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IN-SITU COMBUSTION PROCESS, ONE OF IOR METHODS LIVENING THE RESERVOIRS

Ghafoor Karimi, Arvin Khadem Samimi

NIOC-Research Institute of Petroleum Industry, E-mail: karimigh@ripi.ir

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ABSTRACT

The oil resources of Iran are still estimated to be high enough but an increasing worldwide consumption is the reason to begin a large scale Improved Oil Recovery (IOR) of oil deposits in Iran, nowadays. A special consideration ought to be given to huge and now unrecoverable reserves from fractured carbonates.

In-Situ Combustion has one unique characteristic that it is the only IOR process which may be applicable over a wide range of crude gravities and viscosities.

High Pressure Air Injection (HPAI) is an IOR process in which compressed air is injected into a high gravity, high pressure oil reservoir, with the expectation that the oxygen in the injected air will react with a fraction of the reservoir oil at elevated temperature to produce carbon dioxide. The resulting flue gas mixture, which is primarily hot CO2, nitrogen and steam, provides mobilization force to the oil downstream of the reaction region, sweeping it to the producing wells. The gas-oil mixture may be immiscible, or partly or completely miscible. In some situations, the elevated temperature reaction zone itself may provide a critical part of a sweep mechanism in terms of incremental recovery.

Obviously, crude oil with present and future prices will not remain underground with only 10% to 15% recovery. This in turn requires properly designed CIS scenarios for each particular reservoir, such as foam injection, followed by air injection at high pressure, mixed with appropriate catalysts and inhibitors, for strong combustion initiation and combustion front steering.

Therefore, multiple IOR processes become active as a result of smoldering combustion reaction. The subsequent temperature gradient activates a series of IOR processes chasing each other, intermingling under the influence of gravity, “Livening the Reservoir”.

Key Words: In-situ Combustion; IOR; Ignition; Oxidation; Fracture Carbonate Reservoir.

1. Introduction

In-situ combustion has been utilized for over 80 years in more than two hundred fields around the world. It is normally employed as a recovery process in more difficult reservoirs as a secondary or tertiary process. [1]

Until 1979, the In Situ Combustion (ISC) was commercially applied mainly in heavy-oil, non-fractured, and non-carbonate reservoirs. However, the widespread acceptance of air flooding as an IOR process came in 1994, when the results of commercial HPAI processes in the Williston basin, North and South Dakota, U.S.A., were published. These processes were developed directly in the field without any laboratory support or reliable numerical simulation. The main drive behind their development was a pressing need to find an injecting agent with acceptable injectivity (better than that of water). It is interesting to note that these processes were reported after 15 and 7 years, respectively, of commercial operations. [2]

High pressure air injection can be used to increase oil recovery from water flooded reservoirs. Some of the benefits from high pressure air injection include 1) reservoir pressurization, 2) mobilization of combustion oil, 3) flue gas stripping of the reservoir oil, 4)oil swelling,5) improvement in the density and viscosity contrast between the injected gas and the resident oil and water, 6) injection gas substitution(air instead of methane), 7) spontaneous oil ignition and complete oxygen utilization, 8)supercritical steam effects, 9)miscibility effects, and 10) increased oil reactivity.[3],note(Fig. 1)[4]

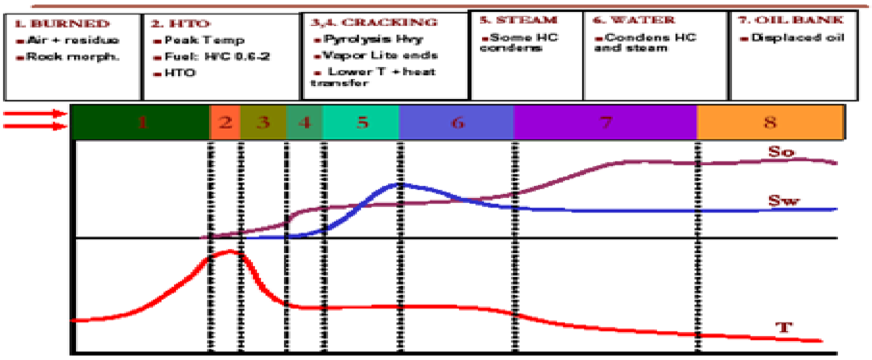


Figure 1 Schematic temperature, oil, and water distributions over space for forward combustion [23].

2. Combustion process

2.1 Chemistry

The critical factor for success of HPAI is the reaction between the oxygen and the hydrocarbons. Two possible reaction pathways exist. The first is referred to as "bond scission" reactions, and represents where the oxygen breaks up the hydrocarbon molecules to principally produce, carbon dioxide and water; in other words, these are the traditional combustion reactions, namely, high temperature oxidation mode (HTO). Bond scission reactions are critical to the success of HPAI process. The second possible set of reactions between oxygen and hydrocarbons are called "oxygen addition" reactions. In this scenario, oxygen atoms are chemically bound into the molecular structure of the liquid hydrocarbons, and compounds tend to further react and polymerize with each other, forming heavier, less desirable, higher viscosity oil fractions low temperature oxidation (LTO). In short, when oxygen addition reactions dominate, the thermal zone becomes very ineffective at displacing oil and the flowing gas stream undergoes significant shrinkage. The key to success in HPAI is to design the process such that it ensures operation in the bond scission mode. [5]

Fortunately, for many high gravity, high pressure, light oils, the bond scission reaction is the favored reaction path, and air injection processes tend to operate there quite readily, under a wide range of operating conditions. Heavier oils, however, do not always enjoy the same predisposition for success. [5]

HTO reactions are specific to temperatures higher than 270°C and are associated with the peak temperature of the ISC front, while LTO reactions can take place downstream of the ISC front, when the oxygen is not consumed completely in the HTO reactions. Also, the LTO reactions are responsible for fuel (CHAR) deposition, which aids in the initiation of ISC by spontaneous ignition.

The chemical factors that favor smoldering must be complemented by physical factors as well.

2.2 Physical factors

The combustion actually happening at the pore scale in HPAI process is best described by smoldering process familiar to fire control scientists.

Smoldering is a slow, flameless form of combustion, sustained by the heat evolved when oxygen directly attacks the surface of a condensed-phase fuel.

Burning cigarette is a familiar example of true smoldering combustion. [6]

The finely divided fuel particles in cigarette provide a large surface area per unit mass of fuel, which facilitates the surface attack by oxygen. The permeable nature of the aggregate fuel particles permits oxygen transport to the reaction site by diffusion and convection. [6] Note (Fig. 2) [7], (Fig. 3) [8], the striking similarity of sandstone microstructure with the polyurethane foam of interest to smoldering combustion scientist.

An increased oxygen supply rate causes a greater rate of heat release and increased peak temperature in the reaction zone which, in turn, increases the heat transfer rate to adjacent fuel, thus accelerating the smolder spread rate.

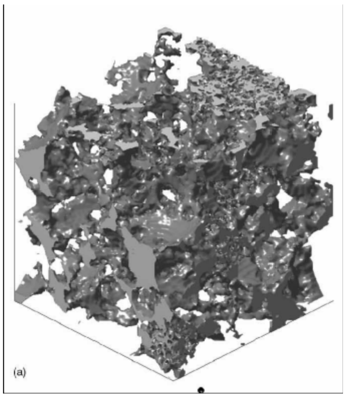


Fig. 2 Three-dimensional image of a sandstone along with [25]

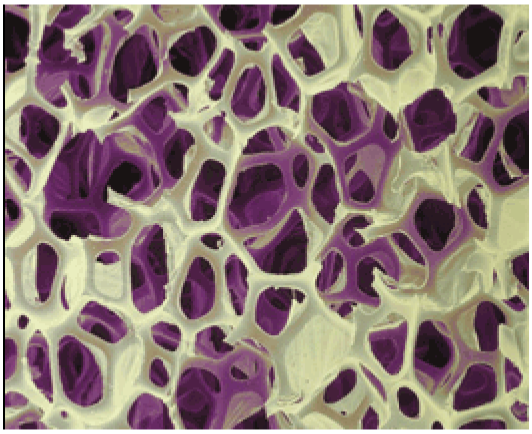


Fig. 3 Microstrostructure of poly- urethane foam

It should always be born in mind the strong role that oxygen supply rate has on the smolder process. The other very important factor is the relative direction of movement of oxygen supply and smolder propagation. This can be somewhat obscure in many realistic configurations. The actual chemical nature of the fuel is relatively secondary, at least with regard to smolder rate. [6]

3. Spontaneous ignition

When air is injected in an oil reservoir, slow oxidation (LTO reactions) occurs at the reservoir temperature, and in some cases, the heat generated can initiate the ISC process. Ignition delay, t_{ign}, is defined as the time required for the temperature to exceed 210°C around the air injection well [9]. It is expected that once this temperature is reached, the oxidation rate is high enough to be sustained until the peak temperature at the ISC front is obtained. Most of the experience with spontaneous ignition has been gained during heavy-oil exploitation using the ISC process. In general, an ignition delay t_{ign} of 10 to 20 days is seen in oil reservoirs with temperatures of 50 to 60 °C.

On the other hand, where the reservoir temperature is higher than 70 to 80°C., ignition takes place very quickly, sometimes within hours [2].

The combustion front is the highest temperature zone. It is very thin, often no more than several inches thick, and therefore at least two orders of magnitude smaller than reservoir dimensions of tens of feet thickness and hundreds of feet inter well distance [10].

4. High pressure air injection [3]

After ignition, either spontaneous or induced, the combustion front is propagated by continuous flow of air. As the front progresses into the reservoir, several zones are found between the injector and the producer as a result of heat and mass transport and the chemical reactions occurring in the process . [3]

(Fig. 1) shows an idealized representation of the location of the various zones and temperature and fluid saturation distributions . [4]

As shown in (Fig. 4), there are six major zones in an air injection process: 1) air saturation from the injection well bore to the oxidation front, 2) the oxidation front, 3) steam plateau, 4) carbon dioxide saturated hot water and oil, 5) nitrogen and methane gas, and 6) water flooded reservoir near residual oil saturation to the production well [3].

The injected air warms and expands to almost twice its injected volume as it approaches the oxidation front. Once the hot air enters the oxidation front, the oxygen reacts with a coke like substance to create steam and carbon dioxide. In turn, the superheated steam reacts with tars and waxes to make coke and light hydrocarbons. Next, the saturated steam and carbon dioxide vaporize the medium to heavy oil components and the mixture condenses as it moves forward to make a temporary foamy oil-water emulsion. The emulsion bank has a viscosity 2 to 3 times the viscosity of liquid water and this reduces fingering of the air and oxidation fronts through the oil bank and prevents premature oxygen production in the producing wells. The new oil bank is upgraded by 2 to 4 API units due to the removal of tars and waxes. Then the nitrogen strips out, primarily methane as it diffuses through the oil bank and creates a nitrogen and methane bank in front of the oil bank. If there is a mobile saturation, a small dispersed oil bank will form in front of the nitrogen bank (not shown). Finally, there is undisturbed reservoir [3].

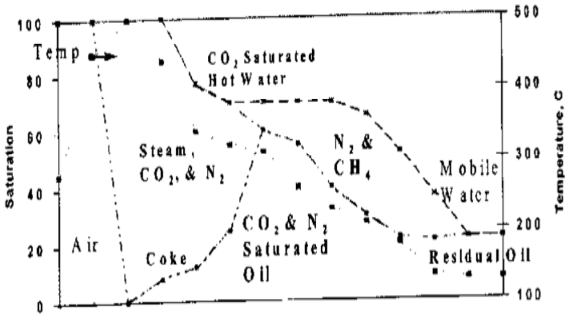


Figure 4 Six major zones in an air injection process [3]

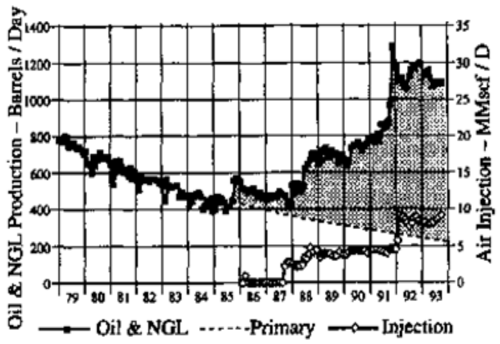


Figure 5 MPHU production performance (1970 -92) [13]

Air injection for oil recovery from deep light oil reservoirs has been recommended for the following reasons. Compressing air is generally cheaper than injecting nitrogen or CO2. Also, because of mass transfer between the oil and flue gas or air at reservoir conditions, the light hydrocarbon components are stripped off the oil. These components appear as NGL in the producing gas stream. Because of in situ combustion, part of the residual oil to gas is mobilized and moves towards the producing well. Generally, the deeper and warmer reservoirs are better candidates for ISC [11].

Therefore CIS process function like an underground refinery. "We create a very high temperature environment which acts to both crack the oil and mobilize all the lightest parts of the oil. It leaves behind the less valuable parts—the coke, the heavy carbon as fuel for smoldering" [1]. Higher pressure enhances miscibility and higher temperatures improves oxygen utilization [11].

5. Air-injection in very light, deep, Willison Basin [2]

An important milestone in the advance of Air Injection Process was the implementation of commercial air-injection projects in the Williston basin of North and South Dakota, U.S.A., starting in 1979 [12-14]. The process was applied in a dolomite reservoir with low porosity (11 to 19%), low permeability (less than 20 md), and very light oils (viscosity of less than 2 mPa.s under reservoir conditions), where water injection encountered significant problems owing to extremely low injectivity. The dolomite contains some micro fractures, but extensive fracturing or faulting was not known to exist. Both these projects took full advantage of gravity by locating the injection wells at the uppermost part of the structure. In the first pilot, the reservoir has a dip of 23 to 35°, while in the second, the dip is 60° [2].

As determined from a nitrogen miscibility correlation, the first one is an HTO-Miscible Air Flooding, while the second one is an HTO-Immiscible Air Flooding. The oil production increased by 30% for the first test and 65% for the second test, probably indicating that the formation dip is more important than miscibility. The second project, also applied in a dipping reservoir (reservoir temperature = 104°C), was started in Horse Creek reservoir [15].

It seems that the main mechanism of enhanced oil recovery for light-oil reservoir applications is not viscosity reduction, but an increase in volumetric sweep efficiency. For instance, in the May Libby field ISC project [16], the vertical sweep efficiency of the burning front, as determined from coring wells, was 100% (for a net thickness of 3 m).

6. Naturally fractured reservoirs

Considering a core of naturally fractured carbonate from an oil reservoir with residual oil saturation after gas and water flooding is placed in an autoclave at the reservoir temperature of 75°C. This is heated to 475°C. One can visualize that multiple IOR processes becoming active simultaneously. For example, vaporization of lighter cuts within core causes expulsion of crude oil from matrix to nearest fracture. Added to these processes, is an energetic chemical reaction brought about by hot air channeling and diffusing into matrix pore space, now vacant from water and volatile hydrocarbons. In actual ISC process, the char residues and pre flame LTO Scale deposits have a healing effect in the fractures, reducing permeability contrast between matrix and fracture.

Results from study by Bertin [17] are striking. When the heterogeneous layers are in capillary communication and cross flow is allowed, foam fronts move at identical rates in each porous medium as quantified by the CT-scan images.

De-saturation by foam is efficient and typically complete in about 1 PV of gas injection. When cross flow is prohibited, foam partially plugs the high permeability sand and diverts flow into the low permeability sandstone. The injected foam front moves through the low permeability region faster than in the high permeability region . [17]

Another challenge may be the ability to access high temperature oxidation regime in highly fractured carbonate reservoir. Overcoming fluctuations in fractured reservoir behavior, such as oxygen concentration fluctuations [18]. These types of variations are the rule in the future IOR reservoir production management, rather than the exception. Fortunately, today we have the past experience of our pioneers to start with, and array of better tools, like three dimensional subsurface imaging, capable of tracing the flue gas front in the reservoir as a function of time, better understanding of the process mechanisms and production procedures. Thus, Air injection can offer unique economic and technical opportunities, note (Fig. 5)

7. Combustion surface steering

We are also interested in the orientation, shape, location and movement of displacement fronts within the reservoir. Our assumptions about displacement fronts scenario in any EOR project are crucial, because we design our projects in such a way as to maximize oil production based on the fluid flow that our assumptions predict [18]. Design in this case, relates to producer and injector location and spacing, completion interval and injection rate and production choking [19].

Garthofner [18] hypothesizes that:

1. Injected air will create a secondary gas cap and combustion will take place at the horizontal interface between the oil and air. We will use the nomenclature

"Combustion surface" (CS) introduced by Prats [20]. This gas cap may be localized if reservoir dip is low or will migrate to an up dip area of closure if the dip is high, say over 10°.

2. Within the burned zone convection currents will develop that will remove very hot exhaust gases from the combustion surface and bring in fresh air and oxygen to continue the process.

3. Under certain conditions we expect the intensity of the combustion process to vary from place to place on the combustion surface.

He defines the CS as a large, smooth, nearly flat interface between the burned zone and the remaining oil (Fig. 6). The combustion front is defined as the line connecting the furthest points of growth of the CS. He states that the combustion rates vary from place to place on the CS to the extent that we can say that some areas are "on" (actively burning) and some are "off'(hot but not burning just now).

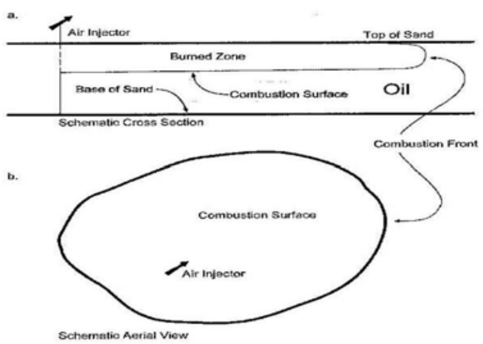


Fig. 6 Schematic diagrams of horizontal combustion surface development [18]

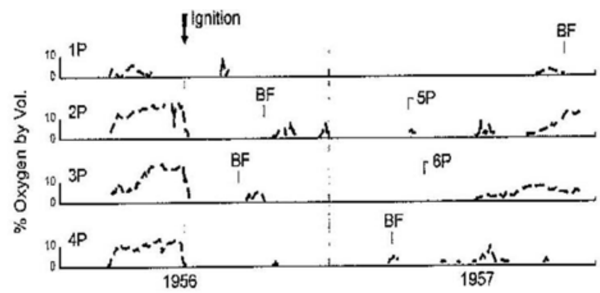


Fig. 7 Approximate oxygen concentration in produced gas at each producer versus time [18].

8. Fluctuation oxygen concentration [18]

How can we explain the fact that oxygen concentrations increased for a time and then went to zero again in the South Belridge Thermal Recovery Experiment (SBTRX) (Fig. 7).The fact that the oxygen content goes from zero to some higher value and back to zero again sometimes repeatedly, is not only readily explained.

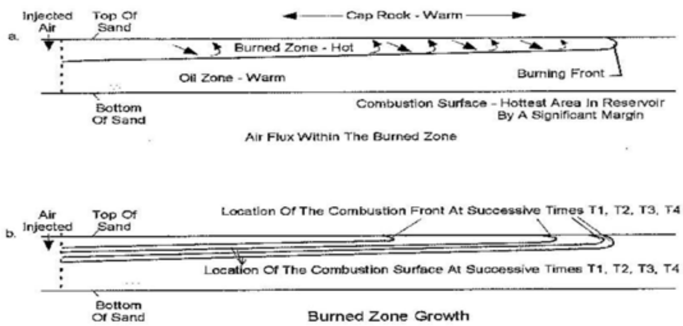
Note that in an ordinary gas injection project we have a pressure gradient with the highest pressure at the injector and the lowest pressure at one or more producers. Between the injector and producer the gradient changes, but always in the same direction. However, in ISC projects that is not necessarily so. As burning off begins and progresses in an area, the “exhaust” gases cause a local pressure drop which increases the inflow rate of new air and accelerates the combustion process. At some point the temperature of the “exhaust” gases becomes high enough to raise the pressure sufficiently to overcome the 5% drop in volume.

In addition, at much higher temperatures, more steam is made from irreducible (under ordinary circumstances) formation water, and this increases the pressure above that of the “intake” gas stream in the local area and no new air flows into the area until the pressure drops again. So the air moves on to a new area. It is not suggested that this phenomenon occurs in quantum steps but rather as a gradual shift. We will refer to these selective combustion areas as “cells". This effect is enhanced when the oxygen flux is less than adequate to keep combustion going everywhere, at all times [18].

As the thickness of the burned zone grows the rate of expansion of the burning front decreases. This is because more and more oxygen is consumed growing the CS downward. This is exactly what happened at SBTRX. Over the last two years of the project, as the average area grew 25% but the volume burned doubled.

In (Fig 8) he shows graphically for a single cell, what is discussed under “fluctuating” oxygen concentrations. This movement of the cell is also affected by convection currents.

The simple diagram in (Fig. 9) is two dimensional. We must remember that convection currents will move in three dimensions. As stated, we expect the movement of the cells to be a gradual thing and there will be multiple cells of varying size over the CS [18]. This in turn can be manipulated by production throttling of wells in an orchestrated scheme [19].



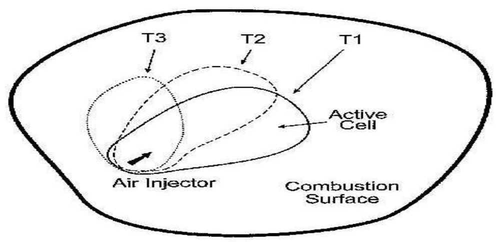


Fig. 8 Aerial view of combustion surface showing concept of how combustion activity shift from an active cell over time [18].

Fig. 9 Schematic cross sections showing convection currents and burned zone growth [18].

This could also explain, often observed phenomena that a good producer after being shut in for some time, when returned to production becomes uncharacteristically low producer, possibly due CS hopping in different direction in the reservoir [21], (Fig. 8).

Following up on what was learned at SBTRX, Mobil Oil designed and conducted successful long term projects at Mococ and Lost Hills. One feature these projects have in common is the location of all the injectors high on the structure to as the CS area grows, there will be combustion at selected cells and the combustion will gradually shift to new cells until the entire CS is swept. This process is repetitive. Because our injected air forms a secondary gas cap, the volumetric conformity of a project will be high [18].

Another steering parameter is water and water soluble catalysts, injected with the air to recover some of the heat from the hot post burn air chest, resulting in a chase steam. The volume, timing and location of the chase steam could be a tool to influence the combustion front temperature, speed and direction.

9. Piloting and expansion to commercial operations

A commercial implementation can occur only after critical uncertainties about the feasibility of the proposed recovery process are resolved. One way of evaluating and resolving these risks and uncertainties is to conduct an air-injection pilot. It is very important that the pilot be located at the uppermost part of the reservoir [2]. At West Hackberry, because of its steeply dipping beds, gravity drainage plays a key role. Gravity drainage has two aspects: first the displaced oil drains down ward at a rate given by

Darcy's law second the accumulated oil at the bottom of the pay flows down structure to join the oil column drainage is slow. Generally, vertical drainage rate increases with higher horizontal to vertical oil permeability anisotropy and higher density difference between the oil and the injected gas. For each set of conditions, there exists a critical rate below which the displacement is stable. At this rate, the viscous and gravity forces are balanced [11]. *The* life of each pattern is about 8 years. Drilling, completion, and other development were completed in the first 2 years. Air and water injection began in year 3 and continued through year 8 for a total productive life of 6 years.

10. Past trials

We have to admire all those people that initiated and continued CIS application in the fields, all over the world, stepping into unknowns to assist nature to assist us all to recover natural resources. Admiring and is still challenging is to manage a well designed CIS operation. However causes for poor performance are seldom discussed in the technical literature. One of the few cases reported was the Demjien-East19 ISC pilot [2]. Faulty igniters, insufficient air injection so vital to the process, and permeability restrictions due to the rapid mobilization of oil into cooler, downstream part of the reservoir, can all lead to domination of the oxygen addition reactions. Indeed the less than spectacular history of in-situ combustion in heavy oils arises from operation in the oxygen addition regime-often referred to as the "low temperature oxidation" LTO mode. All of the projects were horizontal floods that resulted in disappointing performances [2].

11. Operating team

As with all IOR operations, the project can be no better than the people involved. An important contributor to the success is the inclusion of all levels of stakeholders from early on in the project design. This is not a novel concept, but if ignored, can lead to a general reluctance by the staff to believe in the process [2] .

12. Discussion

"It is state-of-the-art now, because it's the only technology that has the economics. But gas prices and the need for water means, those economics are getting very, very thin." Saturates are the desired product; sulphur, nitrogen and asphaltenes are best left in the ground. The quality upgrade intrinsic to the in-situ combustion process saves building an above-ground refinery and disposing of the unwanted by products.

"There really isn't any other technology that has the potential to create such a step change in the business. Everything else is incremental," [1].

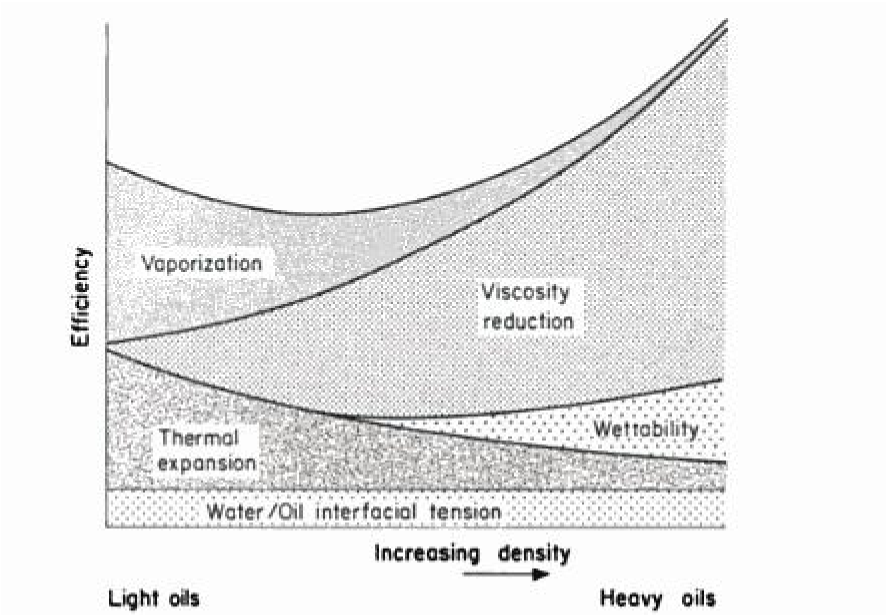


Fig. 10 Contributions of the different mechanisms to the improvement of oil displacement by hot fluid instead of unheated water [9]

Whereas, CIS is generally classified as a technique that is applicable for heavy oils because of the dramatic reduction in oil viscosity with temperature, (Fig. 10)in-situ combustion also promotes production through flue-gas drive, thermal expansion, and vaporization of lighter oils [22]. In-situ combustion recovers oil economically from a variety of reservoir settings. It has proven to be economical in recovering heavy oil from shallow reservoirs and lighter oil from deep reservoirs, where steam injection and water flood are economically unattractive). It is also an ideal process for producing oil from thin formations, being most effective in 10-50 ft thick sand bodies [23]. There's no fear of a fire burning uncontrolled, like coal seams that have smoldered underground for decades or even centuries in Australia, China, Indonesia, Colorado and Pennsylvania. The fire will go out when the company stops injecting air. We create the only source of air and we have our hand on the valve" [1]. A combination of steam stimulation followed by ISC has merit, and would not cost more on a present value basis than would infilling a steam stimulation project .In addition, it would recover more oil. Steam and air are compatible and are synergistic [24].

13. Conclusions

The future of EOR is bright "All of the bits and pieces of this process have already been tested in different environments," Wright tells *Oilweek*. "There's no new part to this technology other than the way we've configured it. Horizontal wells-we know how to do that. Vertical wells, air injection, we're just putting it together in a novel way. We have discovered it's a very robust process with a wide range of applications. That's gotten us excited about getting this thing going" [1]. Since, in-Situ Combustion has one unique characteristic that it is the only IOR process which may be applicable over a wide range of crude gravities and viscosities in its most successful form, the process has been applied in deep, carbonate reservoirs [2].

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