Design and Operation of Laboratory Combustion Cell for Air Injection into Light Oil Reservoirs: Potential Application in Sindh Field

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ABSTRACT

Historical experimental work on the combustion oil recovery processes consists of both laboratory and field studies. Although field experiments are the ultimate test of any oil recovery process, they are costly, time consuming and difficult to analyze quantitatively. Laboratory CC (Combustion Cell) experiments are cost effective and less time consuming, but are subject to scaling and interpretation challenges. Experimental set up has been developed to understand air injection process for improving oil recovery from light oil reservoirs taking into account the sand pack petro physical and fluid properties. Some important design problems; operational criteria and considerations important to interpretation of results are pointed out. To replicate subsurface reservoir conditions or pressure and temperature, experiments up to 6895 KPa, at non-isothermal conditions with 5°C/min ramp-up are performed on unconsolidated cores with reservoir oil samples. Correlations were obtained for low temperature oxidation rate of oil, the fuel deposition rate and the rate of burning fuel as a fuel concentration.

Various parameters such as (sand pack, pressure, oil saturation and flow rate/air flux) were changed to investigate their impact on reaction and chemical nature of the fuel burned. To determine the importance of distribution and pyrolysis on these reactions, the hydrogen-carbon ratio and m-ratio was calculated. For further confirmation Arrhenius graphs were drawn by assuming 1.0 order of reaction with carbon concentration which is also confirmed.

This research will contribute to the overall understanding of air injection process; help to determine the most appropriate IOR (Improved Oil Recovery) technique in the development of the tertiary phase of production in light oil reservoirs in Lower Indus Basin (Sindh) fields.

Key Words: **Air Injection, Oil Recovery, Light Oil, Combustion Cell and Oxidation Kinetics.**

1. INTRODUCTION

Injection of air into depleted light oil reservoir may be regarded as a new alternative IOR method for both secondary and tertiary processes. Many field and laboratory studies of the forward combustion oil recovery process have been conducted since the early publication of Kuhn, and Koch [1] and Grant and Szasz [2]. In view of

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the complex and costly nature of this type of investigation, it is not surprising that no complete theory of the nature of the forward combustion process is yet developed. However, gross effects are well understood and reasonable design procedure is available for planning field operations.

Laboratory combustion tube studies have already yielded important information regarding the combustion process. However, concerning the design, construction and operation of combustion tubes and combustion cells are not available in this region. Combustion tubes and CC used by various investigators vary in size, length and mode of the operation.

Therefore, one purpose of this paper is to present considerations important to the design, construction and operation of combustion cell in order to better understand the air injection process into oil reservoirs particularly for the Lower Indus Basin region. Nelson and McNeil [3-4] have published two comprehensive papers regarding design procedures. Greaves, M., suggested that, large field well spacing provides the more residence time required for complete oxygen utilization [5]. Gordon Moore has observed that, fire flooding of heavy oil deposits is much more displacement process than thermal process [6]. An accelerating rate calorimeter with adiabatic temperature control has also been employed to study oil reactivity [7]. Laboratory experiments and computer simulations show that air injection is feasible for IOR after water flooding in light oil fractured chalk reservoir [8-9]. The air injection project in WBRRU (West Buffalo Red River Unit) has been technically more successful in terms of incremental, quick response and higher production as compared to the water flood project in WBRRU [10].

The air injection LTO (Low Temperature Oxidation) process works by removing the oxygen from the injected air through LTO with oil in the reservoir [11-12]. Unlike in-situ combustion, a stabilized high temperature front, or combustion zone, is not necessary. The LTO reaction is spontaneous and independent of oxygen partial pressure so that complete oxygen consumption can be achieved in the reservoir. A small amount of oxygen will be left in the oil if there is an insufficient reactive component left to react with the oxygen. The process is quite flexible regarding air injection rate. The only restriction on the air injection rate is to ensure a sufficiently long residence time in the reservoir for complete oxygen removal. This will not present any problem in reservoirs with a fairly long well spacing. In light oil reservoirs, well spacing between injection and production wells is hundreds of feet or meters Greaves, M., et. al. [5, 11].

2. EXPERIMENTAL SET-UP

Experimental apparatus was constructed in the Institute of Petroleum & Natural Gas Engineering, Mehran University of Engineering and Technology, Jamshoro, Pakistan, for understanding air injection process for depleted light oil reservoirs.

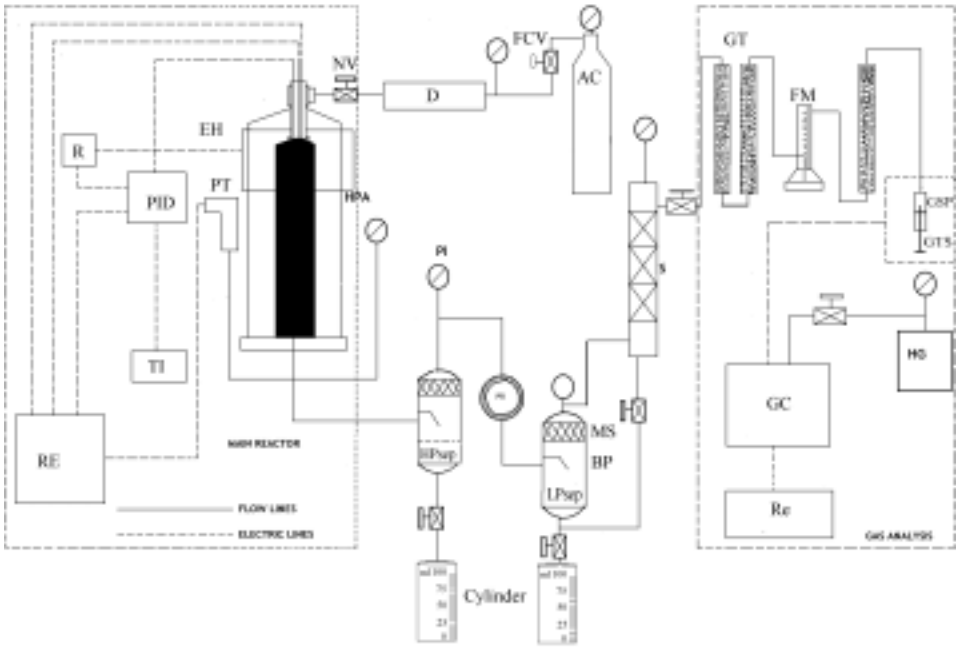
Fig. 1 shows the schematic diagram of the air injection experimental apparatus with GC (Gas Chromatograph). The CC and assembly were enclosed in an angle iron frame 6x4x2 ft. Components mounted in this frame include the pressure shell, and combustion cell with the necessary heating device, temperature processor controller, digital temperature indicator, product separation, recording equipment, thermocouples, pressure regulator, pressure gauges, control valves and high pressure air cylinder.

High-pressure autoclave/reactor detail is presented in Fig. 2. Reactor comprises of a thick wall autoclave made up of 304 stainless steel and has flanges at the bottom of the reactor along with 5.08 cm nut. The reactor has dimensions of 8.255cm OD, 5.715cm ID, 35.56 cm length, and 1.27cm wall thickness designed for a working pressure of 20685 KPa and temperature up to 600-700^{o}C. The reactor was hydraulically tested up to 34475 KPa.

A thin wall CC made up of stainless steel 316, with dimensions of 3.81cm OD, 3.175cm ID and 25.4cm length is placed inside the autoclave. Two stainless steel wire screens of 200 meshes size are placed at the bottom of the

CC to prevent the sand entering to the production line. The volume of the combustion cell is 325cm^3. Reactor assembly was fabricated using local vendors of Hyderabad, Sindh, Pakistan.

In the first series of experiments one electric heater (1.0KW) was wrapped around the top of the reactor to heat the autoclave to simulate reservoir temperature to create ignition in the sand pack. The heater is enclosed in a close muffled type demountable container and controlled by Honey well, PID temperature processor controller. In these experiments two heaters (1.0KW each) were installed; one at the top of high pressure autoclave for the ignition purpose and another at the centre of the autoclave to maintain reservoir conditions of temperature. Finally, three heaters (1.0KW each) were installed; one at the top of the autoclave and another two heaters were installed to cover the full length of the autoclave. A transformer/regulator was installed to maintain the constant temperature of the heaters. The thermowell of 0.635cm diameter was held in the centre of the CC and contained three chromel-alumel thermocouples of 0.1cm diameter to measure the temperature of the reaction zone at different depth intervals. T1 (Thermocouple-1) was placed in the upper most area of the CC (2.54cm to inlet), T2 (Thermocouple-2) was placed at 12.7cm from top of the CC, and T3 (Thermocouple-3) was placed at 17.78cm from top of the CC. These thermocouples are connected with recorder to record the values of different temperatures i.e. T1), T2 and T3. The upper most thermocouple placed very close to the inlet of CC was used to control the ramp-up temperature through PID controller. At the outlet of the reactor, the pressure transducer was installed and connected to the recorder to record the injection pressure. High pressure and low-pressure separators were installed along with deflector plates at the out let of the reactor with three sieve plates.



AC is Air Cylinder, BP is Baffle Plates, D is Dryer (filled with silica gel), FCV is Flow Control Valve, FM is Flow meter, GC is Gas Chromatograph, GSP is Gas Sampling Point, GT is Glass Tubes (Absorbent), HG is Hydrogen Generator, HPA is High Pressure Autoclave, HP Sep is High Pressure Separator, LP Sep is Low Pressure Separator, NV is Needle Valve, PG is Pressure Gauge, PR is Pressure Regulator, PT is Pressure Transducer, PID is Temperature Processor, R is Relay (PID Type), Re is Recorder/Chromatocorder-12, RE is Recorder/Eco-Graph (Six Pen Paper Less), S is Scrubber (filled with wire mesh), and TI is Temperature Indicator (Digital)

FIG. 1. SCHEMATIC OF THE AIR IJECTION EXPERIMENTAL APPARATUS

GC-1880 was connected with the experimental set-up for the analysis of exhaust gases by injection of 1.0 ml sample with tight gas syringe at the top of the column of injection port, after every 10 minutes, the various peaks of the produced gases were recorded and integrated. Pressure regulator attached at the outlet of the autoclave reduced pressure from 34475 KPa to atmospheric pressure for better separation of fluids and flow rate of effluent gas was controlled by pressure regulator for accurate analysis. However, due to blockage of pressure regulator caused by the oil production from the reactor, the flow of the exhaust gas was not smooth and fluctuated. It varied from 50-200 ml/minute. After few experiments the set-up was modified to avoid the blockage of pressure regulator and to maintain the constant outlet flow. The reduction in pressure to atmospheric level was achieved by large volume of down stream equipments. Later the pressure regulator was installed at downstream of the high-pressure separator. This maintained the constant flow rate. Regulator needed cleaning with ethanol after 2-3 experiments due to oil accumulation inside it. Equipment was modified and tested upto 12411 KPa. Pressure beyond the regulator was maintained up to 34.5 KPa maximum, which eventually decreased to around 6.895-13.79 KPa at sampling point.

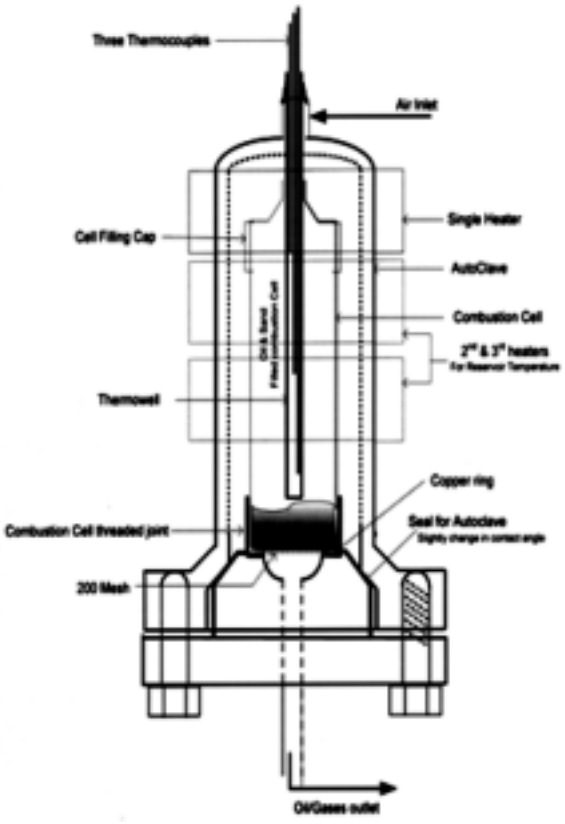


FIG. 2. HIGH PRESSURE AUTOCLAVE

3. EXPERIMENTAL PROCEDURE

A given weight of the sand was placed in a container and the required weight of the oil added to the sand and mixed with the help of spatula, until the mixture became homogenous. Unconsolidated sand equivalent to the weight of the consolidated core was placed into the combustion cell. The sand mixture impregnated with light oil was packed into the CC using a steel rod with a flat metal plate attached to it to closely pack the mixture. The top of the sand pack was set at 24.1cm from the bottom flange. The clean sand was packed up to the level of the igniter in order to prevent premature cracking reactions with oil in the sand pack. The sand pack properties are presented in Table 1. Packed with the CC, the bottom flange assembly was secured in placed, the cell was inserted in the pressure shell and connected to the inlet gas lines and the outlet production and gas analysis system.

The air was supplied by high-pressure (13652 KPa) cylinder of compressed synthetic air with high-pressure regulator. The inlet gas stream was admitted at the top of the reactor (Vertical), while the exhaust gases were withdrawn from the bottom of the reactor. The injected flow rate of air was controlled by needle valve/flow control valve. Pressure regulator was used to control the pressure of the reactor. Downstream of the regulator produced gases were allowed to flow through the low pressure separator, scrubber and to the sample collection point. After 30 minutes the required pressure was maintained, stabilized and then both the heaters were turned ON. The reactor was heated with a ramp of (5°C/min.) up to the ignition was observed by change of slope versus time on the recorder The igniter

was switch OFF and another heater was used to maintain the reservoir temperature (about 100°C), which was controlled by transformer/regulator (120V) for the duration of experiments and held constant. Required air flow was established through the pack while the different thermocouples were measuring the temperature at the sand face and also at the different depth intervals of the combustion cell. The ignition could be observed on the temperature recorder by change of slope on the temperature versus time chart. Samples of exhaust gases were analyzed at 10-minute intervals for the entire duration of reaction. For each oxidation run, the CO_2, CO, O_2 and N_2 concentrations in the exhaust gas were determined as function of time. The produced liquid from the high-pressure and low-pressure separators was collected after the end of the experiment (Tunio, A.H., [13]).

4. COMBUSTION CELL TEMPERATURE PROFILES

The impregnated unconsolidated core sample was placed in a CC which was heated by igniter with a ramp of 5°C/min. The temperature profiles during the combustion are shown in Fig. 3. A small variation in the peak temperature is noticeable. This is due to rate at which exothermic combustion reaction generated heat as compared with heat losses from the combustion. Heat losses from the combustion zone are the result of conduction through the radial cell wall, combined with axial heat conduction and convection down stream to the steam zone. Little disturbance was`created on the process because of very quick ignition that takes place as shown in Fig. 3. After switching OFF the igniter, the combustion front propagation stabilizes quickly and thereafter continues to

TABLE 1. SAND PACK PROPERTIES

Length of the Combustion Cell, cm	CL	25.4
Length of the sand Pack, cm	L	24.1
Radius of the Cell, Cm	rc	1.5875
Bulk volume, cubic cm	Vb	325.0
Sand density, gm/cc	Ps	2.67
Oil density, gm/cc	Po	0.836
Oil saturation, %	Sw	57.41 -80
Weight of the sand in the Cell, gms	Ws	200
Weight of the oil in the Cell, gms	Wo	66
Volume of the oil, cubic cm	Vo	80
Water Saturation, %	Ws	20-41.25

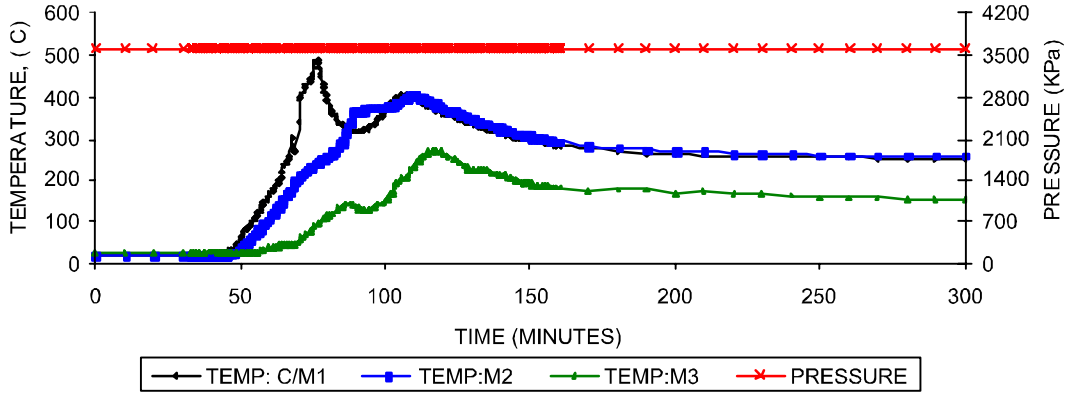


FIG. 3. GAS COMPOSITION AND TEMPERATURE VERSUS TIME FOR RUN-5

maintain constant temperature of about 250°C at the end of the experiment. The ignition temperature was noted at about 500°CC. Due to movement of the combustion front from 1st-2nd zone and finally in 3rd zone of the CC, ignition took place and the peak temperatures of both the zones were noted at about 380 and 280°C respectively. The increasing trend of the average peak temperature with oxygen concentration is shown in Table 2. With air-assisted combustion, the peak temperature is not significantly affected by the increase in pressure, varying from 300-350°C over the pressure range of 2069-3448 KPa as presented shown in Table 2. One explanation for this is that at higher injection pressures, the distillation rate of volatile components in the steam zone is lower. This means that more fuel is potentially available for combustion. As a consequence, a peak temperature would be expected but the convective heat transport from the CC/zone also increases due to larger fraction of nitrogen in the combustion gases. Thus, when this is combined with the radial heat loss by conduction, the net result is to suppress any increased temperature effect resulting from higher fuel concentration.

5. PRESENTATION AND DISCUSSION OF RESULTS

The analysis is based on the effluent gas data obtained from the various experiments. The analysis will be quantitative and qualitative description of the general trends observed. Experiments were performed for obtaining useful kinetic data for air injection process for the improved recovery of the light oil. These experiments were conducted so that more reliable and comprehensive data could be obtained for air injection process in the incremental recovery of light oil reservoirs at high pressure and high temperature usually after water flooding. The unconsolidated core (sand pack) with different sand grain size impregnated with light oil was used in this series of experiments.

A total of 50 kinetics runs were made. The parameters that were varied from run to run- included system pressure, rock formation/sand matrix, flow rate (Air flux), oxidation temperature/heat input, and oil and water saturations.

TABLE 2. SUMMARY OF COMBUSTION CELL RESULTS

Parameters	R-5	R-2	R-4	R-17	R-20	R-24	R-29
Run Duration, (Minutes)	300	460	420	240	300	300	180
Cumulative Oil Production, Ml	67	65	70	46	65	62	61
Final Oil Recovery, (% OOIP)	83.75	81.25	87.5	61.33	86.66	82.66	81.33
Average Combustion Front Peak Temperature (C)	489	372	499	350	448	486	400
Maximum Conclude of Produced $CO2_2$, Mole %	10.14	7.18	6.3-2.5	5.55	9.21	10.15	5.7
Maximum Conclude of Produced CO, Mole %	5.43	4.052	3.8-1.2	4.83	4.69	5.41	3.1
Maximum Conclude of Consumed O_2, Mole %	19.16	19.21	16.55-7.63	13.76	19.25	19.2	15.9
Utilization of O_2, %	97	96.5	96.3	65	92	92	76
Apparent Hydrogen Carbon Ratio				1.92	2.83	3.21	2.25
m-Ratio				0.33	0.23	0.25	0.13
Peak Temp. (K) Of H/C & M-Ratio				608	660	580	692
Activation Energy (E) KJ/Mole				35.0	59.0	34	21
Fuel Combustion (E1)				29.5	42.5	33	25
Fuel Deposition (E2)							
LTO (E3				16.0	36.0	33.	8.0

However, oxygen concentration was kept constant for all the runs. The effect of each parameter upon the oxygen conversion was determined from analysis of the inlet oxygen and exhaust gases, oxygen and carbon oxides. The pressure was varied from 690-11032 KPa; outlet flow rate from 50-500 ml/min at room temperature and atmospheric pressure. These rates correspond to air fluxes ranging from 3.797-37.97 Sm^3/m^2-hr. At temperature below 100°C, the oxygen conversion was too small to be satisfactorily used in the quantitative analysis of the kinetic data. The data reported here are for oxidation temperatures above 200°C.

5.1 Effluent Gas Analysis

Fig. 4 represents only one peak that appears in the production of carbon oxides at temperature about 300°C. In this peak amount of oxygen consumed exceeds that recovered as carbon oxides gas. Oxygen mole fraction decreasing in the produced gas indicates that the produced reaction gases exhibit an increased amount of CO_2 generated gradually displaced the air saturation in the sand pack. The final O_2 consumed was less than 2%.

Fig. 5 shows two apparent peaks in the production of carbon oxides at different temperature. This as well as the result of differential Thermal Analysis, confirm the existence of at least two reactions. First peak appears at temperature (around 300°C); the mole fraction of the oxygen consumption is equal to mole fraction of the produced CO_2 and 0.5 CO. But the 2nd peak at high temperature (about 425°C), the O_2 consumption is larger than CO_2 and CO produced. The temperature below 100°C, some O_2 is consumed but no carbon oxides are produced. The first peak at low temperature in the gas concentration graphs corresponds to the oil oxidation however, the small peak corresponds to fuel combustion at high temperatures.

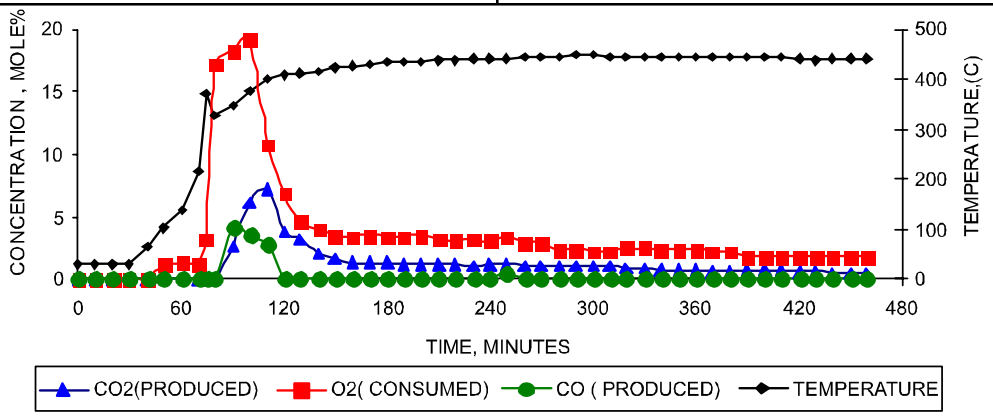


FIG. 4. GAS COMPOSITION AND TEMPERATURE VS TIME FOR RUN-2

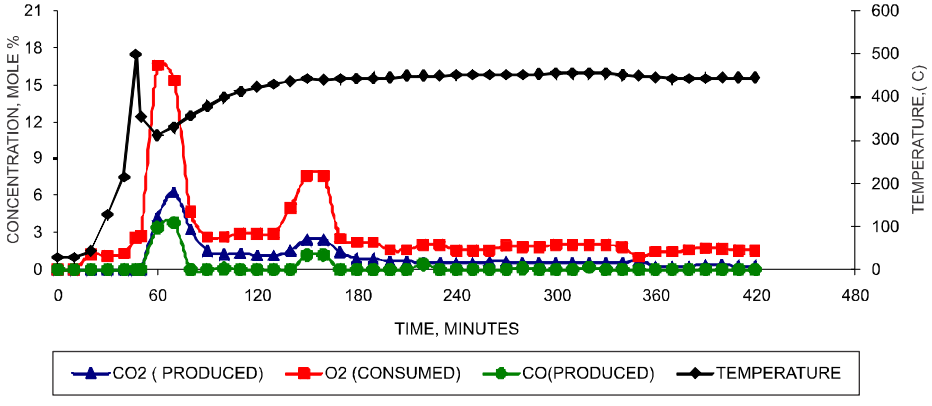


FIG. 5. GAS COMPOSITION AND TEMPERATURE VERSUS TIME FOR RUN-4

Comparing the results presented in Figs. 4-5, it is clear that the first peak is higher or smaller than the 2nd one, depending on the rock proerties and crude oil properties. As shown in Figs. 4-5, the light oil of Badin Oil Field due to its high reactivity with oxygen at low temperature has a first peak, which is much higher than the second one. In contrast, for the heavy viscous Wolf Lake Oil, the combustion peak is much higher than the low temperature peak. Kazi, R.A., [14], who used 10° API Wolf Lake Oil. This indicates the propensity of this crude oil for fuel deposition. The produced carbon oxide gases can account for almost all the oxygen consumed at high temperatures. Since the production of carbon oxide gases represents the removal of carbon, the reaction associated with 2nd peak is controlled by the simultaneous availability of fuel and O_2 at high temperature. The fuel is considered to be burning when conditions associated with the 2nd peak prevail i.e. the amount of O_2 consumed is eventually balanced by the amount of produced carbon oxide gases. In this low temperature region the fuel is being oxygenated, rather than burned; a smoldering rather than burning takes place.

5.2 Effect of System Pressure

Fig. 6-9 present the gas production rate with operating pressure as a parameter (Tables 3-4). Fig. 10 presents consumption of oxygen at various pressures. it was observed that with increasing pressure (6895 KPa) the reaction rate is low. Although comparing 2069-3448 KPa, pressure has an identical increase in reaction rate. However, comparing 3448-3585 KPa, pressure has almost an identical behavior. An observation was made that the carbon monoxide production seems too early in these experiments conducted up to 6895 KPa. The rate of CO produced seems unusual than to the rate predicted to this type of reaction scheme. The possible argument for the high rate of products at low temperature could be that the light components are reacting with free oxygen available to large quantity, producing higher amount of carbon oxide, where as in high pressure of 6895 KPa, the light components are suppressed. The low level of products in 6895 KPa experiment may be due to dilution effect, which is taking place by large number of moles present in the reactor at increased pressure. One can conclude that the distribution of the products are inadequate and does not behave ideally. The main results of experiments are presented in Table 2.

5.3 Oil Recovery

Recovery of oil is mainly affected by the characteristic of the oil properties (viscosity, composition and density) and core properties (permeability, wettability and porosity). It is affected by air injection rate and amount of residual oil. The recovery of oil from most of combustion tube/

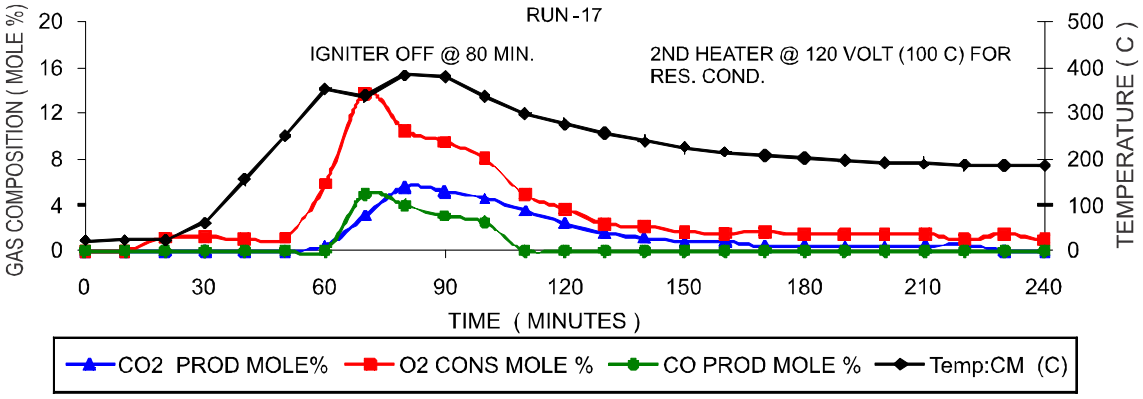


FIG. 6. GAS COMPOSITION AND TEMPERATURE VERSUS TIME AT 2069 KPA

oxidation tube tests above 75% of original oil in place was obtained leaving residual oil saturation of about 15% in the sand packs, the latter is, of course, governed by the limited duration of the oxidation inside the CC. As the pressure increased from 2069-3448 KPa, cumulative oil production increased about 15%, however, at pressure 6895 KPa no significant effect was observed as given in Table 2.

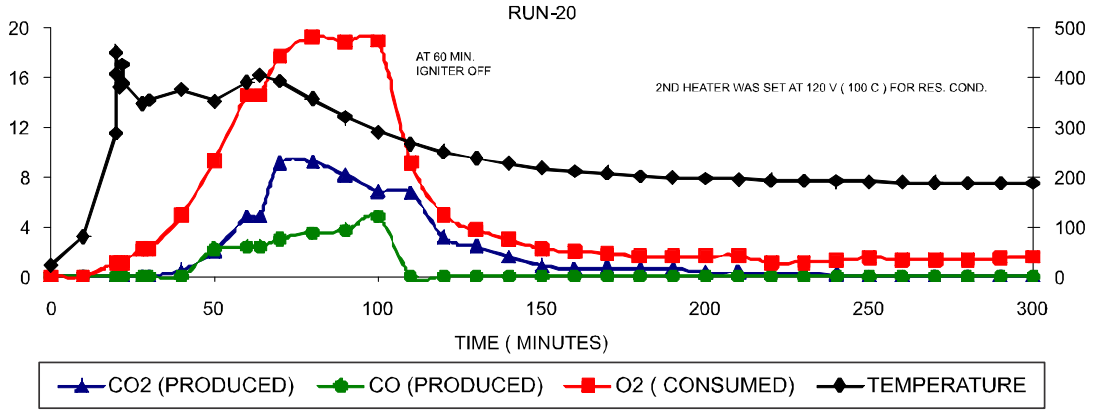


FIG. 7. GAS COMPOSITION AND TEMPERATURE VERSUS TIME AT 3448 KPA

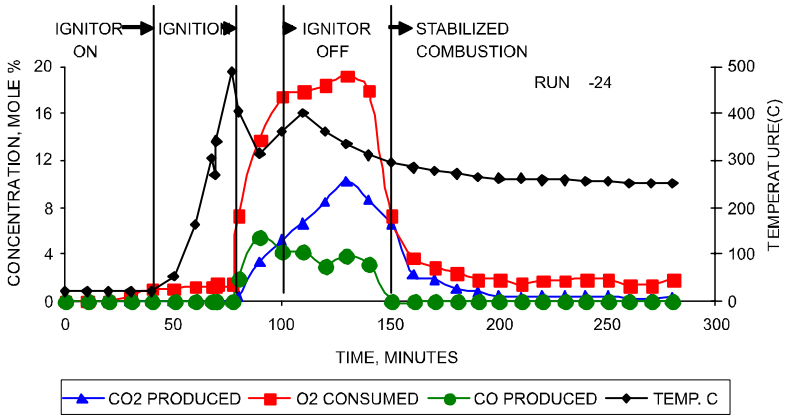


FIG. 8. GAS COMPOSITION AND TEMPERATURE VERSUS TIME AT 3585 KPA

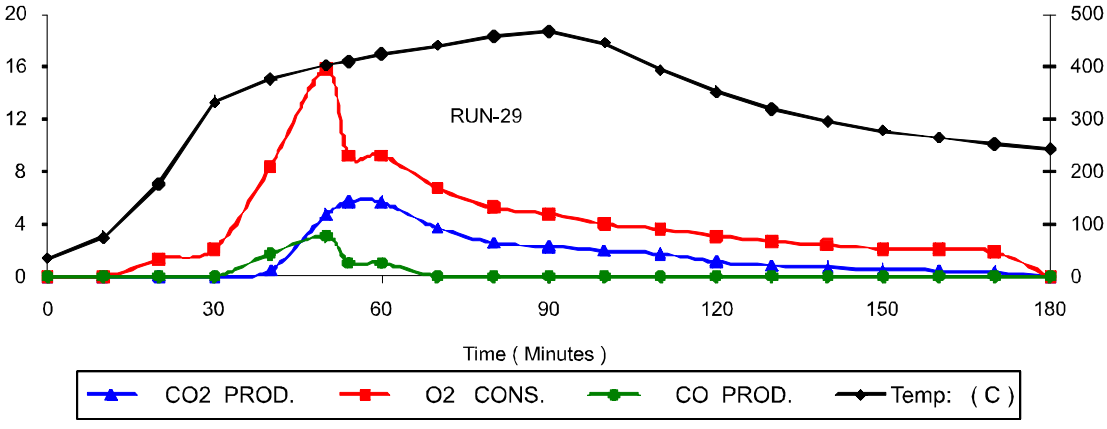


FIG. 9. GAS CONCENTRATION AND TEMPERATURE VERSUS TIME AT 6895 KPA

5.4 Apparent Hydrogen Carbon Ratio

Apparent HC (Hydrogen Carbon) ratio which characterizes oxidation and is indicative of the nature of the fuel being burned is a useful indicator for a process involving both simultaneously hydrocarbon and a coke oxidation. The nature of the fuel changes as the hydrocarbons and coke are oxidized simultaneously. In most of the runs LTO reactions were observed. Therefore, the calculations are based on assumption that 100% was not observed in the exit gas had reacted from water and have been averaged to the temperature range of interest (HTO zone). The HC ratios for these experiments are presented in Fig. 11. Table 2 presents HC ratio, peak temperature and detailed results are presented graphically.

Abu-Khamsin, et al., [15] found the distillation of crude plays an important role in shaping the nature and extent of the cracking reactions. With extensive distillation they observed less weight loss due to visbreaking, leaving a larger oil fraction transforming to coke. When LTO occurs in unconsolidated formations the heavier residual oil is produced and visbreaking is more effective leading to larger

TABLE 3. SUMMARY OF SAND PACK PARAMETERS

Run No.	Percent by Wight			Total Weight (%)	Oil API	Volume of Oil (ml)	So (%)	Oil by Weight (%)
	80M	100M	200M					
5	10	80	10	100	37.5	80	81.25	24.5
2	22	65	13	100	37.5	80	81.25	24.5
4	10	60	30	100	37.5	80	81.25	24.5
17	10	76	20	100	36.0	70	64.0	22.5
20	10	70	20	100	36.0	70	64.0	22.5
24	10	70	20	100	36.0	70	64.0	22.5
29	10	70	20	100	36.0	70	64.0	22.5

TABLE 4. SUMMARY 0F OPERATING AND CONTROL PARAMETERS

Run No.	Injected Gas Analysis Mole (%)		Operating Pressure (KPa)	Temperature Conductivity (C)	Flow Rate (ml/min)	Air Flux (Sm^3/m^2-hr)
	O_2	N_2				
5	21	79	3600		100	7.595
2	21	79	3516		100	7.595
4	21	79	3516	Non-Isothermal 5 (C/min)	100	7.595
17	21	79	2069	2nd Heater Installed @ 120V to	125	9.493
20	21	79	3448	Maintain the Reservoir temperature (100C)	125	9.493
24	21	79	3585		125	9.493
29	21	79	6895		125	9.493

amount of coke and higher fuel deposition with a smaller HC ratio of the fuel burned. Dabbous and Fulton [16] observed similar HC ratio in the presence and absence of LTO reactions. High HC ratio was obtained from soft brown coke in absence of LTO reactions. In contrast a low HC ratio was obtained from hard black coke in presence of LTO reactions. Ramey [17] obtained oxidized residues at temperatures as low as 149°C.

5.5 m-Ratios

The behavior of m-ratio under these conditions versus combustion time is presented in Fig. 12. The production of (CO_2 and CO) gases was very low at the low temperature range of 180-280°C. m-ratio decreased from 0.7-0.15 and fairly constant (0.15) was measured at temperatures from 340-370°C. Table 2 presents the m-ratio, peak temperature and few results are presented graphically (Fig. 12).

Lewis [18] observed that m-ratio for the combustion reaction for charcoal is about 0.24. The value of 0.24 is attributed to the carbon oxidation or coke combustion; value different from this indicates that different reactions are taking place. Fassihi, et. al., [19] has attributed values higher than 0.24 to the burned fuel in the combustion as hydrocarbon reaction. The trend of the both the HC and the m-ratio in consolidated formations indicates that the burned fuel in the HTO region may consist of a heavy

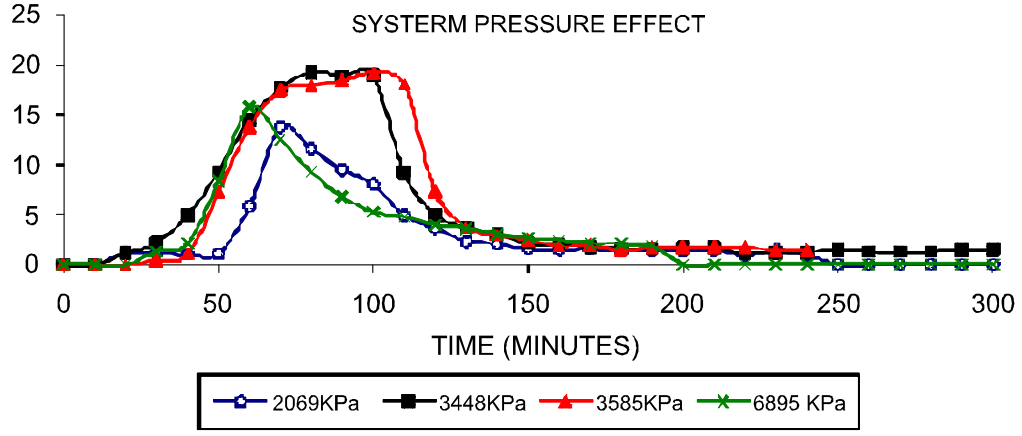


FIG. 10. OXYGEN CONSUMPTION WITH DIFFERENT SYSTEM PRESSURE VERSUS TIME FOR R-17,20,24 AND R-29

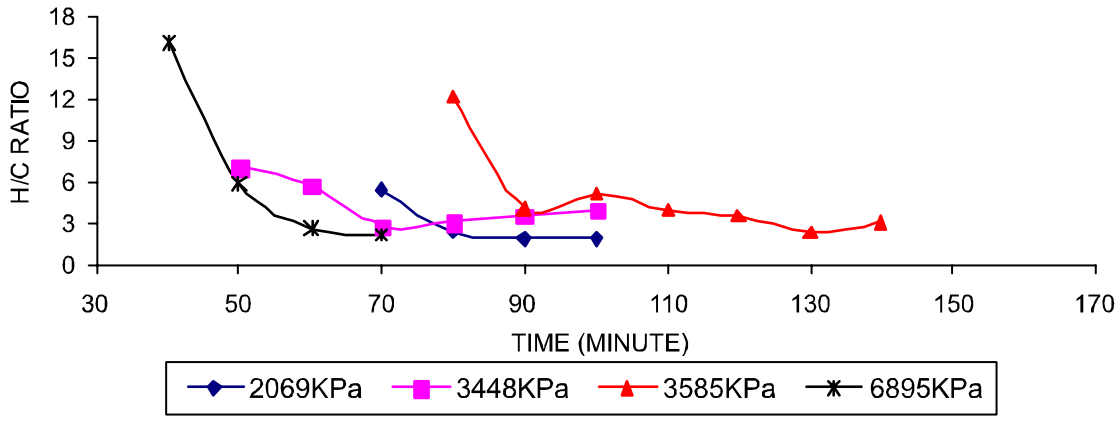


FIG. 11. APPARENT HC RATIO VERSUS TIME FOR DIFFERENT SYSTEM PRESSURES

residue plus coke in the temperature range considered. The decrease of the HC and m-ratio in unconsolidated formations suggests that the burning fuel in the HTO region is more likely coke.

5.6 Total System Pressure Effect

Arrhenius graphs were drawn by assuming (1.0, 0.5 and 2) order of reaction rate with concentration of carbon , which also confirmed that increased pressure (3446 KPa) has high activation energy of 59 KJ/mole than to the experiments conducted at lower pressure (2069 KPa), 35 KJ/mole for high temperature reaction zones. The possible argument for the high rate of products at low temperature could be that the light components are reacting with free oxygen available. To large quantity, producing higher amount of Carbon oxide, where as in high pressure of 6895 KPa the light components are suppressed. The low level of products in 6895 KPa experiment may be due to dilution effect, which is taking place by large number of moles present in the reactor on increased pressure. One can conclude that the distribution of the products are inadequate and does not behave like ideal. This non-ideal behavior of the reactor could be attributed to the mixing of the reactor. This is in depth investigation of the effect of pressure on this process was conducted using 36°API oil.

6. KINETIC PARAMETERS

As mentioned earlier Arrhenius method for the analysis of kinetic data were used for considering the relative reaction rate of carbon burned in terms of carbon oxides produced effluent gas. As the reactant is the crude oil, or its residue, whatever the composition, the resultant kinetic parameters are only accounted for over a limited temperature range. Fig. 13 shows the effect of system pressure for air 21% O_2. The plots did not behave as expected. The high pressure line should lie above the low pressure line, where as no such trend was observed. This phenomenon is not completely under stood. But up to the pressure of 3585 KPa low pressure line lies above the high pressure line. Similar curves were drawn for 21% O_2 concentrations in inlet gas and the same mixed plots were obtained for fuel deposition and LTO reactions as presented in Figs. 14-15 respectively. The kinetic parameters were calculated for each run at different depth of combustion cell. Table 2 presents the kinetic data evaluated using Arrhenius method by considering the order of reaction with respect to fuel n is equal to (1.0, 0.5 and 2.0). The kinetic parameters for various runs at different pressures show that the calculated activation energies are similar but not in complete agreement. Again, the discrepancy appears to be an artifact of the data analysis procedure by which the temperature

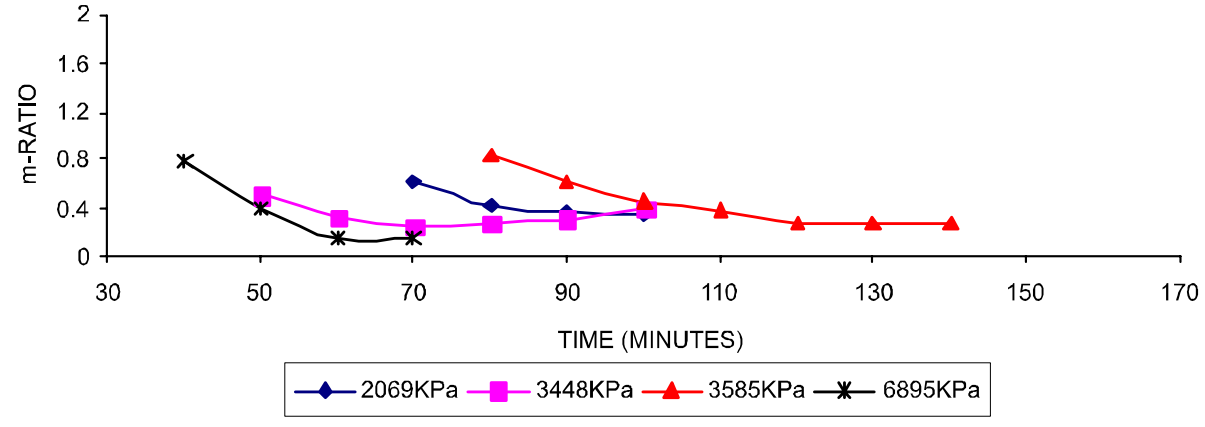


FIG. 12. M- RATIO VERSUS TIME FOR DIFFERENT SYSTEM PRESSURE

ranges were decoupled. Irrespective of small differences in activation energies these have been plotted against the total pressure and for better observation, these values were linearized.

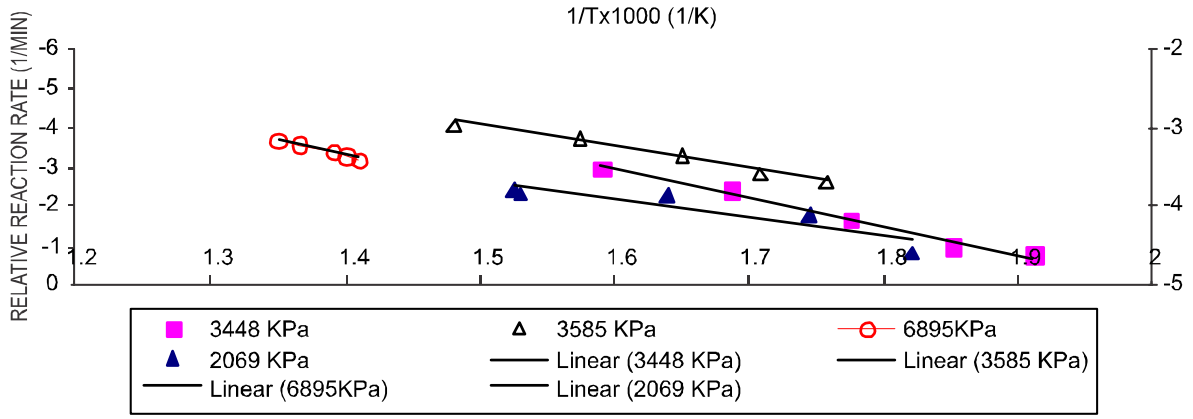


FIG. 13. ARRHENIUS PLOT FOR FUEL COMBUSTION REACTION WITH DIFFERENT SYSTEM PRESSURE

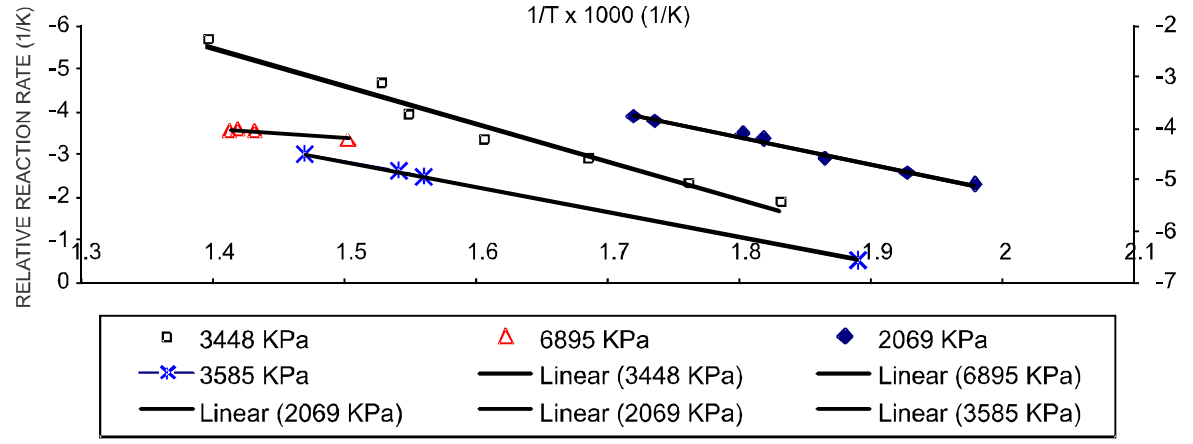


FIG. 14. ARRHENIUS PLOT FOR FUEL DEPOSITION REACTION AT DIFFERENT SYSTEM PRESSURE

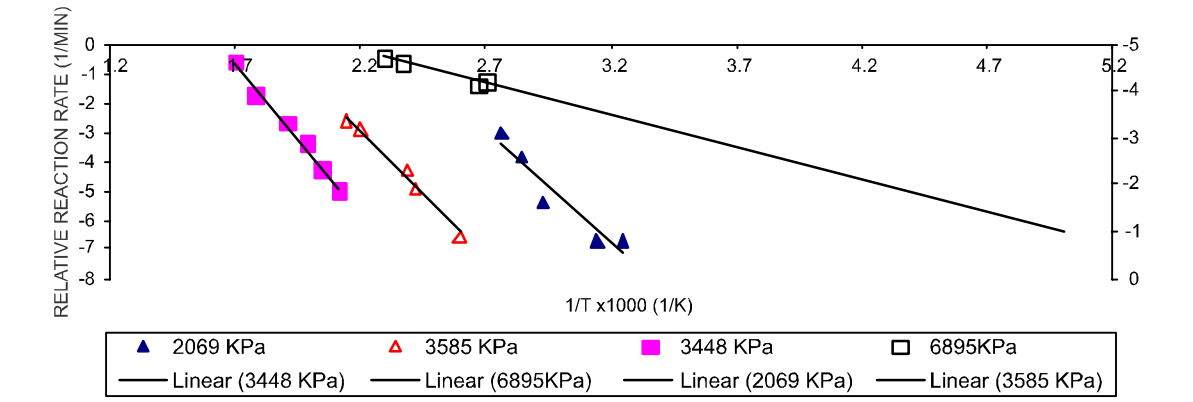


FIG. 15. ARRHENIUS PLOT FOR LTO REACTION WITH DIFFERENT SYSTEM PRESSURES

7. REPEATABILITY AND ACCURACY OF RESULTS

All runs were repeatable using the same fuel in repeated runs. The run results are not reported in this paper due to the similar results. The same procedure was followed in matching the other results and the repeatability of the test was confirmed. To verify that the activation energies and the reaction orders derived from the analysis were reasonable. The amount of oxygen consumed in the three reactions was supper imposed upon one another and the results were compared to the experimental oxygen consumption curves. The match was good for these and other similar data. To integrate the area under the oxygen consumption curve trapezoidal rule was used. This induced some errors when there was a sharp change in gas composition. It also introduced some errors into the calculations of curve fitting and extrapolation of the reaction rates of lower temperatures. These calculations were particularly sensitive to the choice of the point at which the relative reaction rate curve would deviate from the straight line. Thus in all runs using the same fuel except few runs; the calculated activation energy (E) was not the same. Therefore to normalize the data, first the E, which was quite different from the average value, were not present in the graph. Then calculated values of the activation energy of the slope of straight line were drawn through experimental data points on the Arrhenius plot (Fig. 13 and 15). This was achieved by selecting an arbitrary data point at the mid range of the abscissa as the focal point. For a combustion reaction (Fig. 13), this point was about $1.5x10^{-3}k-1$. The corresponding points of deposition of fuel as presented in Fig. 14 and LTO kinetic reaction is shown in Fig. 15. Relative reaction rate versus inverse of temperature for fuel deposition and LTO are $1.6x10^{-3}$ and $2.3x10^{-3}k-1$, respectively.

8. CONCLUSIONS

(i) A new slim and short CC strategy was developed to assess the recovery potential by air injection into depleted light oil reservoirs of Sindh, Pakistan. All the experiments are performed with loose sand pack mixed with Light oil.

(ii) At high, medium and low temperature, ignition was observed and efficient combustion takes place in all reported runs. It was observed that flue gases were generated by oxidation reaction at different temperature. The average percentages of gases are as follows:

- Production of carbon dioxide is 10.2%.
- Production of carbon monoxide is 4.4% and balance is unreacted oxygen.
- Oxygen consumption varies from 65 97%.

(iii) It was observed that by increasing the pressure increased, the peak in temperature and decreased velocity in combustion zone were resulted.

(iv) Direct Arrhenius method was applied with respect to carbon concentration for evaluating order of reaction from 0.5, 1.0, 1.5 and 2. In loose rock formations, behavior of kinetic indicates moderate reactive depositiopn of fuel. Activation energy for fuel combustion, fuel deposition and LTO reactions varied from 21-59, 25-43, and 8-36 KJ/mole respectively.

(v) m-ratio (about 0.13) and hydrogen carbon ratio (about 1.92) were calculated at various temperature and pressure for this air injection process. The results obtained from the air injection equipment, indicate that the light oil is highly reactive at reservoir conditions for air injection process.

(vi) These first stage experiments are very positive indication of the potential viability of the air injection process in light oil fields.

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REFERENCES

[1] Kuhn, C.S., and Koch, R.L, " In-Situ Combustion Newest Method of Increasing Oil Recovery", Journal of Oil and Gas, Volume 92, August 10, 1953.

[2] Grant, B.F., and Szasz, S.F., “Development of an Underground Heat Wave for Oil Recovery", Transactions on AIME, Volume 201, No. 108, 1954.

[3] Nelson, T.W., and McNeil, J.S., "Thermal Methods Provide Three Ways to Improve Oil Recovery", Journal of Oil and Gas, Volume 86, January 19, 1959.

[4] Nelson, T.W., and McNeil, J.S., "How to Engineer an In -Situ Combustion Project", Journal of Oil and Gas, Volume 58, June 5, 1961.

[5] Greaves, M., Ren, S.R., Rathbone, R.R., Fishlock, T., and Ireland, R., "Improved Residual Light Oil Recovery by Air Injection (LTO Process)", 49th Annual Technical Meeting, Volume 39, No. 1, Calgary, Alberta., Canada, January, 2000.

[6] Moore, R.G., "New Strategies for In-Situ combustion", Journal of Canadian Petroleum Technology, Volume 32, No. 10, 1993.

[7] Yannimaras, D.V., and Tiffin, D.L., "Screening of Oils for In-Situ Combustion at Reservoir Conditions by Accelerating-Rate calorimeter", SPE Reservoir Engineering, Volume 10, pp. 36, February, 1995.

[8] Greaves, M., Benther, A.H., and Rathbone, R.R., "Air Injection into Light Oil Reservoirs-Oxidation Kinetics and Simulation", European Symposium on Improved Oil Recovery, Budapest, April, 2005.

[9] Stoka, S., Rogaland, R.F., and Oesthus, A., "Evaluation of Air Injection as an IOR Method for The Giant Ekofish Chalk Field", SPE International IOR Conference in Asia Pacific, Kuala Lumpur, Malaysia, December, 2005.

[10] Kumar, V.K., Gutierrez, D., Moore, R.G., and Mehta, S.A., "Air Injection and Water Flooded Performance Comparison of Two Adjacent Units in Buffalo Field: Technical Analysis", SPE Paper/DOE Symposium on IOR, Tulsa, Oklahoma, USA, April, 2006.

[11] Greaves, M., Ren, S.R., and Rathbone, R.R., "Air Injection Technique (LTO Process) for IOR from Light Oil Reservoirs: Oxidation Rate and Displacement Studies", SPE Paper/DOE IOR Symposium, Tulsa, Oklahoma, USA, April, 1998.

[12] Greaves, M., Ren, S.R., and Xia, T.X., "New Air Injection Technology for IOR Operations in Light and Heavy Oil Reservoirs", SPE Paper on Improved Oil Recovery, Kuala Lumpur, Malaysia, October, 1999.

[13] Tunio, A.H., "To Investigate the Use of Air Injection to Improve Oil Recovery from Light Oil Reservoirs", Ph.D. Thesis, Institute of Petroleum & Natural Gas Engineering, Mehran University of Engineering & Technology, Jamshoro, Pakistan, March, 2008.

[14] Kazi, R.A., "A High Pressure Kinetic study of the In-Situ Combustion Process for Oil Recovery", Ph.D. Thesis, University of Salford, 1995.

[15] Abu-Khamsin, William, E.B., and Ramey, "Reaction Kinetics of Fuel Formation for In-Situ Combustion", Society of Petroleum Engineering Reserviors, pp. 1308-1316, November, 1988.

[16] Dabbous, M.K., and Fulton, P.F., "Low Temperature Oxidation Reaction Kinetics and Effects of the In-Situ Combustion Process", Society of Petroleum Engineering Reserviors, pp. 253-262, June, 1974.

[17] Ramey, H.J., Jr., "In-Situ Combustion" Proceedings of the 8th World Petroleum Congress, pp. 253-262, Moscow, 1971.

[18] Lewis, W.K., Gilliland, E.R., and Pakston, R.R., "Low Temperature Oxidation of Carbon", Industrial and Engineering Chemical, Volume 46. No. 2, pp. 1327-1331, 1954.

[19] Fassihi, M.R., and Brigham, W.E., "Analysis of Fuel Oxidation in In-Situ Combustion Oil recovery", Topical Report, Stanford University Petroleum Research Institute Stanford, California. August, 1982