Recovery. Editions Technip, Paris; Gulf Publishing Company, Houston. 1985. 430 p.

Gadelle C., Clause O. Laboratory Studies as a Screening Tool for Enhanced Oil Recovery Methods. *Proc. Int. Conference «Heavy Oils and Natural Bitumens: Increasing Efficiency of Development of Mature Oil Fields»*. Kazan, Russia. 2013. Pp. 11-16.

Gadelle C., Clause O. In-Situ Combustion: Why Lab Experiments Are Needed for Field Exploitation? *Proc. Int. Conference «Heavy oil and natural bitumen – Problem aspects and improving efficiency of upstream activities»*. Kazan, Russia. 2012. Pp. 12-19.

Gadelle C., Burger J., Bardon C., Machedon V., Carcoana A., Petcovici V. Heavy Oil Recovery by In-Situ Combustion. Trans. Soc. Petroleum Engrs AIME. *J. Petroleum Technol*. 1981. Vol. 271. Pp. 2057-2066.

Gates C.F., Ramey H.J., Jr. A Method for Engineering In-situ Combustion Oil Recovery Projects. *J. Petroleum Technol*. 1980. Vol. 32. Pp. 285-292.

Hernando Bottia-Ramirez, Maria Aguillon-Macea, Humberto Lizcano-Rubio, Claudia Lorena Delgadillo-Aya and C. Gadelle. Numerical modeling on in-situ combustion process in the Chichimene field: ignition stage. *Journal of Petroleum Science and Engineering*. 2017. http://dx.doi.org/10.1016/j.petrol.2017.02.023

Nelson T.W., McNiel J.S., Jr. How to Engineer an In-situ Combustion Project. *Oil and Gas J*. 1961. Vol. 59. N° 23. Pp. 58-65.

Renard G. Enhanced Recovery. Chapter 8 in «Heavy Crude Oils: from Geology to Upgrading, An Overview». Editions Technip, Paris. 2011. 440 p.

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Manuscript received 30 June 2016;
Accepted 9 March 2017;
Published 30 March 2017

Пилотный проект внутрипластового горения: проектирование и лабораторные эксперименты

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Аннотация. При разработке месторождения с применением методов увеличения нефтеотдачи прежде всего необходимо построить качественную геологическую модель месторождения. Затем, с помощью предварительных исследований, следует выбрать наиболее подходящий метод. При разработке месторождения с применением внутрипластового горения, учитываются различные закономерности; попутно анализируется длительность перехода фронта горения от нагнетательной к добывающей скважине. Представлены примеры различных моделей. Для проектирования воздушных компрессоров и водяных насосов необходимо определить количество нагнетаемого воздуха в случае сухого горения и воздуха и воды в случае влажного горения. Количество воздуха зависит от коэффициента охвата по объему и пластовой нефти и матрицы коллектора. Лабораторные испытания должны выполняться в матрице коллектора с пластовой нефтью для определения количества воздуха, необходимого для сжигания единицы объема коллектора. Количество воды также определяется лабораторными испытаниями. Затем определяются потоки воды и воздуха. Количество добываемой нефти рассчитывается с учетом эффективности вытеснения в разных зонах фронта горения. Приводятся данные о добыче нефти, воды и газа, а также их составных компонентов, полученных в лабораторных условиях. Показана схема добычи, обработки и хранения при эксплуатационном испытании. В заключении на диаграмме показаны общие рекомендации по подготовке и проведению эксплуатационных испытаний с применением внутрипластового горения.

Ключевые слова: повышение нефтеотдачи, внутрипластовое горение, пилотный проект, проектирование, лабораторные эксперименты

Для цитирования: Gadelle C. In-situ Combustion Pilot Basic Design and Laboratory Experiments. *Georesursy = Georesources*. 2017. V. 19. No. 1. Pp. 2-8. DOI: http://doi.org/10.18599/grs.19.1.1