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In-Situ Oil Combustion For Enhanced Oil Recovery

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Abstract

The inescapable fact that hydrocarbon reserves in the world are decreasing, has led to considerable research and investment in exploration for new conventional hydrocarbon reserves, and development of unconventional hydrocarbon resources such as oil shale or tar sand. Developing a production technique that will recover close to one hundred percent of the oil in a petroleum reservoir has been the dream of petroleum engineers and production managers for years . In situ combustion involves initiation of propagation of firefront or combustion zone in the reservoir , by air injection . In this article investigated experimental and numerical simulation studies of the wet combustion recovery process .

Keywords : In situ combustion , Firefornt , Air Injection , Wet Combustion

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1. Introduction

In situ combustion involves the creation of a firefront in the reservoir , and its subsequent propagation by air injection . The burning front , or combustion zone , thus created , would move in the formation as a narrow band , consuming or displacing the fluids encountered ahead of it , into producing wells . The heat generated within the combustion zone is transported downstream by the burned gases , and it also conducted through the rock-fluid system . A certain proportion of the heat is transmitted to the overlying and underlying formations , and may be considered to be lost for all practical purposes . In view of this , the combustion zone heat generation rate should be such that , in spite of heat loss , its temperature stays above the minimum ignition temperature of the crude oil involved ; otherwise , the combustion zone will become extinct . (Figure 1)
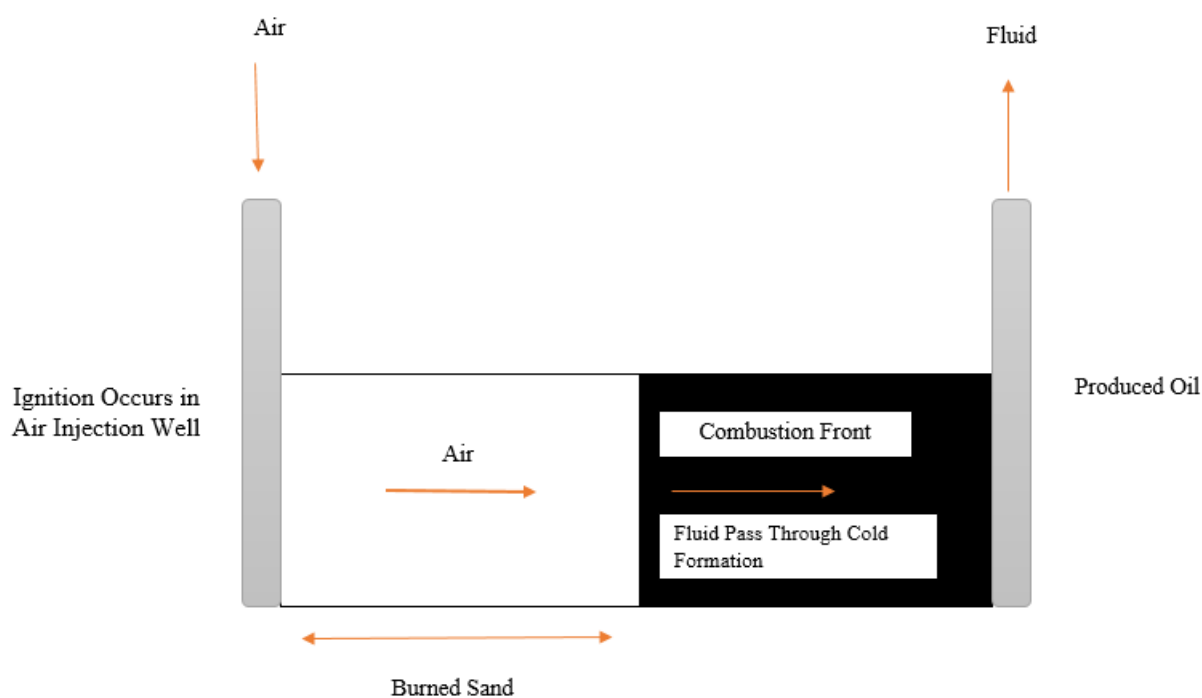

Figure 1 , Schematic of Dry , Forward Combustion

2. Mechanism of Dry Forward Combustion

Fuel Content : The key factor in the in situ combustion is the fuel content typical of the rock-fluid system involved . Fuel content (C_m) is the mass of coke deposited per unit bulk volume of the rock . It consists of the heavy fraction of the in-place oil , which are deposited as a carbonaceous residue just ahead of the combustion zone , and thus represent the end of product of complex reactions to which the in-place oil is subjected . The fuel content is really not a constant for a given rock-fluid system , and should be calculated on the basis of a suitable reaction rate equation . However , it is frequently taken to be a constant quantity

, and is used as such in combustion calculations . Comparison of field test results with laboratory data shows that this procedure may be satisfactory for engineering purposes .

The combustion of the fuel deposited which is a carbonaceous residue , having a composition CH_n , having an atomic ratio of H to C equal to n , can be described by the stoichiometric equation :

$$CH_n + \left[\frac{2m+1}{2m+2} + \frac{n}{4}\right] O_2 = \left[\frac{m}{m+1}\right] CO_2 + \left[\frac{1}{m+1}\right] CO + \frac{n}{2} H_2O \tag{1}$$
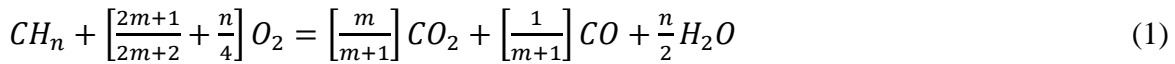
$$m = \frac{C_{CO_2}}{C_{CO}} \tag{2}$$

$$n = \frac{1.063 + 2C_{CO} - 5.06(C_{CO_2} + C_{CO} + C_{O_2})}{C_{CO_2} + C_{CO}} \tag{3}$$

$$C_m = \frac{V_g}{CV_b}\left[\frac{4C_{N_2}C_{O_2}^*}{C_{N_2}^*} - 4C_{O_2} + 8C_{CO_2} + 10C_{CO}\right] \tag{4}$$

V_g ： Total volume of burned gas produced (Scf)

V_b ： Bulk Volume of the sand pack (cu ft)

C ： 23.644 for SI Unit

$C_{O_2}^*$: 0.21

$C_{N_2}^*$ ： 0.79

Air Requirement : Assuming that the fuel content is constant , and the fuel composition is known , it is possible to determine the amount of air required to burn the fuel deposited . The volume of air in scf , required to burn the fuel deposited in one cubic foot of the rock is called the air requirement . Given the air requirement , the air-oil ratio can be determined . The air oil ratio is defined as the volume of air to be injected in order to displace one stock tank barrel of oil , and is expressed in scf/bbl .

Air Injection Rate : The air injection rate is an important parameter in in-situ combustion. It as also difficult to determine . The air injection rate , is expressed in scf/day . It determines the combustion zone velocity , fluid production rate , and the extinction radius combustion zone .

$$P_i^2 = P_w^2 + \frac{i_a \mu_a T_R^* P_{sc}}{\pi T_{sc} K_g h}\left[ln\frac{a^2}{r_w V_b t_1} - 1.28\right] \tag{5}$$

P_i: is the injection well pressure , Psia

P_W ： is the producing well pressure , Psia

μ_a ： is air viscosity , cp

T_R^* ： is the reservoir temperature , $^\circ R$

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K_g : is the air permeability , Darcy

h : is the formation thickness , ft

r_w : is the well radius , ft

V_b : is the combustion front velocity , ft/day

t_1 : is time , day

$$t_1 = \frac{i_a}{\pi h V_b^2 a} \tag{6}$$

$$i_a = G(P_i^2 - P_w^2) \tag{7}$$

G : is the function of the air and rock properties , and of reservoir geometry .

Combustion Zone Velocity : If the air injection rate is i_a scf/day , then for radial flow at a radial distance r_f from the injection well , the local combustion zone velocity is V_b ft/day , given by :

$$V_b = \frac{dr_f}{dt} = \frac{U}{r_f} \tag{8}$$

$$U = \frac{i_a}{2\pi h a} \tag{9}$$

Water Formed By Combustion : The volume of water formed by combustion is given by:

$$V_m = \frac{36}{B}\left[\frac{C_{N_2} C_{O_2}^*}{C_{N_2}^*} - C_{O_2} - C_{CO_2} - \frac{C_{CO}}{2}\right] \tag{10}$$

B: 23,644 for SI units

3.   Mechanism of Wet In-Situ Combustion

Figure 2 shows the process of wet combustion under steady state conditions. Five zones exist in the reservoir between the injection well and the production well. These are described below:

Zone 1 : This zone has already been swept by the combustion front and contains little or no hydrocarbons. However, since the temperature is lower than the boiling point of water, the pores contain a liquid water saturation, the remainder of the space being occupied by the injected air.

Zone 2 : Water is in the vapour phase in this zone, and the pores are saturated with a mixture of injected air and steam .

Zone 3 : The combustion zone. Oxygen is consumed in the combustion of the hydrocarbons and of the deposited coke formed in the downstream part of the zone.

Zone 4 : The vaporization-condensation zone. Progressive condensation of steam and combustion water takes place in this zone. In addition, some light and intermediate oil

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fractions are vaporized and carried downstream. If the temperature is high enough certain chemical reactions may occur in this zone.

Zone 5 : Just downstream of the vaporization condensation zone is a zone of high back pressure, due to the formation of a water bank preceded by an oil bank. Further downstream the formation gradually approaches its initial conditions .
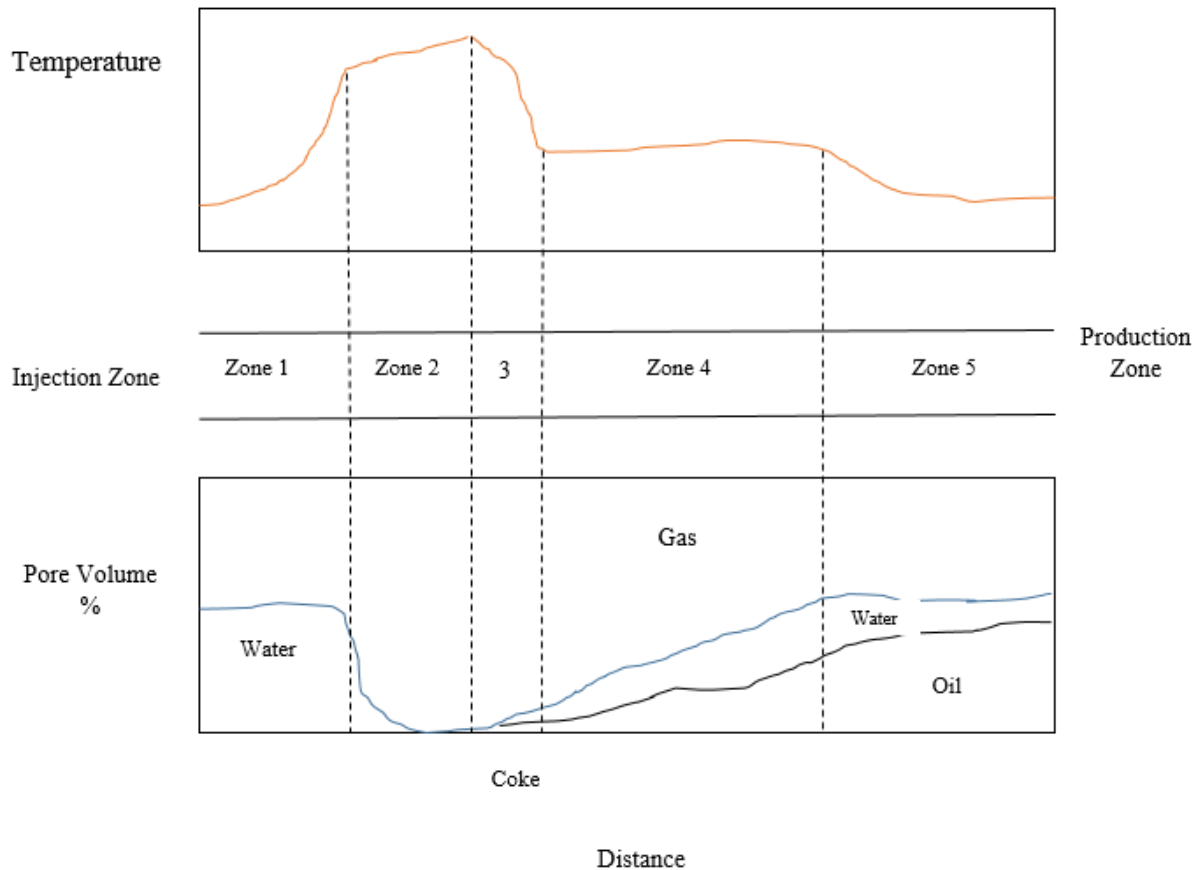

Figure 2 , Wet Combustion

4. Mechanism Reverse In-Situ Combustion

Reverse combustion might be likened to blowing through a cigarette, rather than inhaling, to propagate combustion. In reverse combustion, air flow is counter to the direction of the movement of the combustion front. This process was originally conceived from preheating cold, highly viscous oils, as in the Athabasca tar sands, where there would be no movement of the highly viscous oil bank ahead of the combustion front in a forward drive.

The process consists of injection of air until there is communication with the producing well, then using a downhole heater or other means to ignite the oil sand around the producing well. The combustion front burns back toward the injection well .

Four zones can be defined, starting from the injection well, as shown in figure 3 :

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Zone 1 : The formation is at original conditions. However it is being swept by air, and if the formation temperature and oxidability of the oil are high, certain oxidation reactions may occur .

Zone 2 : The temperature increases by conduction from the hot zone downstream. The start of oxidation also contributes to the temperature increase. The following phenomena occur: vaporization of the formation water, distillation of the light fractions of the oil and cracking of certain hydrocarbons in the presence of oxygen. The liquid and vapour fractions are displaced downstream, while certain components form the carbon deposit or "coke".

Zone 3 : The combustion zone. The temperature reaches its maximum value. The oxidation and combustion reactions involving the most reactive hydrocarbon molecules consume all the oxygen not used by the reactions in the preceding zones .

Zone 4 : The unburnt coke remains deposited on the matrix while the vapour and liquid phases flow downstream. If there were no heat losses, the downstream temperature would remain equal to that of the combustion front. In reality, the temperature decreases with distance from the combustion zone. Thus condensation of the distilled oil fractions occurs, and possibly of the steam also .
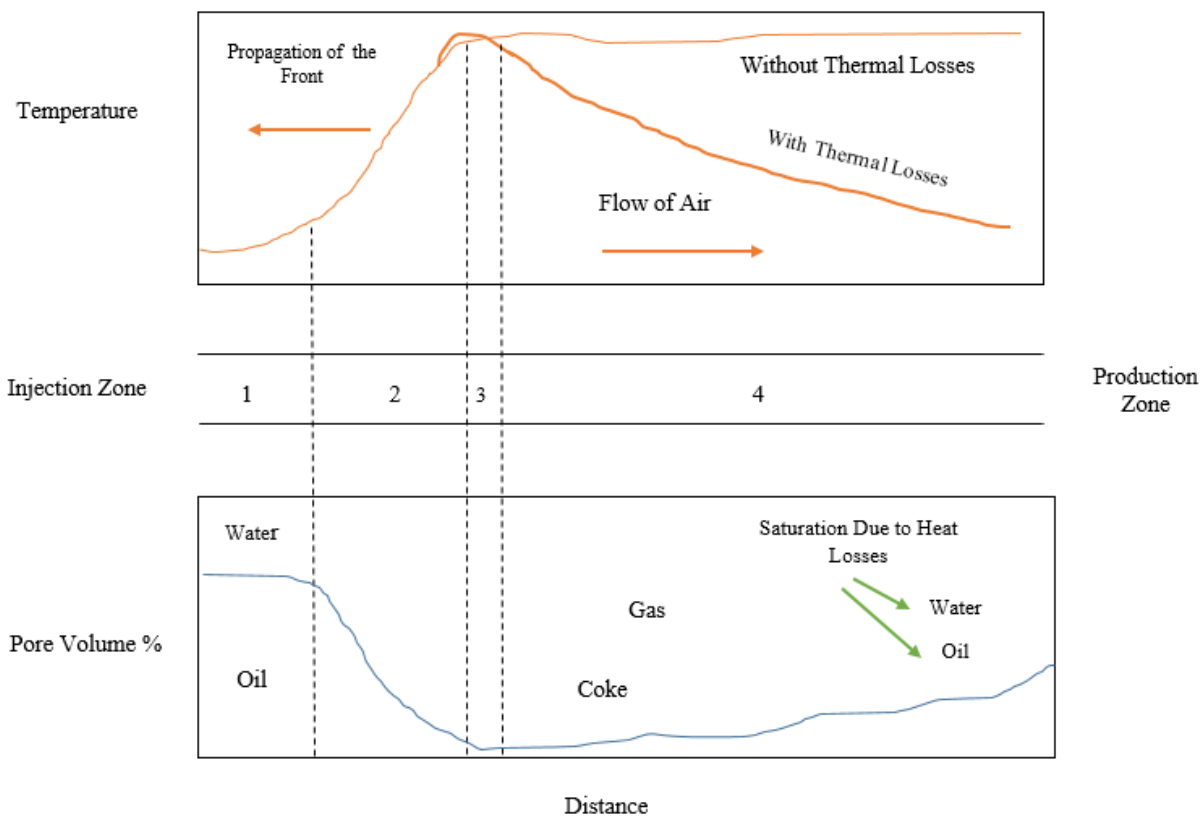

Figure 3 , Reverse Combustion
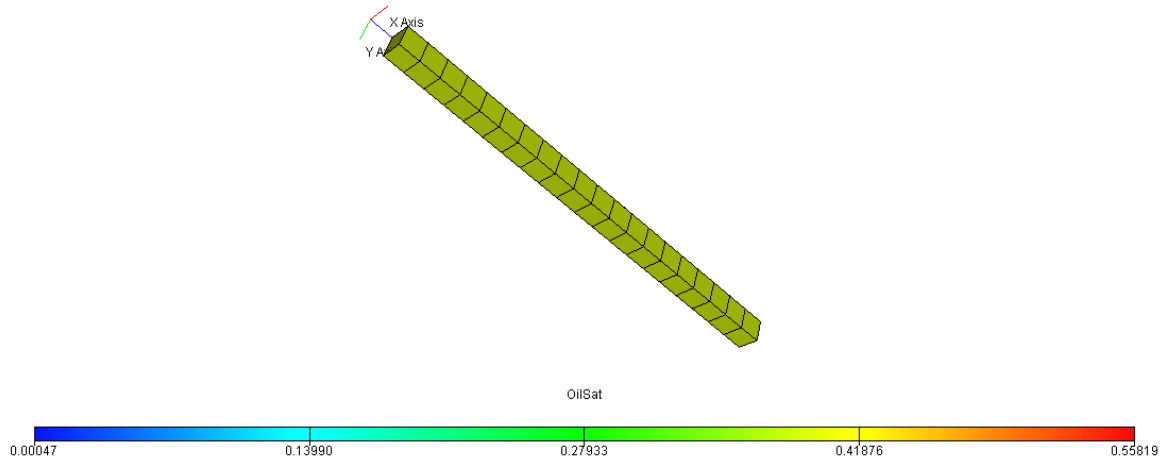
5. Simulation

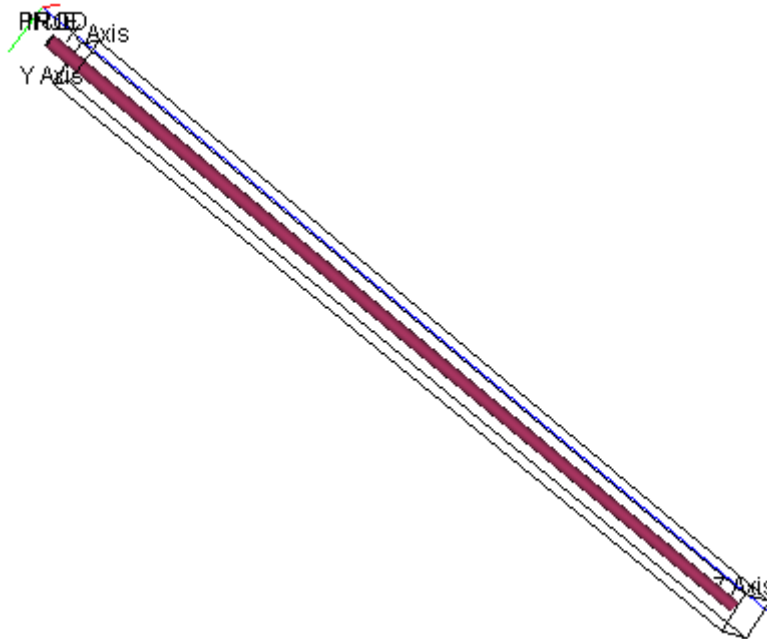## Introducing the Reservoir

Figure 4 , 3D View of The Reservoir

Figure 5 , Well Pattern

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Table 1 , Reservoir Dimension

X	Y	Z
1	1	20

Table 2 , Component Data

Component Name	C32+C47	C20	C6-C12	O2	N2-COx
Component Volatility Type	Dead*	Live *	Live	Gas*	Gas
Molecular Weights	508.9	282.6	131.4	32	32
Critical Pressures(Psi)	50.7	162	336.6	730	750
Critical Temperatures (R)	1*	1381	1067	1*	1*
Reference Densities(lb/ft3)	61.15	56.6	44.9	1*	1*
Oil Component Compressibility (1/Psi)	1E-5	1E-5	1E-5	1*	1*
Thermal Expansion Coefficient (1/R)	3.8E-4	3.8E-4	3.8E-4	1*	1*
Oil Component Specific Heat (Btu/lb/R)	0.6	0.6	0.6	0.24	0.226

Dead : For components that are only in the oil phase .

Live : For components that are both volatile and condensable .

Gas : For components that are only in the gas phase .

Table 3 , Names for Components

Component	Name
C1	C32+C47
C2	C20
C3	C6+C8+C12
C4	O2
C5	N2-COx
W	H2O

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Table 4 , Reactions

Reaction	Stoichiometry
1	C1+45.17C4→ 37.46 C5+29.71W
2	C2+25.08C4→20.8C5+16.5W
3	C3+11.66C4→9.65C5+7.67W

Table 5 , Reaction Rate Constants, Activation Energy and Reaction Enthalpy Values

Reaction	Rate Constant	Activation Energy (Btu/lbm)	Reaction Enthalpy (Btu/lbm)
1	3.4054E10	32,785	814,2400
2	0.28164E10	32,785	4,521,600
3	0.4035E10	32,785	2,102,400

Reaction Rate : The reaction rate R_r for reaction r in a grid cell is given by :

$$R_r = V_b . A_r . \exp\left(-\frac{E_r}{(RT)}\right) . \prod C_{ri}^{n_{ri}} \tag{11}$$

Where

V_b ：is the bulk volume

A_r ：is a reaction rate constant

E_r ： is the activation energy

R ： is the gas constant

T ： is the temperature

n_{ri} ： is the index or order of the component dependent term

Component Concentration : The term C_{ri} represent the component concentration in the reacting phase .

If the reactant is in the oil phase :

$$C_{ri} = \theta . b_o . S_o . X_i \tag{12}$$

If the reactant is in the gas phase:

$$C_{ri} = \theta . b_g . S_g . Y_i \tag{13}$$

If the reactant is water in the water phase:

$$C_{ri} = \theta . b_w . S_w \tag{14}$$

If the reactant is in all phases:

$$C_{ri} = \theta . m_i \tag{15}$$

Where

θ : is the porosity

b_o : is molar density of oil

b_g : is molar density of gas

b_w : is molar density of water

S : is saturation

X : is mole fraction of oil

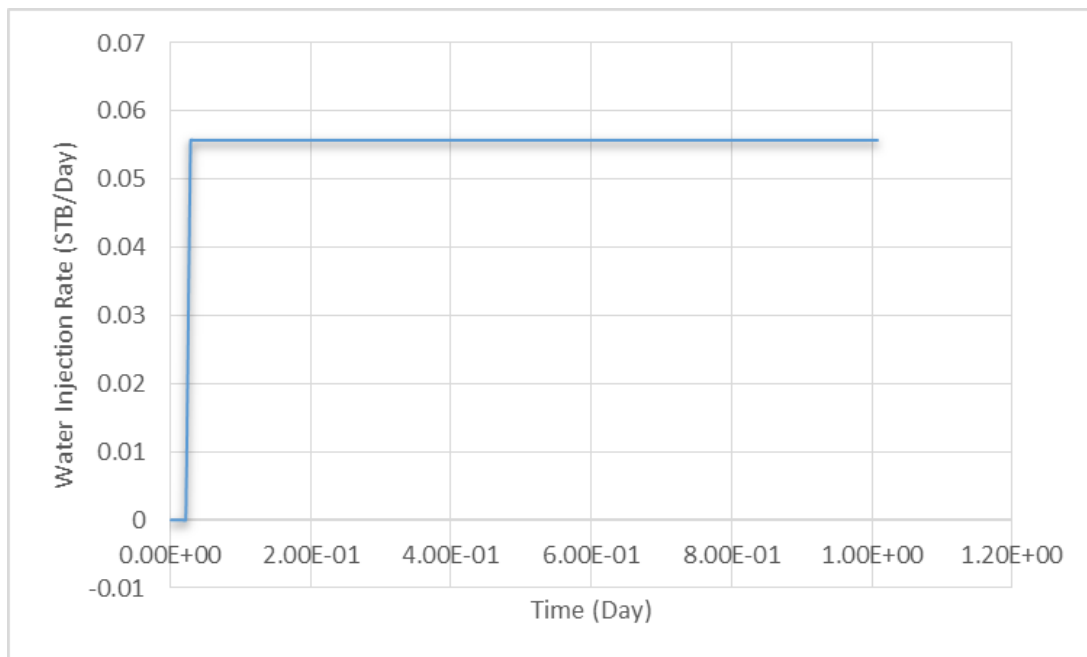Y : is mole fraction of gas

m_i : is molar density of component i
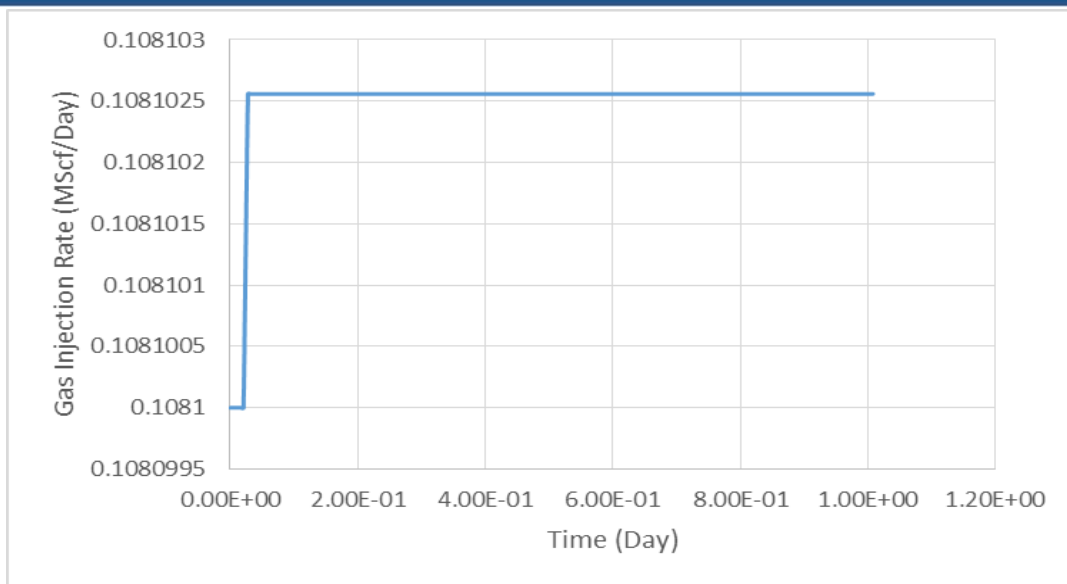

Figure 6 , Water Injection Rate

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Figure 7 , Gas Injection Rate

Table 6 , Injection Specification

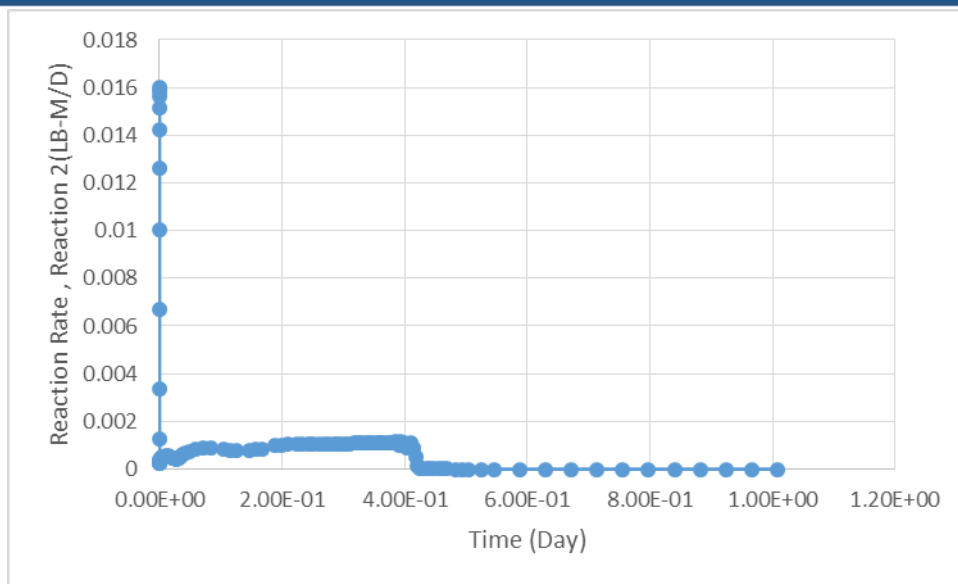| Temperature (°F)	Pressure (Psia)
120	815

6. Results
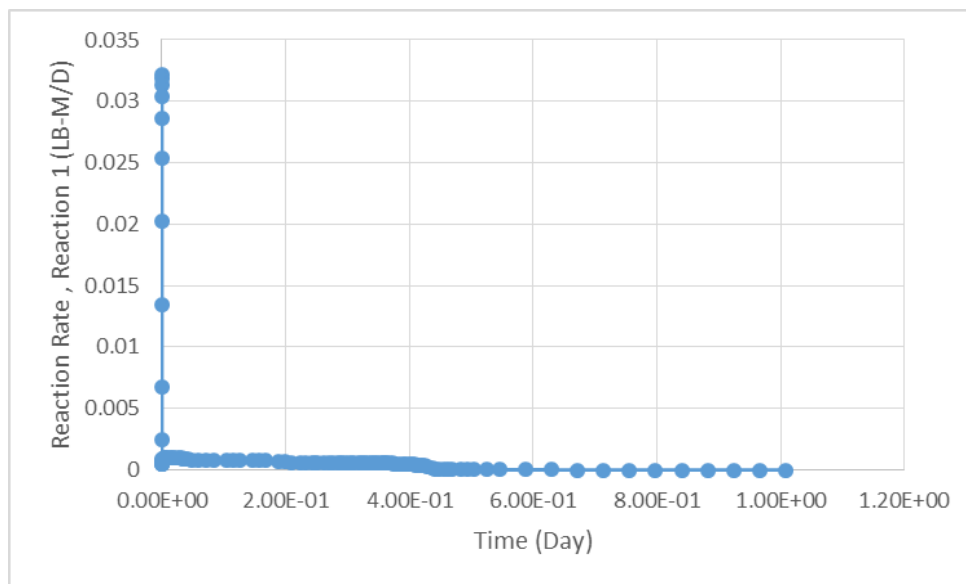
Figure 8 , Reaction Rate For Reaction 1

Figure 9 , Reaction Rate For Reaction 2
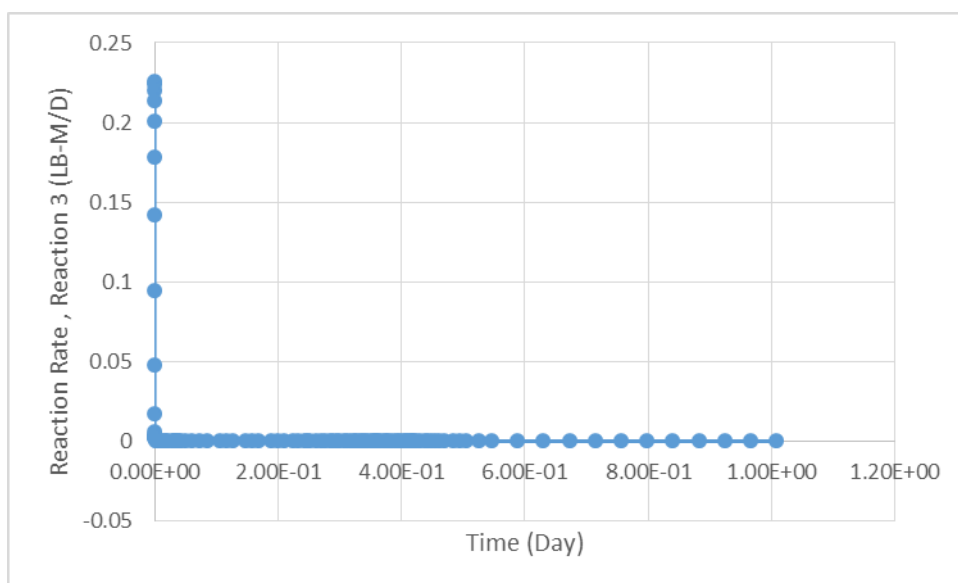
Figure 10 , Reaction Rate For Reaction 3

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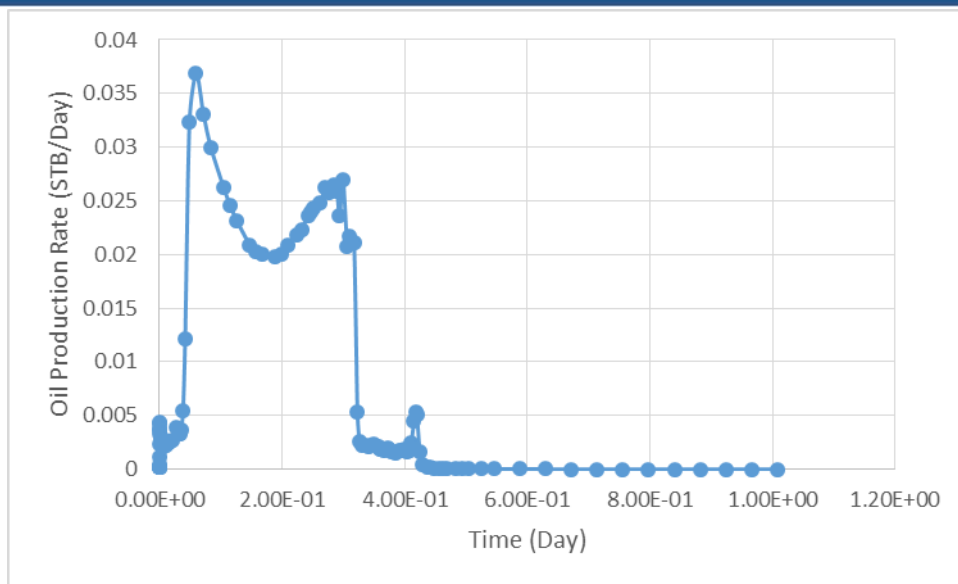
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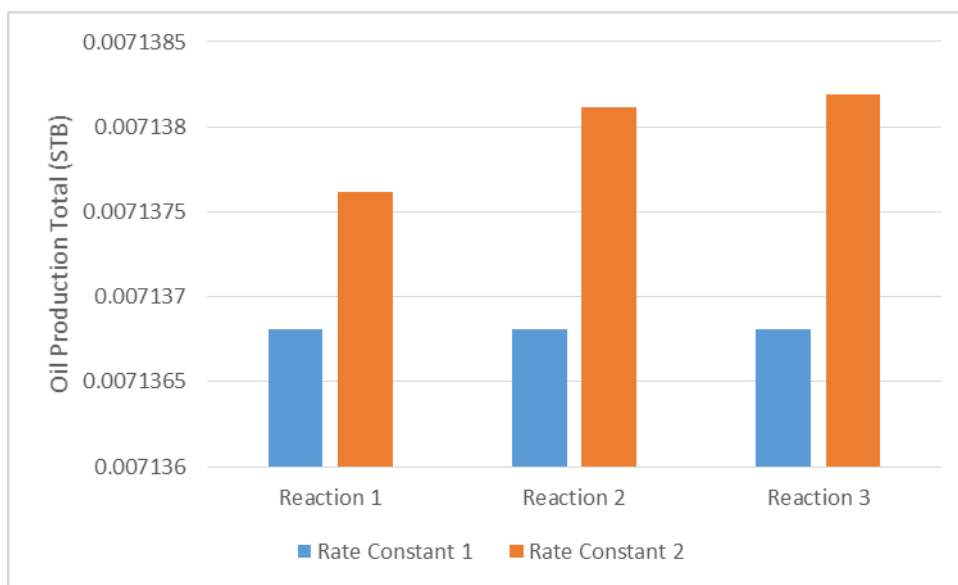**Figure 11 , Oil Production Rate**

Figure 12 , Sensitivity Analysis on Rate Constant and It's Effect On Oil Production Total

Table 7 , Amount of Rate Constant 1 & 2

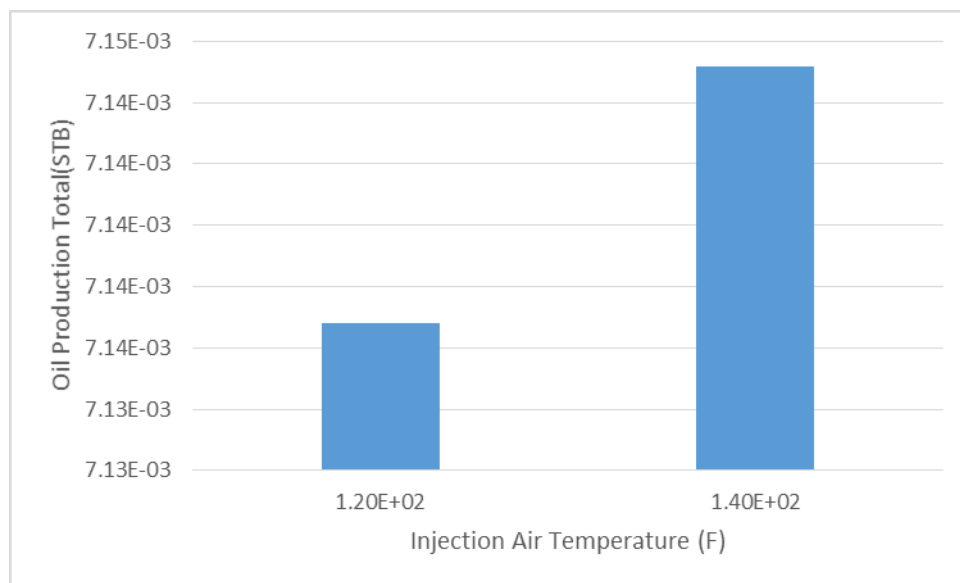|	Rate Constant 1	Rate Constant 2
Reaction 1	3.4054E10	3.5054E10
Reaction 2	0.28164E10	0.38164E10
Reaction 3	0.4035E10	0.5035E10

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Figure 13 , Sensitivity Analysis on Injection Air Temperature and It's Effect on Oil Production Total
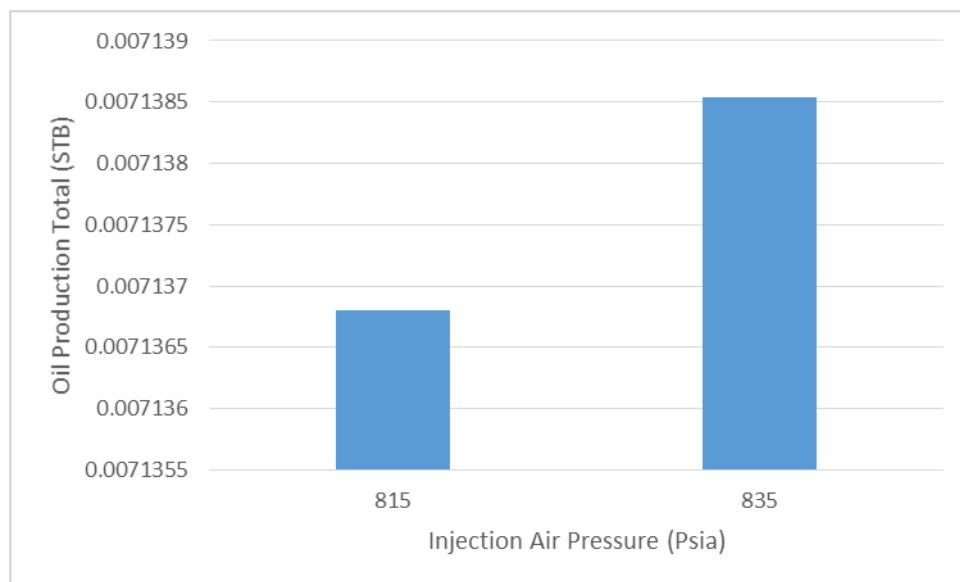

Figure 13 , Sensitivity Analysis on Injection Air Pressure and It's Effect on Oil Production Total

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7. Conclusion

The flow rate and oxygen concentration of the injected gas are very important factors in controlling the time needed to achieve maximum recovery. System pressure was also affected. Oxygen concentration of the injected gas can dramatically effect the peak temperatures .

Oil relative permeability affects the time needed to achieve maximum recovery as well as the peak temperatures and the system pressure .

0il viscosity is very important in determining the amount of oil that can be recovered as well as the time needed to achieve maximum recovery. It was also found to affect the peak temperature and the system pressure .

Reaction enthalpies as well as the kinetic parameters determine the amount of heat generated by the reactions which in turn affects the amount of oil that can be recovered and the time needed to achieve maximum recovery. Also, the heat generated by the reactions controls the overall temperatures of the formation .

References

[1]. Davies, R.: "Numerical Simulation of In-Situ Combustion", Ph. D. Thesis, University of Bath, 1988.
[2]. Eggenschwiler, M. E., and Farouq Ali, S. M.: "Two-Dimensional, Single Phase Simulation of Fireflood", Can-Venezuela Oil Sands 1977 .
[3]. El-Khatib, N.: "A Mathematical Model of Thermal Oil Recovery in a Forward In-Situ Combustion Process", Ph.D Thesis, Univ. of Pittsburgh (1973) .

[4]. Ewing, R.E.: " Efficient Adaptive For Fluid Flow Applications", Comp. Meth. Appi. Mech. Eng. 55(1986), 89-103.
[5]. Ewing, R. E., and Lazarov, R. D.: "Adaptive Local Grid Refinement",SPE paper No. 17806, presented at the SPE Rocky Mountain Regional Meet., held in Casper, WY, 1988.
[6]. Farouq Ali, S. M.: "Multiphase, Multidimensional Simulation of In Situ Combustion", Paper SPE 6896, presented at the 52nd Annual Fall Meeting of SPE, Denver, Oct. 9-12,1977.
[7]. Genrich, J. F., and Pope, G. A.: "A Simplified Performance Predictive Model for In-Situ Combustion Process", SPE Res. Eng., (May,1988)410 .
[8]. Gottfried, B. S.: "A Mathematical Model Of Thermal Oil Recovery in Linear Systems", Soc. Pet. Eng. J., (September 1965), 196-210.
[9]. Han, D. K., Han, D. L., Yan, C. Z., and Peng, L. T.: "A More Flexible Approach of Dynamic Lacal Refinement for Reservoir Modeling", SPE paper No. 16014, presented at the Ninth SPE Symp. on Res. Sim. held in San Antonio, Texas, 1987.
[10].   E1-Khatib, N.: "A Mathematical Model of Thermal Oil Recovery in a Forward In-Situ Combustion Process", Ph.D Thesis, Univ. of Pittsburgh (1973).