# Combustion Recovery Applied to "Light Oil" Reservoirs

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The original stimulus for in situ combustion as an oil recovery tool was the presence of large quantities of "unrecoverable" low gravity, high viscosity crudes. Since most of these oils are likely to be recovered only by thermal methods, in situ combustion has been regarded as a recovery tool primarily adaptable to these so-called unrecoverable crudes.

There have been in situ combustion tests conducted in the United States on "light oil" reservoirs. A good example is the Fry In Situ Combustion Test, conducted by Marathon Oil, in Illinois. In the Fry Test, the crude oil had a specific gravity of 28.6° API and a viscosity of about 40 cps at the reservoir temperature of 65°F. If we arbtrarily define a "light oil" reservoir as one having an oil with a specific gravity of 25° API or more and a viscosity less than 100 cps, then the Shannon Test by Pan American[2] was in a "light oil" reservior. The test conducted by Sinclair in Nowata County, Oklahoma, between 1948 and 1951 was in a reservoir with a 35-37° API crude oil[3]. Tests have been attempted in reservoirs with crude oils of greater that 40° API gravity; an example is the unsuccessful Bradford-Alleghany Test[4].

In situ combustion as an oil recovery tool has now reached the stage of development where it should be considered as one of several tools in the oil recovery arsenal. This holds true for secondary or tertiary operations and for light or heavy oil reservoirs. The best tool for the job should be picked only after a thorough engineering and economic analysis. Even though in situ combustion will likely not be the best alternative in most cases for "light oil" reservoirs, it will be the best alternative in some.

This is very likely to be the case where primary recovery has been poor, oil-in-place is relatively high, and the viscosity of the oil is too high for efficient water flooding. The Fry In Situ Combustion Project is an example of this situation. An attempt to water flood the reservoir failed; yet the oil-in-place exceeded 1,000 bbl acre-ft, and in situ combustion has proved highly effective and economically attractive.

In any in situ combustion operation, the most important parameter bearing on the economic attractiveness is the air requirements per barrel of oil produced. The air-oil ratio, in turn, is a function of (1) oil-in-place, (2) fuel content, (3) oxygen utilization efficiency, (4) composition of fuel consumed, and (5) the nature of the combustion products. The relationship between these parameters is well defined by the stoichiometry of combustion. The stoichiometry has been presented by A. L. Benham and F. H. Poettmann[5]. The chemical reaction of in situ combustion may be described by the following equation:

$$CH_n + \frac{1}{Y}\left(\frac{2m+1}{2m+2} + \frac{n}{4}\right)O_2 \rightarrow \left(\frac{m}{1+m}\right)CO_2 + \left(\frac{1}{1+m}\right)CO + \frac{n}{2}H_2O + \left(\frac{2m+1}{2m+2} + \frac{n}{4}\right)\left(\frac{1}{Y} - 1\right)O_2 \qquad [1]$$

This equation assumes a hydrocarbon fuel is consumed by reacting with oxygen, and that the combustion products are carbon dioxide, carbon monoxide, and water only. CHn is a mole of hydrocarbon fuel with an atomic hydrogen-to-carbon ratio of n; m is the molar ratio of carbon-dioxide-to-carbon- monoxide; and Y is the oxygen utilization efficiency (fraction of $O_2$ consumed).

Starting with the stoichiometrical equation, equations can be derived relating air requirements to fuel content, oil-in-place, and the parameters of Eq. 1. To this end, the following terms are defined:

OIP – oil-in-place, bbl/acre-ft

UOD – unit oil displacement, bbl/acre-ft of burned reservoir

OP – oil produced, total bbl

RAR – reservoir air requirements, scf/ft³ of reservoir burned

AOR – air-oil ratio, scf/bbl

TAR = total air requirements, scf

$Z$ – fuel content, lb/ft³

$\rho_o$ – desity of the oil, lb/ft³

$\phi$ – porosity of reservoir, fraction

$S_o$ = oil saturation, fraction of pore volume

$F_{vc}$ = volumetric conformance factor for reservoir, fraction

$V_R$ = reservior volume, acre-ft

with these terms defined, the following relationships hold:

$$OIP = 7762\ \phi S_o \qquad [2]$$

$$UOD = OIP - \frac{7762\ Z}{\rho_o} \qquad [3]$$

$$OP = V_R \cdot UOD \cdot F_{vc} \qquad [4]$$

Eqs. 2, 3, and 4 show the relationship between oil-in-place, fuel content, and ultimate oil production.

Define

$$F_{mn} = \left(\frac{2m+1}{2m+2} + \frac{n}{4}\right)\frac{1}{12+n} \qquad [5]$$

Then, the following equations defining air requirements are derived:

$$RAR - \frac{1805\ F_{mn}\ Z}{Y} \qquad [6]$$

$$TAR - V_R \cdot RAR \cdot F_{vc} \qquad [7]$$

$$AOR - \frac{10{,}124\ F_{mn}\ Z}{Y}\left[\frac{1}{\phi S_o - \frac{Z}{\rho_o}}\right] \qquad [8]$$

or

$$AOR = \frac{(78.58 \times 10^6)\ F_{mn}\ Z}{Y\ (UOD)} \qquad [8a]$$

Eqs. 6, 8, and 8a apply only to the burned portion of a reservoir. The air-oil ratio determined from air injection rates and produced oil rates defined by Eq. 8, but the cumulative airloil ratios defined by Eq 8, but the cumulative air-oil ratio for a project should ultimately approach that defined by Eq. 8 Eq. 7 defines the total air requirements for a reservoir.

Now let's consider in situ combustion in a "light oil" reservoir in terms of Eqs. 2 through 8. Fuel content is a most important parameter, and in a light oil reservoir, it is usually less than for a heavy oil reservoir. Although attempts to correlate fuel content with API gravity have not been very successful, generally speaking, fuel content can be expected to decrease as API gravity increases. This is illustrated by Alexander, Martin, and Dew[6]. Woith ananticipated lower fuel content in light oil reservoirs, the unit-oil-displacement is higher than for a heavy oil reservoir, assuming the same oil-in-place. But, again, in light oil reservoirs, the oil-in-place is generally lower than for heavy oil reservoirs at the time secondary recovery operations are considered. By Eq. 3, unit-oil-displacement decreases as oil-in-place decreases and fuel content increases.

Economically, the air-oil ratio is the most important variable. As shown by Eq. 8, the air-oil ratio is directly proportional to fuel content and inversely proportional to the unit-oil-displacement and oxygen utilization efficiency. Thus, the lower fuel content likely to be encountered in a "light oil" reservoir indicates a lower air-oil ratio with lower air injection costs per bbl of oil produced. However, a low oil-in-place figure means an increased air-oil ratio.

The preceding discussion shows how difficult it is to generalize as to what kind of reservoir is a good in situ combustion prospect. Each case presented must be evaluated individually. Using Eqs. 2 through 8, it is possible to evaluate the combustion potential of any reservoir, assuming the parameters in these equations can be estimated or measured.

The really critical variables are fuel content and oil-in-place, and these must be known quite accurately if good evaluation is to be made. Fuel content can be estimated in the laboratory, preferably using oil and rock samples from the reservoir in question. Alexander, Martin, and Dew[6] have presented results using different techniques. Fortunately, the other variables, m, n, and Y, have been shown by experience to be less critical. Generally speaking, in a reservoir in which combustion is technically feasible, Y usually exceeds 0.80 and can be nearly 1.0. F varies between 0.086 and 0.102, where 0.5 n 1.5 and m 15.

As mentioned above, a generally lower fuel content is likely to be encountered in light oil reservoirs. Other things being equal, this means relatively low air requirements. However, a fuel content too low to support combustion is a real likelihood in many light oil reservoirs. This problem is discussed in papers by H. R. Bailey and B. K. Larkin[7] and also by H. J. Ramey, Jr.[8], both papers presenting a theoretical investigation of the heat conduction problem associated with in situ combustion. A simple equation defining the minimum fuel content is:

$$Z_m = \frac{\rho_r C_r \left(T_{cm} - T_i\right)}{\Delta H_c} \qquad [9]$$

where

$\rho_r$ = the bulk density of the reservoir rock

$C_r$ = the heat capacity of reservoir rock

$T_{cm}$ = the minimum temperature required to support combustion

$T_i$ = the temperature of reservoir rock before combustion

$Z_m$ = the minimum fuel content

$\Delta H$ = the heat of reaction

This equation describes the adiabatic temperature rise as the result of burning the quantity of fuel, Z, in a cu ft of reservoir. $\Delta H$ is the heat of reaction per pound of fuel burned. Heat losses will necessitate a fuel content greater than indicated by Eq. 9. When heat losses are taken into consideration, it appears the minimum fuel necessary to support combustion may be between 0.6 and 0.8 lbs per cu ft of reservoir[7], depending on many things, such as the thickness of the reservoir, the rate of front propagation, and the heat losses. This assumes T is about 600°F.

It is easy to deduce from the above discussions that it is very important to know fuel content. First, it has a direct bearing on air requirements, a major economic parameter. Secondly, it is important to know if at least "minimum fuel" is present in a "light oil" reservoir.

Some factors in favor of combustion in light oil reservoirs will now be discussed. Since the lighter oils have lower viscosities, a higher air injectivity is probable, which in turn, means a lower unit air injection cost. With a greater air injectivity, higher air injection rates are possible with a consequent greater well spacing. In fact, in some light oil reservoirs, it is possible to utilize well spacing comparable to any other oil field operation. This means that the over-all investment in the project can be lower, or alternatively, the life of the project can be shortened. Another factor in favor of combustion in light oil reservoirs is the sale price of produced crude. The price of crude oil generally increases as API gravity increases. Thus, for a given air requirement per bbl of oil produced, the profit per bbl increases as the API gravity of the crude increases. This definitely shows up in an economic analysis of in situ combustion on light oil reservoirs as compared with heavy oil reservoirs.

Operating problems associated with combustion in light oil reservoirs will not be much different than for heavy oil reservoirs. Whereas, in heavy oil reservoirs, ignition can take place spontaneously with the injection of air, ignition must invariably be accomplished in light oil reservoirs by artificial means, usually an electrical or gas igniter.

With the usually lower fuel content of light oil reservoirs, it may be necessary to supply a considerable amount of heat energy during ignition to overcome the high heat losses in the first few feet of front movement. This is particularly true when the fuel content is not much above the minimum.

There is no information published nor is there anything in the experience of field operations to indicate that sweep eficiencies and volumetric conformance are any different than for heavy oil reservoirs. There is less likely to be a pronounced oil banking effect ahead of the combustion zone with a later surge in oil production. An example is the Fry Combustion Project. Here, the oil banking ahead of the front was rather small and the oil production rate from the beginning was comparable to the rate at which oil was displaced by the combustion zone. The advantage here is that the oil production rate load on production wells remains relatively constant.

## SUMMARY

In summary, it is recommended that in situ combustion be considered as a tool in the arsenal of oil recovery tools for any type of reservoir. In the case of light oil reservoirs, if the oil-in-place is sufficient and there is sufficient fuel to support combustion, it may be that in situ combustion will prove to be the best oil recovery tool. When it is, the profits for combustion in light oil reservoirs can be very attractive. Where in situ combustion is considered as a tertiary recovery tool following water flooding in light oil reservoirs, the chances for economic success are likely to be handicapped by too little oil-in-place. This is also true of any process considered for tertiary recovery; the ideal procedure is to select the best process for secondary recovery so that the questoin of tertiary recovery need not arise.

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