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RESERVOIR ENGINEERING EQUATIONS FOR IN-SITU COMBUSTION

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ABSTRACT

The high-temperature underground combustion reaction for the oxidation of coke deposited on sand grains can be described by a chemical equation. This equation serves as the basis for the derivation of general useful reservoir engineering equations relating the variables involved in the in-situ combustion process.

Dependent variables such as the volume of gas injected at a well per unit volume of bulk reservoir burned, volume of gas injected to displace a unit volume of oil, volume of water generated per unit volume of reservoir burned, volume of gas produced at the combustion front per unit volume of gas passing through the combustion front and volume of gas produced per unit volume of bulk reservoir burned are just some examples of the equations derived. These equations serve as valuable tools in evaluating field performance of in-situ combustion projects. The independent variables are the produced gas and injected gas analysis both on a water free basis and the fuel content.

Some of the equations were compared with the steady-state results reported from 136 experimental tube runs consisting of ten data sets. The calculated results from the derived equations when compared with the results reported from the tube runs were generally good to excellent. Both enriched oxygen and air injection tube runs were compared. Comparisons were also made on several sets of wet combustion data.

INTRODUCTION

Conventional in-situ combustion is a thermal recovery process in which heat is generated within the formation by burning part of the crude oil to sustain combustion. A small fraction (approximately 3 to 10 percent) of the crude consisting of the heavy ends is consumed in the form of coke. A narrow combustion zone (a matter of inches) advances through the formation, heat is transmitted ahead of the combustion zone by the flowing fluids and a multiplicity of production mechanisms take place to increase crude recovery from the rock.

In the forward combustion process the heavier fraction of the crude forms a carbonaceous deposit on the sand grains that serves as the fuel for combustion. The amount of fuel deposited is a function of the rock properties, oil characteristics and temperature and pressure. The amount of fuel deposited for a successful project ranges from approximately 1 to 2.5 lbm/ft^3.

The ignition temperature of this fuel is of the order of 400° to $600^\circ F$. The injected gas flux must be great enough to sustain combustion at or above the ignition temperature. Generally combustion temperatures will range from 600° to $1500^\circ F$. At these temperatures the combustion reaction forms carbon dioxide, carbon monoxide and water. If the oxygen utilization efficiency is low in the combustion zone and depending on the nature of the crude oil being displaced, some low-temperature partial oxidation may take place with certain reactive components in the heavy ends of the crude ahead of the combustion front. However, these heavy oxygenated ends will ultimately crack and form coke so that in this instance the partial oxidation could be considered as one step in the total oxidation of the fuel. In a few crudes, intermediate components of the crude might be reactive enough to be partially oxidized by the oxygen that passes through the combustion zone. In this case these oxygenated components will stay in the produced crude. However, the primary reaction in an in-situ combustion process is the high temperature combustion of the coke on the sand grains.

Combustion tube tests conducted in the laboratory have become an accepted method of evaluating the fuel content and air requirements for a combustion prospect as long as the porous medium and crude are representative of the reservoir. The injected gas requirements and the fuel deposited generally are not dependent on the configuration of the apparatus. The stoichiometry of the combustion reaction is controlled by the coke characteristics, pressure and temperature. However, the precision with which experimental measurements are made varies widely from operator to operator. The precision depends on combustion tube design, accuracy of physical measurements, and procedure used by the operator in conducting the tube runs. All measurements should be made under steady-state conditions. Steady-state combustion implies that the concentrations of the combustion gases remain relatively constant for a period of time. If steady-state conditions are not achieved, the experimental data will fluctuate widely and will be in considerable error. Comparisons of different data sets reported in the literature indicate considerable variation in accuracy.

The experimental data usually reported in combustion tube runs is fuel content, fuel hydrogen-to-carbon atomic ratio, velocity of front movement, oxygen utilization efficiency, injected gas required to burn a pound of fuel, injected gas required to burn out a cubic foot of sand pack, and the analysis of the injected and produced gas under steady-state conditions on a water-free basis. Additionally some operators will report the amount of injected gas required to displace a barrel of oil.

RESERVOIR EQUATIONS

There is no comprehensive treatment describing the reservoir engineering equations for in-situ combustion in the literature. There have been a few papers published where stoichiometric equations were described for the combustion process. These were limited in scope and were applied to the evaluation of a specific situation[1-4]. The equations were not general and dealt with the injection of air only. Most texts that deal with in-situ combustion treat the subject of the stoichiometric equations cursorily or not at all. Prat's treatment of the subject is the most extensive, however, his treatment deals with the injection of air only[5]. His equations are not valid for the injection of a gas consisting of any composition of oxygen or nitrogen or for the case of 100% oxygen injection. Oxygen utilization efficiency is applied inconsistently. Some other useful stoichiometric equations are not mentioned at all in his treatment.

The basis of the reservoir engineering equations for in-situ combustion is the high-temperature oxidation of the coke deposited on the sand grains. This is the primary reaction of interest in in-situ combustion. The reaction equation is

$$CH_{F_{HC}} + \frac{1}{\left(Y_{iO_2}\right)\left(e_{O_2}\right)}\left[\frac{2\ m+1}{2\ m+2} + \frac{F_{HC}}{4}\right] IG \rightarrow$$

$$\frac{m}{m+1}\ CO_2 + \frac{1}{m+1}\ CO + \left(\frac{2m+1}{2m+2} + \frac{F_{HC}}{4}\right)\left(\frac{1}{e_{O_2}} - 1\right)\ O_2$$

$$+ \frac{\left(Y_{iN_2}\right)}{\left(Y_{iO_2}\right)\left(e_{O_2}\right)}\left(\frac{2m+1}{2m+2} + \frac{F_{HC}}{4}\right) N_2 + \left(\frac{F_{HC}}{2}\right)\ H_2O \qquad (1)*$$

* All symbols are defined in the nomenclature

This equation is based on the following assumptions. The fuel is a hydrocarbon material that has a hydrogen-to-carbon atomic ratio of F_{HC}. When the fuel is oxidized by the oxygen in the injected gas it generates CO_2, CO and H_2O as the combustion products. "IG" symbolizes the injected gas consisting of a mixture of nitrogen and oxygen. It is assumed that nitrogen is completely inert in the reaction and passes through the combustion front.

For the general situation where the injected gas consists of any composition of oxygen and nitrogen

$$m = \frac{y_{pCO_2}}{y_{pCO}} \tag{2}$$

$$F_{HC} = \frac{4\left(\frac{y_{iO_2}}{y_{iN_2}}\right) + 2\ y_{pCO} - \left(4\ \frac{y_{iO_2}}{y_{iN_2}} + 4\right)\left(y_{pO_2} + y_{pCO} + y_{pCO_2}\right)}{y_{pCO_2} + y_{pCO}} \tag{3}$$

$$e_{O_2} = 1 - \frac{y_{iN_2}}{y_{iO_2}} \cdot \frac{y_{pO_2}}{y_{pN_2}} \tag{4}$$

For the situation where the injected gas is pure oxygen, Eqs. 3 and 4 simplify to:

$$F_{HC} = \frac{4\left(1 - y_{pO_2} - 0.5\ y_{pCO} - y_{pCO_2}\right)}{y_{pCO_2} + y_{pCO}} \tag{5}$$

$$e_{O_2} = 1 - y_{pO_2} \tag{6}$$

From the chemical reaction Eq. 1 and the variables m, F_{HC}, e_{O_2} and y_{iO_2} the following reservoir engineering equation for the injected gas required to burn one lbm of fuel can be derived:

$$G_F = \left[\frac{(10.72)\left(T_{sc} + 460\right)}{\left(Y_{iO_2}\right)\left(e_{O_2}\right)\left(P_{sc}\right)}\right]\left[\frac{2m+1}{2m+2} + \frac{F_{HC}}{4}\right]\left[\frac{1}{12 + F_{HC}}\right] \quad (7)$$

By multiplying Eq. 8 by the fuel content m_R, pounds coke per cubic foot of reservoir, one obtains the amount of injected gas necessary to burn out one cubic foot of reservoir, G_{CF}.

$$G_{CF} = \left[\frac{(10.72)\left(T_{sc} + 460\right)}{\left(Y_{iO_2}\right)\left(e_{O_2}\right)\left(P_{sc}\right)}\right]\left[\frac{2m+1}{2m+2} + \frac{F_{HC}}{4}\right]\left[\frac{1}{12 + F_{HC}}\right] m_R \quad (8)$$

However, the chemical reaction takes place in the narrow combustion zone, and Eq. 8 takes into consideration only the injected gas that is used to burn the coke. One must add to this the injected gas that is stored in the burned-out zone; thus, total gas injected both used in combustion and stored is

$$G_i = \left[\frac{(10.72)\left(T_{sc} + 460\right)}{\left(Y_{iO_2}\right)\left(e_{O_2}\right)\left(P_{sc}\right)}\right]\left[\frac{2m+1}{2m+2} + \frac{F_{HC}}{4}\right]\left[\frac{1}{12 + F_{HC}}\right] m_R + \left[\frac{\phi_R}{B_{gi}}\right] \quad (9)$$

where $\frac{\phi_R}{B_{gi}}$ represents the injected gas stored in one cubic foot of burned out reservoir. The stored gas may represent only 1 to 3 percent of the total gas injected in the case of a laboratory tube run. However, in a field combustion project where the reservoir pressure can be considerably higher than in a tube run, the stored gas can represent a considerably greater percentage.

Knowing the injected gas flux u_{Rf} (scf/ft^2 hr) the velocity of a point in the combustion front can be calculated.

$$V_b = \frac{u_{Rf}}{G_i} \tag{10}$$

Similarly knowing the oil saturation and the equivalent oil saturation burned as fuel, the standard cubic feet of total injected gas required to displace one barrel of oil can be calculated.

$$G_{io} = G_i \left[\frac{5.615}{\phi_R \left(S_o - S_{FrR}\right)}\right] \tag{11}$$

$$\text{where } S_{FrR} = \frac{m_R}{\phi_R \ \rho_o} \tag{12}$$

m_R, the fuel content, is obtained from a laboratory measurement corrected for the differences in laboratory and field porosity (see Eq. 17).

The amount of water generated per cubic foot of reservoir volume burned is

$$\delta_{wb} = 0.02571 \ \frac{F_{HC} \ m_R}{12 + F_{HC}} \tag{13}$$

To this must be added the residual water saturation to obtain the total amount of water generated and displaced per cubic foot of reservoir.

$$\delta_w = \delta_{wb} + 0.1781 \ \phi_R \, S_{wr} \tag{14}$$

The volume of combustion gas produced at the combustion front per cubic foot of injected gas passing through the combustion front is given by:

$$G_{pi} = \frac{\left(Y_{iO_2}\right)\left(e_{O_2}\right)}{\left[\frac{2m+1}{2m+2} + \frac{E_{HC}}{4}\right]} + \left[1 - \left(Y_{iO_2}\right)\left(e_{O_2}\right)\right] \tag{15}$$

The standard cubic feet of produced gas per cubic foot of reservoir burned, corrected for the gas saturation displaced ahead of the combustion front, is

$$G_{pCF} = \left[\left(G_{CF}\right)\left(G_{pi}\right)\right] + \left[\frac{\phi_R \left(1 - S_{WR} - S_o\right)}{B_{gp}}\right] \tag{16}$$

This is a very useful equation, since in any field project a prudent operator would monitor the gases produced at a production well from the start of ignition. The cubic feet of gas produced divided by G_{pCF} would give the reservoir volume swept that the particular producing well responded to. From this one could then estimate the sweep efficiency for the assigned drainage volume for the well, and ultimately total sweep efficiency for the project.

Fuel content, m_E, is usually obtained from laboratory tube runs. On the assumption that all parameters of the sand pack are the same as in the reservoir with the exception of porosity, the laboratory-determined value of m_E should be corrected to reservoir porosity ϕ_R as follows:

$$m_R = m_E \left[\frac{1 - \phi_E}{1 - \phi_R}\right] \tag{17}$$

COMPARISON WITH TUBE RUN RESULTS

A literature search of combustion tube data resulted in ten sets of data consisting of 136 tube runs[2,3,6-17]. The number of tube runs in a set varied from as low as one to a high of forty-four in a study that involved oxygen enrichment of the injected gas. Two sets of data reported on the effect of wet combustion[6,13]. In seven of the data sets the reported results were experimentally measured. In two data sets the reported results were theoretically calculated using the stoichiometric equations[2,3]. In another data set a combination of experimental measurements and stoichiometry was used to report the results[14].

The reported results generally but not always consisted of F_{HC}, e_{O_2}, G_F, G_{CF} and V_b. Other very important reservoir parameters such as G_{iO}, δ_W, G_{pi} and G_{PCF} were never measured. In eight data sets G_F and G_{CF} as reported included the gas stored behind the combustion front. In one data set it appeared that steady-state combustion was not attained and oxygen utilization efficiencies of less than 100 percent were reported even though there was no oxygen reported in the produced gases[16]. This same data set also reported relatively high concentrations of hydrocarbon gases even though the combustion temperature ranged from 850°F to 1382°F. Generally where the produced gas data were reliable, the agreement between the reported data and the calculated values was good to excellent.

For the calculated variables, the injected and produced gas analyses, on a water-free basis, obtained during the steady-state portion of the combustion tube test was used to calculate m, F_{HC} and e_{O_2}. Other independent variables used in the calculations were m_R, ϕ, S_O and S_{wr}. Other combustion tube experiments were also reported in the literature; however, the reported data were incomplete so that comparison calculations could not be made[18,19].

Space limitations make it impossible to present a complete detailed comparison of all the calculated versus reported results. Table 1 summarizes the results for each

Table 1

Reported Versus Calculated Agreement

Author	Ref.	F_{HC}	e_{O_2}	V_b	G_F	G_{CF}	Comments
Cady et al.	9	E	NR	E	G	E	Oxygen enriched gas, six tube runs Comb. tube temp. 910-1050°F
Martin et al.	10	NR	E	E	NR	E	Six tube runs. Comb. temp. 650-850°F Air injection
Shu et al.	11-12	E	E	E	P	P	Two tube runs. Comb. temp. 900°F Air, CO_2 - O_2 Mix
Fassihi et al. Satman et al.	14-15	G	NR	G	G	G	14 tube runs. Comb. temp. 649-1112°F air, exper. & stoich.
Petit	16	P	P	P	NR	G	Poor gas analysis, 44 runs. No O_2 reported Enriched gas injection, comb. temp. 850-1382°F
Burger et al.	17	G	E	E	NR	G	5 runs, air injection, comb. temp. 761-824°F only dry comb. used
Bousaid	6,7,8	DC-E WC-P	E	G	NR	E	14 runs, wet and dry comb., comb. temp. 689-910°F
Showalter	2	E	NR	NR	E	E	Should agree. Used stoichiometric equation. 16 runs air, 650-1000°F
Showalter	2	G	NR	NR	G	NR	Used well gas analysis from Belridge test. Used stoichiometric equations, 8 analyses
Pusch	13	P	P	NR	P	P	Dry and wet comb. No steady-state gas analysis, temp. 823-1531°F., 20 runs, air
Luengo et al.	3	E	NR	P	E	E	1 run, used stoichiometry to calculate results 1100°F, agreement should be exact

E - Excellent, G - Good, P - Poor, NR - Not Reported

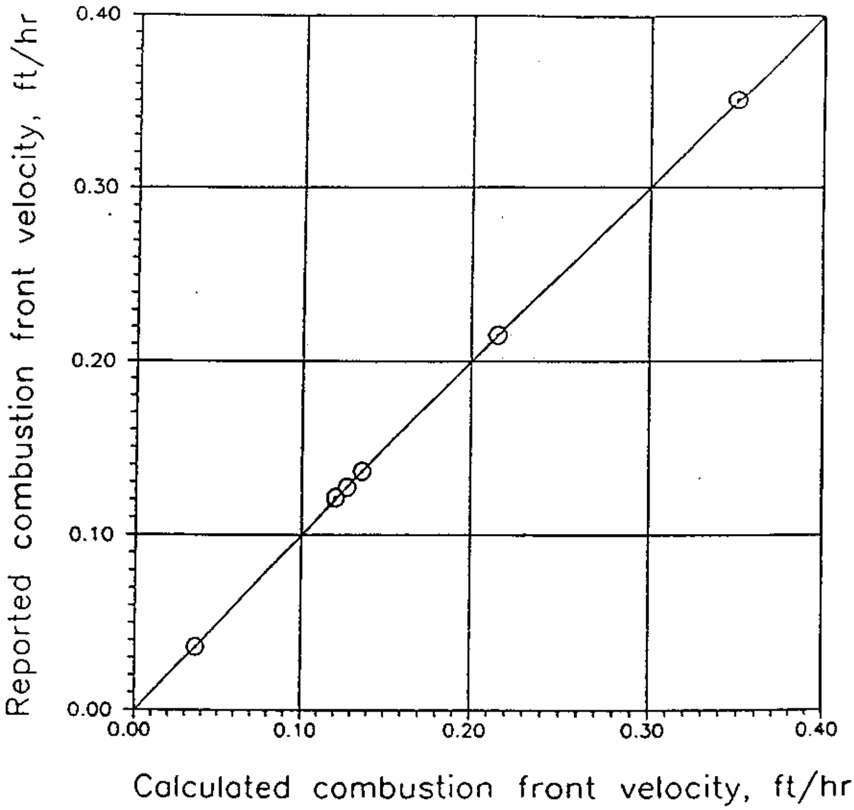

FIG. 1. Comparison of calculated vs. reported frontal velocity, data of Martin et al[10].

reported variable in each set of reported data. Figures 1 through 3 give an indication of what is meant by the Excellent, Good and Poor comparisons respectively.

The equations gave excellent agreement with the reported results for all the reported variables in a given data set for 72 of the combustion tube runs, which is 53 percent of the total combustion tube runs, used in the study. Of the remaining 47 percent of the tube runs the agreement for a set

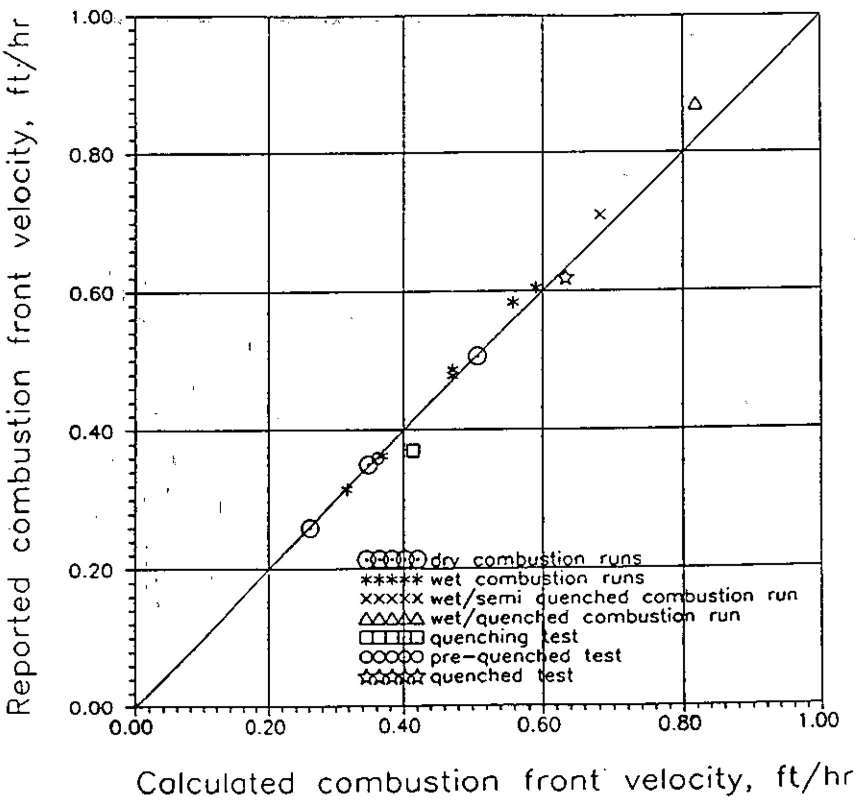

FIG. 2. Comparison of calculated vs. reported frontal velocity, data of Bousaid[6,7].

of variables within a tube run varied depending on the variable. The most inconsistent variable within the 47 percent of the runs was E_{HC}, varying from Poor to Excellent.

In two data sets the authors calculated their reported results from a stoichiometric relationship, and in this case the comparisons should be essentially identical, which they were[2,3]. In one case a combination of experimental measure-

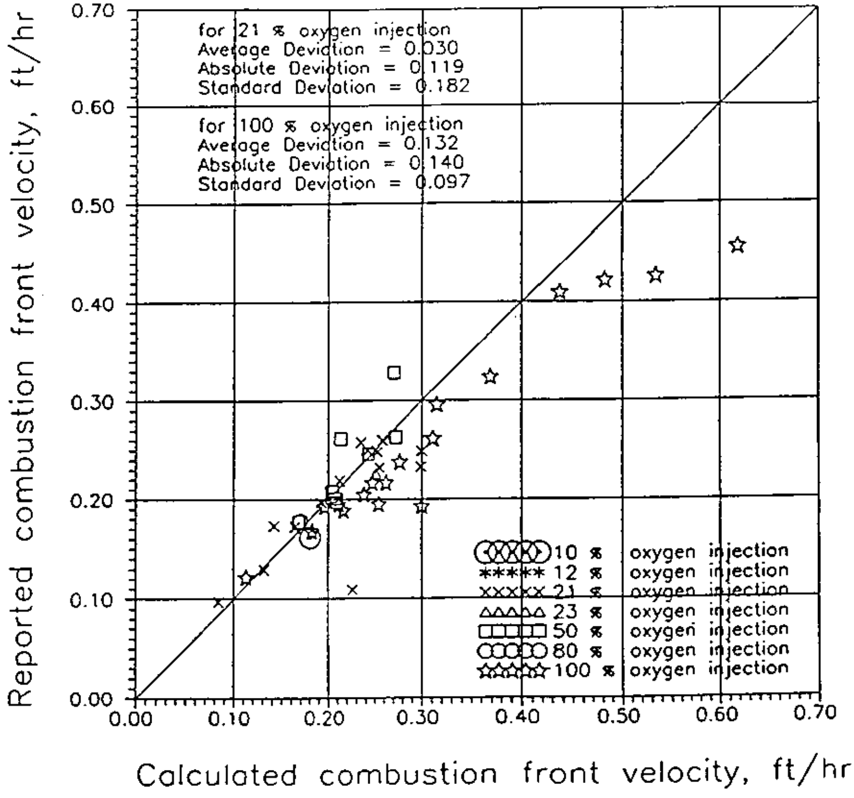

FIG. 3. Comparison of calculated vs. reported frontal velocity, data of Petit[16].

ments and stoichiometric calculations appeared to have been used[14]. In the remaining seven data sets the reported results were experimentally measured.

The value of the comparisons between measured tube run data and those calculated from the equations is to validate the equations. The equations are also useful in analyzing experimental data for apparent inconsistencies.

By far the greatest value of the equations lies in the evaluation of field in-situ combustion projects. To properly apply these equations the project should be carefully monitored as follows:

a) The volume of the produced gases on an individual well basis should be carefully measured from the time of ignition to the end of the combustion project.

b) The analysis of the produced gas should be carefully monitored. The gas analysis under steady-state burning conditions is used in the reservoir equations.

c) The volume of the injected gas should be carefully measured and its oxygen content known.

Laboratory measured fuel content corrected to reservoir porosity should be available.

Eq. 16, the combustion gas produced per cubic foot of reservoir burned, permits one to estimate the sweep efficiency for the drainage area of a given well as well as the sweep efficiency for the entire project.

Knowing the burned-out volume either on a per well basis or total project permits one to estimate the oil displaced (corrected for fuel content). The oil displaced when compared to the actual oil produced should give one an indication of the oil that may have been produced from the unswept zones.

Eq. 14 can be used to estimate the total water generated and displaced in the drainage area of a well or total project, and can be compared with the actual water produced.

The actual oil and water production from a combustion project should approach that calculated from these equations at the end of the project. An example of the application of these equations is given in reference 4.

An example of the application of Eqs. 11 and 16 is as follows:

a) A combustion pilot test on an inverted 1.5 acre five-spot using air as the injected gas produced 350.0 MMSCF of production gas having an average composition under steady-state conditions of

CO_2	11.95
CO	1.45
O_2	3.20
N_2	83.40

The fuel content m_R was 1.7 pounds per cubic foot of bulk volume. The reservoir rock had an average porosity of 30%. The formation had an average thickness of 25.83 feet. The original oil saturation was 0.60 and residual water saturation was 0.20. Estimate the volumetric sweep efficiency assuming all the combustion gas was produced.

Using Eqs. 2, 3 and 4 calculate m, F_{HC} and e_{O_2} respectively.

$$m = 8.24$$

$$F_{HC} = 1.858$$

$$e_{O_2} = 0.8558$$

From Eqs. 8 and 15 calculate G_{CF} and G_{pi} respectively.

$$G_{CF} = 365.068 \text{ scf air/Ft}^3$$

$$G_{pi} = 0.9477 \frac{\text{scf produced gas}}{\text{scf injected air}}$$

From Eq. 16 (B_{gp} was estimated at 0.0633 Ft^3/scf)

$$G_{pcF} = 347.86 \frac{\text{scf produced gas}}{\text{Ft}^3}$$

Total reservoir volume burned

$$\frac{350 \times 10^6}{347.86} = 1{,}006{,}252 \text{ cubic feet of bulk reservoir volume}$$

$$= 179{,}190 \text{ barrels bulk reservoir volume}$$

Total reservoir bulk volume

$$(1.5)(25.83)(7758) = 300{,}584 \text{ bulk reservoir barrels}$$

Volumetric sweep efficiency

$$\frac{179{,}190}{300{,}584} = 0.60$$

b) Using the data from part "a" above, calculate the total air necessary to displace the oil from the test pattern assuming a 70 percent volumetric displacement efficiency. The reservoir oil is a dead oil and has an API gravity of 25°.

Calculate total oil to be displaced.

$$(1.5)(25.83)(7758) = 300{,}584 \text{ barrels bulk volume}$$

$$(0.70)(300{,}584)(0.30) \times \left[0.60 - \frac{1.7}{(.30)(0.9042)(62.4)}\right] =$$

31,561 barrels oil to be displaced

Using Eqs. 9 and 11 calculate the air required.

$$G_i = 369.60 \text{ scf/Ft}^3$$

(The value of B_{gi} for air behind the combustion front was estimated to be 0.0643 Ft^3/scf)

$$G_{io} = 13{,}834 \text{ scf/bbl}$$

Total air required

$$(31{,}561)(13{,}834) = 436.62 \times 10^6 \text{ scf air}$$

SUMMARY

1. Useful reservoir engineering equations are derived from the high-temperature oxidation reaction of the coke deposited on the sand grains in an in-situ combustion process. The most important of which are Eq. 11 describing the amount of injected gas required to displace a barrel of oil and Eq. 16 describing the standard cubic feet of gas produced per cubic foot of reservoir burned.
2. Calculated results from certain of the reservoir equations were compared with the reported results from 136 experimental tube runs comprising ten sets of data. In most instances the comparisons were excellent to good if reliable steady-state produced gas analysis were available.
3. The reservoir equations are useful in analyzing experimental tube run data for apparent inconsistencies.
4. Areal sweep efficiency, sweep pattern, oil displaced and other useful information on a combustion project can be calculated from these reservoir engineering equations. The calculations assume a frontal displacement model.

NOMENCLATURE

B_{gi} = formation volume factor of the injected gas at injection pressure and average reservoir temperature behind the combustion front, cu ft/scf

B_{gp} = formation volume factor of the produced gas at the average pressure and temperature ahead of the combustion front, cu ft/scf

e_{O_2} = oxygen utilization efficiency, fraction

F_{HC} = atomic hydrogen-to-carbon ratio of fuel

G_{CF} = standard cubic feet of injected gas per cubic foot of reservoir at the combustion front

G_i = standard cubic feet of injected gas per cubic foot of reservoir including gas stored behind the front

G_{iO} = standard cubic feet of injected gas per barrel of oil displaced at the combustion front including gas stored behind front

G_F = standard cubic feet of injected gas per pound of coke burned

G_{pCF} = standard cubic feet of gas produced per cubic foot of reservoir burned corrected for gas saturation displaced

G_{pi} = standard cubic feet of gas produced at the combustion front per cubic foot of injected gas at the front

m = molar ratio of CO_2 to CO in produced gas

m_E = fuel content, lbm coke/ft^3 sandpack

m_R = fuel content corrected to reservoir porosity, lbm coke/ft^3 reservoir

p_{SC} = atmospheric pressure, psia

S_{FrR} = reservoir equivalent saturation of fuel, fraction

S_O = oil saturation, fraction

S_{WR} = residual water saturation, fraction

T_{SC} = temperature at standard conditions, $^\circ$F

u_{Rf} = injection gas flux, scf/hr-ft^2

v_b = velocity of the combustion front, ft/hr

y_{iN2} = mole fraction of nitrogen in the injected gas

y_{iO2} = mole fraction of oxygen in the injected gas

y_{pCO} = mole fraction of CO in the produced gas

y_{pCO2} = mole fraction of CO_2 in the produced gas

y_{pN2} = mole fraction of N_2 in the produced gas

y_{pO2} = mole fraction of O_2 in the produced gas

δ_{wb} = barrels of water generated per cubic foot of reservoir burned

δ_{w} = total barrels of water generated and displaced per cubic foot of reservoir

ρ_{O} = density of oil, lbm/ft^3

ϕ_{E} = sandpack porosity, fraction

ϕ_{R} = reservoir porosity, fraction

SI METRIC CONVERSION FACTORS

$$Ft^3/bbl \times 1.781076\ E{-}01 = m^3/m^3$$

$$Ft^3/lbm \times 6.242796\ E{-}02 = m^3/kg$$

$$psi \times 6.894757\ E + 00 = KP_a$$

$$^{\circ}C = \frac{5}{9}\ (^{\circ}F{-}32)$$

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