INVESTIGATION OF AIR INJECTION TO ENHANCED OIL RECOVERY FROM MEDIUM OIL RESERVOIR OF UPPER INDUS BASIN OF PAKISTAN

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Abstract

Previously, air injection is exclusively used in light oil reservoirs; however, laboratory research has shown that air injection can also be very efficient for medium and heavy oil recovery. Due to the low cost of air injection and its indefinite availability, it has an economic advantage over other Enhanced Oil Recovery methods. This study is carried out in an experiment conducted on air injection into medium oil reservoirs. To better understand the air injection procedure for enhancing oil recovery from the X field's medium oil (26.12 °API) of Pakistan reservoir, 14 runs were performed.

The effects of air flux, porous media, temperature, and pressure on oxidation reaction rates were explored and measured. The consumption of oxygen at a rate of 90% was determined. At a moderate pressure of 7300 kPa, a significant oil recovery of around 81% of the original oil in place was observed. Increased air flux and low permeability can have a more significant effect on medium oil recovery.

The technique produced flue gases that were exceptionally low in carbon oxides, with a typical gas composition of 12% CO_2, 6% CO, and unreacted oxygen.
This research will contribute to a better knowledge of the air injection method and allow for the optimum performance for a specified reservoir. In the Enhanced oil recovery, a less costly process using this method will be inspiring due to recovering oil in this region.

Keywords: Air injection, medium oil reservoir, oxygen consumption, flue gases, Enhanced Oil Recovery

1. Introduction

Among EOR (enhanced oil recovery) methods air injection is considered one of the method that has huge potential [1]. Air injection has been only narrowly tested in the form of tertiary fire flooding in the past into light oil reservoirs [2]. Due to complex reaction mechanisms among rock, oil and air, air injection process is different than conventional EOR methods. In recent years due to the potential oil recovery and oxidation reaction, air injection gained more and more attention [3]. Significant amount of heat could be generated during the air injection process, due to which in-situ temperature increases. More oxidation reactions will come into play because of the increment in the temperature. Reservoir pressure is not only maintained during high pressure air injection, but also oxygen contained in the air reacts with crude oil [4]. During the oxidation process, three different reaction regions are identified, known as fuel deposition (FD), high temperature oxidation (HTO) and low temperature oxidation (LTO) [5]. If the combustion temperature is lower than 300 °C, the reactions between hydrocarbons and the injected oxygen produce oxidized hydrocarbons (ketones, alcohols, aldehydes, carboxylic acids peroxides, etc.), referred to as low temperature oxidation (LTO). On the other hand, it is termed high temperature oxidation (HTO), if air injection into the reservoir results in a propagating combustion front process with a temperature higher than 350 °C, where the primary products of oxidation processes are CO, H_2O, and CO_2 [6].
Crude oil oxidation reactions results in thermal drive and flue-gas sweep, and in-situ generated CO_2 has the potential for interfacial tension (IFT) reduction [7]. The generated flue gases and thermal effects provide the main driving mechanism for oil production [8]. Gas flood approach with a contribution of combustion front can enhance the recovery during air injection [9]. The resulting flue-gas mixture, which may be completely miscible or partly immiscible or immiscible consists primarily of carbon monoxide, carbon dioxide and any injected nitrogen. Theses flue gases primarily mobilizing the reservoir oil toward the production wells. Furthermore, in situ combustion yields steam from formation water and the reactions themselves [10]. As an effective, improved oil recovery process air injection in light oil reservoirs has received considerable attention
The influences of injected air under certain injection pressure interval is the main purpose of this work on medium oil nature properties on reservoir conditions and ultimately evaluates the feasibility of high pressure air injection (HPAI) method on medium oil reservoir of X field of Pakistan. This work is performed on medium oil reservoir with API gravity of 26.5° by doing series of experiments on air injection process. In this study the effects different parameters are studied, such as sand pack, system pressure, flow rate and temperature.

2. Method

2.1 Experimental Method

The study method is based on a physical model developed at Mehran University's Institute of Petroleum and Natural Gas Laboratory. A combustion cell is utilized in the physical model to inject air into depleted medium oil reservoirs sampled from Pakistan's X field. A gas chromatograph, high-pressure combustion cell, PID temperature processor controller, digital temperature indicator, high-pressure air cylinder, product separation, thermocouples regulator, recording equipment, and flow system are standard components of the experimental apparatus. Figure 1 depicts the air injection device with all of the necessary accessories for data collecting and calculation. The reactor has a flange at the bottom of the reactor and a 316 stainless steel autoclave with a firm wall. A reactor with an outer diameter of 8.255 cm, an inner diameter of 5.812 cm, a length of 35.61 cm, and a width of 1.31 cm, which clamps the combustion cell, is placed in the autoclave for pressure of 20685 KPa and a temperature range of 600 to 700 °C.

2.2 Procedure

To make air injection research on medium oil reservoirs easier, we implemented numerous significant adjustments.

1. By manipulating the cylinder valve, compressed air was provided by a high-pressure (13652 KPa) cylinder.
2. The injected air flow rate is controlled by a flow control regulator/needle valve positioned at the reactor's inlet.
3. The inlet gas stream from the reactor's top section (vertically) allows flue gases from the bottom.
4. A pressure regulator for a high-pressure separator is installed to control the pressure at the reactor's discharge.
5. Effluent gases flow through the scrubber at the regulator's outlet, to the sample collection point, and the low-pressure separator.
6. Increase the autoclave temperature and simulate reservoir temperature and ignition; a one-kilowatt electric heater/ignitor was enclosed around the upper part of the reactor.
7. To eliminate water vapours contained in the effluent gas stream, air at a pressure of 2069 to 4827 KPa is pushed via a combustion cell, dryer, low-pressure separator, high-pressure separator, scrubber, and silica gel-filled glass tubes.
8. After 30 minutes, the required pressure had been stabilized and maintained. For the duration of the experiments, the reactor was heated at a rate of 5 °C/min and kept at 500 °C.
9. The ignition was monitored using the temperature recorder's change in slope on the temperature versus time graph. The required airflow was set up through the pack, while thermocouples were inserted at varying depths of the combustion cell to gauge the temperature at the sand face.
10. Analyses of exhaust gases (CO_2, O_2, CO, and N_2) were evaluated as a function of duration at 10-minute intervals throughout the length of each oxidation cycle. Using a gas-tight syringe, collect exhaust gas samples of 1 ml downstream of the metering without interrupting the flow.

11. Hydrocarbon recovery from the high-pressure and low-pressure separators was monitored at the completion of each cycle.

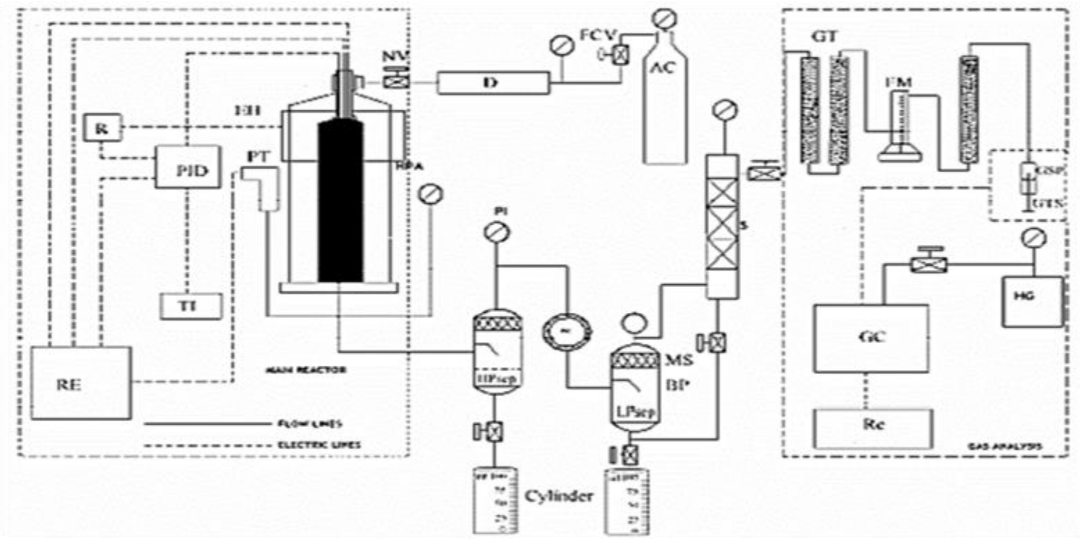

Fig. 1. Air injection experimental systems

2.3 Experimental work preparation

The majority of the studies were carried out with a mixture of sand and oil. Comparable sizes of sand were combined methodically and positioned in a combustion cell with the required amount of reservoir medium oil. The filled tube was subjected to a constant amount of pressure. The sand pack's components were blended in pre-determined proportions to simulate reservoir conditions. Table 1 shows the parameters of the combustion cell with oil and sand pack.

Tab. 1. Medium crude oil and sand pack properties in combustion cell

Oil Properties	Values	Combustion cell and sand pack properties	
API Gravity	26.165	Combustion cell length	25.4 cm
Specific Gravity	0.8976	Radius of the combustion cell	1.5875 cm
Viscosity	12.458	Bulk volume of a combustion cell	201 cm^3
Water Content	0.31%	Sand pack length	24.1 cm
Sulphur	1.072%	The sand in the cell's weight	200 gms
Sludge	0.21%	Weight of oil in the cell,	78.56 gms
Pour point	<-18 C		

2.4 Standardization of ALLTECH DUAL concentration Section

Dual concentric columns with an inner dia. (6 feet in length x 1/8 inch) tube with a porous polymer blend and an outer diameter (6 feet long x. inch) filled with operated filter medium were used to analyse carbon dioxide, carbon monoxide, oxygen, nitrogen, and methane gases. The CTR1 column was calibrated using the suggested calibration gases mixture. This column helps in the analysis of combustion flue gases.

3. Results and discussions

Based on the effluent gas information achieved, Different experiments performed, the examinations were conducted. Several runs were conducted to get valid kinetic data for recovering medium oil from the complete in-situ combustion. For a total of 14 runs, this series employed an unconsolidated core (sand pack) of varied mesh sizes saturated with medium oil. Different experiments of rock formation / sand matrix, System pressure, oxidation temperature/ heat and flow rate (Air flux) input parameters that were analysed. A study of the input oxygen and existing gases, oxygen and carbon oxides, was used to determine the effect of each parameter on oxygen conversion. In the reactor, a combustion cell filled with sand pack impregnated with medium oil was placed. In non-isothermal tests, the temperature ramped oxidation (RTO) was used at a rate of °5 C/min from ambient temperature to 500 °C. All the experiments were conducted on constant flow rate of 100 mL/min and the injected air containing 21% Oxygen and 79% Nitrogen.

3.1 Effect of air flux

To find out the oxidation effect on medium crude oil three distinct air fluxes are used of 7.65, 11.391 and 15.20 Sm^3/m^2-hr. At a ramped temperature of 5° C different runs were conducted at a constant pressure of 9400 KPa on unconsolidated core sample. Table 2 shows the main findings from these experiments. It was found that when the air flux was increased from 7.65 to 15.20 Sm^3/m^2-hr, the maximum oxygen consumption occurred. Furthermore, we notified that at air fluxes ranging from 7.65 to 11.391 Sm3/m2-hr, O_2 consumption was slightly lower than at higher fluxes. Figure 2 shows the results of oxygen utilization, CO and CO_2 production with various air fluxes. Over the temperature under examination increment lead to higher rates of oxygen consumption, as a result the burn rate of carbon increased. Oil production rate is affected by the rise of cumulative carbon burned. It is also found that when air flux increases, distillation decreases and less fuel is deposited; yet, greater flux tends to result in less oil displacement from the bed and more carbon being consumed. This tendency might be explained by the fact that less distillation occurs at low air flux, resulting in medium residual oil for cracking. The lower values of fuel deposition are attributed to low air flux, and when air flux increases in areas with high carbon concentrations, the carbon-burning rate increases [11]. Fig. 3 depicts the cumulative oil production under various air fluxes.

Tab. 2. Results obtained by the influence of air flux

Parameters	Run-1	Run-2	Run-3
Duration of the runs , Min.	211	211	211
Cumulative Oil Production, mL	46.12	52.15	53.19
Final Recovery of oil, (% original oil in place)	66	74.4	75.45
Front Peak Temperature of Combustion, °C	375	368	355
Maximum CO_2 production, Mol. %	5.41	5.4784	6.2857
Maximum CO Concentration Produced , Mol. %	2.7989	2.7351	2.9318
Maximum O_2 Concentration Produced , Mol. %	16.2321	16.8943	17.3463
O_2 consumption, %	77.29	80.51	82.59

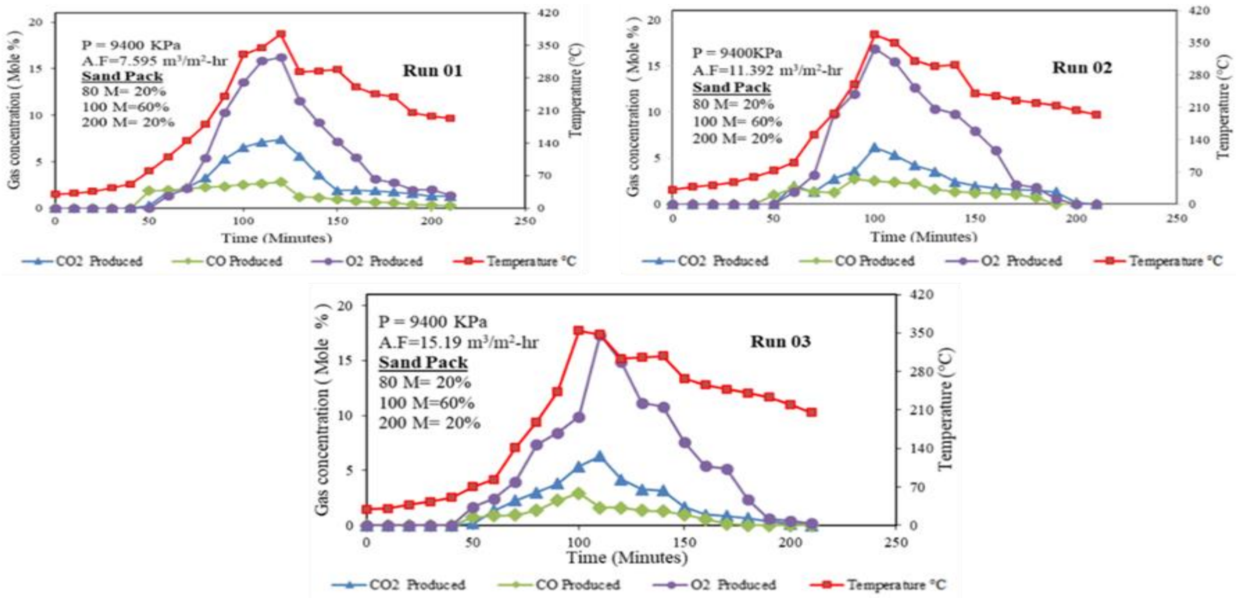

Fig. 2. Temperature and gas composition vs. time at different air fluxes of 7.65, 11.392 and 15.595 Sm^3/m^2-hr

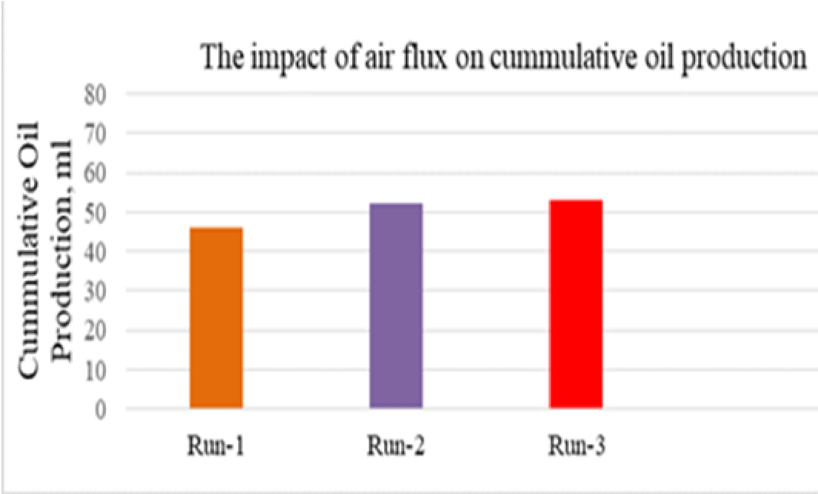

Fig. 3. Cumulative oil production with various air fluxes

3.2 The influence of temperature/heat input

These three runs used one, two, and three heaters, respectively. The number of heaters increased from one to three, enhanced the reaction rate. As illustrated in Table 3 a run with one heater on the reactor's top resulted in 62.57 % oxygen uptake. The addition of a second heater allowed for a second run. Using two heaters to maintain the reservoir condition for the 2nd part by enclosing 1⁄2 of the reactor resulted in oxygen consumption of 77.69 %. The maximum 83.52 percent oxygen consumption was measured for covering the entire length of the reactor to maintain the reservoir state. Figure 4 shows the oxygen utilization, CO and CO_2 production with one, two and three heaters installed. Figure 5 depicts cumulative oil production at various heat inputs. Installing three heaters results in the maximum original oil in place (OOIP) recovery of 78.75 %.

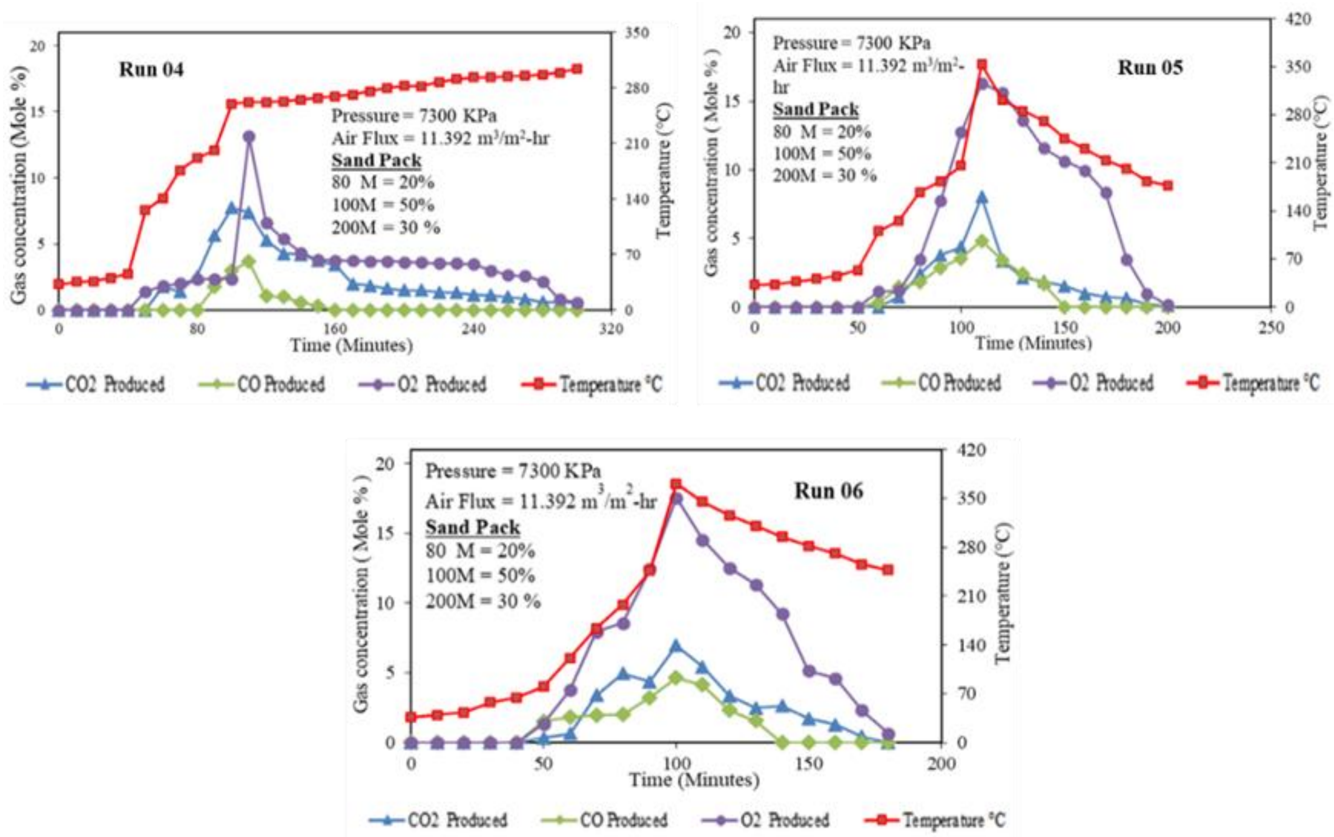

Fig. 4. Temperature and gas composition vs. time by installing one, two and three heaters

Tab. 3. Results obtained by the influence of system temperature

Parameters	Run-4	Run-5	Run-6
Heaters used	one	two	three
Duration of the run , Min.	321	211	182
Cumulative Oil Production, mL	53.40	52.49	55.21
Final recovery of Oil, (% original oil in place)	76.25	74.9	79.1
Peak Temperature of Combustion, °C	258.9	352.89	369.98
Maximum CO_2 Produced, Mol. %	7.69	8.041	6.891
Maximum CO Produced , Mol. %	3.591	4.7912	4.5812
Maximum O_2 Produced , Mol. %	13.21	16.293	17.498
Oxygen consumption, %	62.57	77.69	83.52

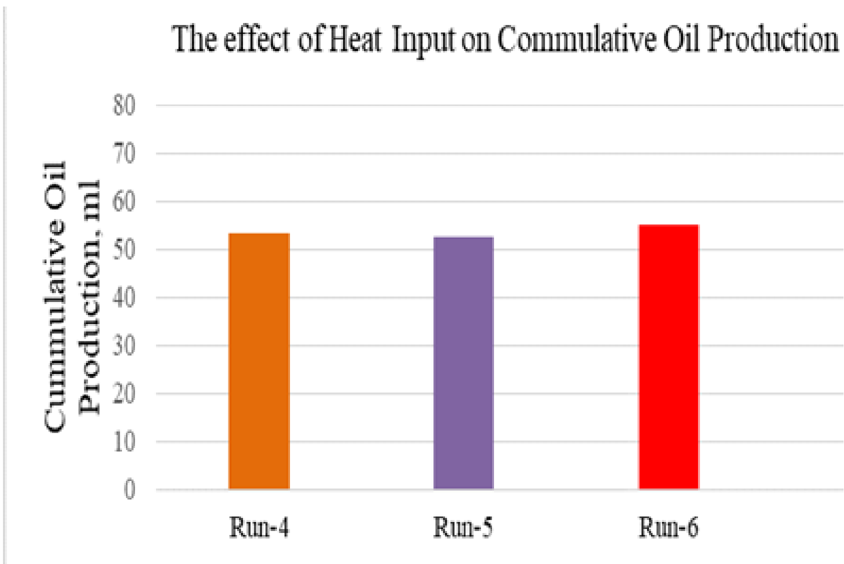

Fig. 5. Oil production with varied heat additions

3.3 The influence of porous media

Gas analysis profiles and oxygen consumption rates (the oxidation and combustion reactions) were determined for different rock formations. Medium oil behaved as expected in an unconsolidated rock formation with low permeability, consuming only a small amount of oxygen. The oxygen consumption and CO, CO_2 production of several sand packs is plotted against time for a better understanding as shown in Fig. 6. The occurrence of medium temperature oxidation (MTO) reactions was linked to the increasing bed thickness in these experiments. The ability to decrease the mesh sizes of low permeability sand particles increased the ease with which oxygen could reach the oil, promoting Medium Temperature Oxidation reactions. The oil displacement from across the dried portion of the reservoir, which enhances the convenience of oxygen availability to the residual oil and favours MTO, is attributed to MTO development. MTO provided more fuel to be burned, resulting in a higher rate of effluent gas production. The above effect was also attributed to the enlargement of the MTO peak.

According to the results, one of the critical causes of fuel deposition could be oil displacement and distillation. The interaction between medium and light components of oil and O_2 may be significant at low permeability, creating CO and CO_2. Because CO may be the primary source of CO_2, prolonged combustion time causes CO to react with O_2 species, resulting in CO_2. The higher CO levels might indicate a shortage of oxygen at the reactivity front, leading to incomplete combustion. The distillation activity may be insufficient at high pressure, resulting in more under-saturated hydrocarbon molecules reacting with oxygen. This indicates that the oxidation reaction is insufficient, owing to the low temperature and longer combustion duration. As a result, the lowest permeability produced the highest oil recovery of 76.27 %. High oxygen consumption, maximum CO_2 and CO generated were recorded with low permeability. Table 4 shows an overview of the main results for these runs. Fig. 7 shows the oil recovery at different sand packs.

Tab. 4. Results obtained by the influence of system sand pack

Parameters	Run-7	Run-8	Run-9	Run-10
Duration of the run , Min.	281	212	213	281
Cummulative oil production, mL	53.4	45.51	44.59	49.69
Final recovery of oil, (% original oil in place)	76.27	65.1	63.76	71.1
Front Peak Temperature of Combustion, °C	379	360	304	336
Maximum CO_2 Concentration Produced, Mol. %	7.21	4.69	4.59	6.40
Maximum CO Concentration Produced , Mol. %	5.41	1.94	5.32	4.13
Maximum O_2 Concentration Produced , Mol. %	17.60	7.47	7.32	12.60
O_2 consumption, %	83.59	35.45	34.79	59.88

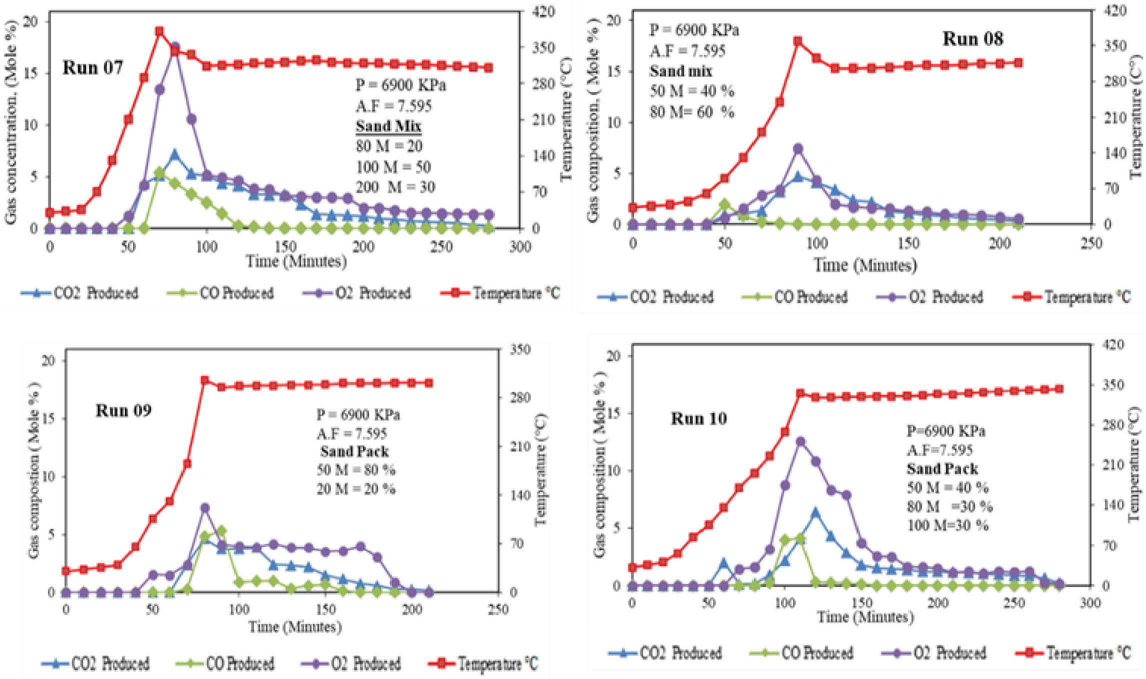

Fig. 6. Temperature and gas composition vs. time at different sand packs

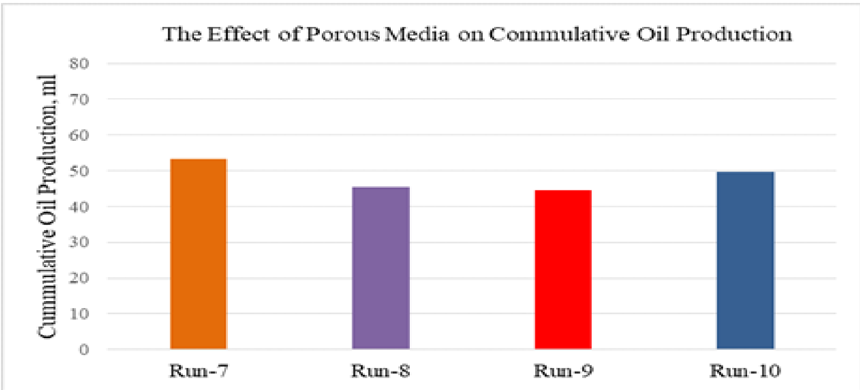

Fig. 7. Oil production with varied mesh sizes properties

3.4 Influence of system pressure

Tab. 5 shows the combustion cell results influenced by the system pressures. Figure 8 shows the oxygen utilization, CO and CO_2 production with various system pressures. The experiments based on different pressures observed that better oxygen consumption at medium pressures of 7300 and 8050. According to an analysis, in these runs done up to 9400 KPa, the CO generation appears to be too early. Carbon monoxide tends to generate a much faster rate than the time estimated for this sort of reaction. The higher proportion of by-products at medium temperature might explain the light and medium components reacting with a significant amount of free oxygen, resulting in more CO_2 and CO. In contrast, the medium components are suppressed at increased pressures of 9400 KPa. The low amount of products in the 9400 KPa run could be due to dilution caused by many moles present in the reactor at increased pressure. It has been established that the component separations are insufficient and not function properly. Oil recovery enhanced by approximately 23% when pressure increased from 6900 to 7300 KPa, but there was no substantial improvement at 9400 KPa, as illustrated in Fig. 9.

Tab. 5. Results obtained by the influence of system pressure

Parameters	Run-11	Run-12	Run-13	Run-14
Duration of the run , Min.	249	289	289	179
Cummulative Oil Production, mL	40.80	57.12	54.1	50.1
Final recovery of Oil, (% original oil in place)	58.31	81.60	77.20	71.41
Front Peak Temperature of Combustion, °C	311	366	378	341
Max. CO_2 Concentration Produced, Mol. %	5.01	5.41	8.41	4.72
Max. CO Concentration Produced , Mol. %	3.53	7.511	5.231	2.91
Max. O_2 Concentration Produced , Mol. %	12.631	18.81	18.12	13.91
O_2 consumption, %	59.76	89.19	86.13	65.91

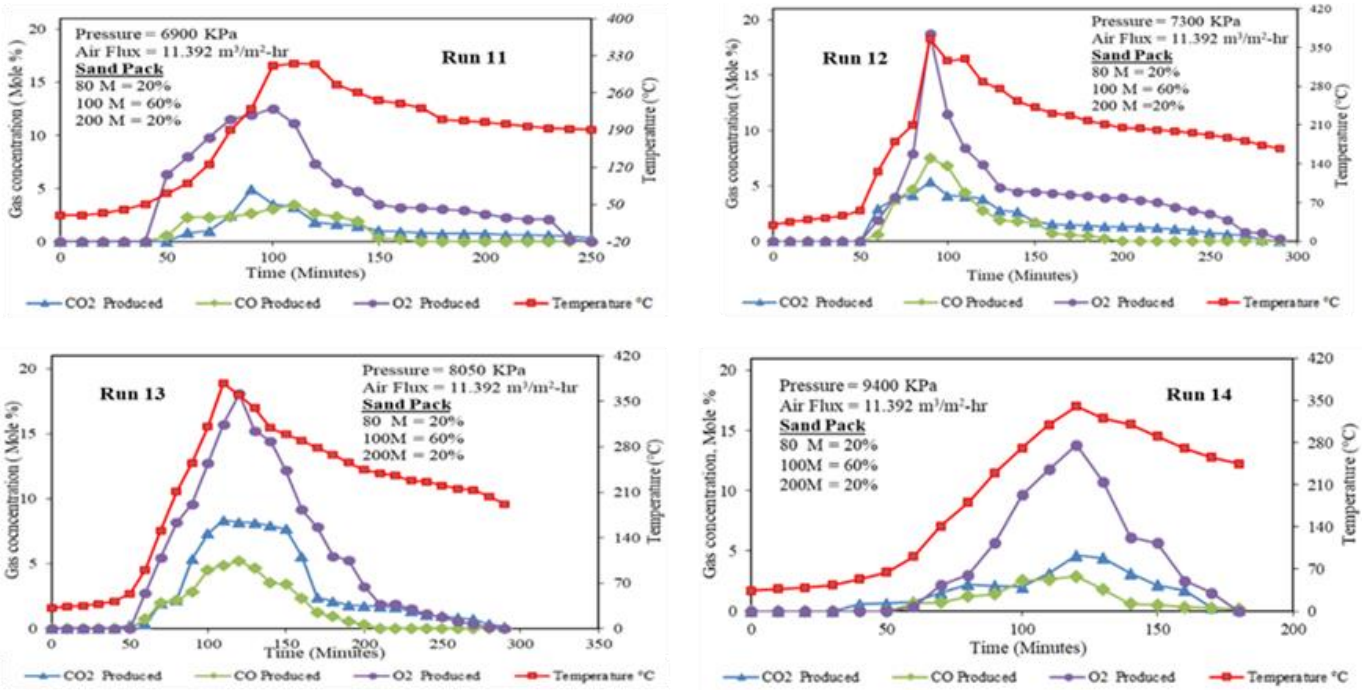

Fig. 8. Gas Composition and temperature vs. time at different pressures of 6900, 7300, 8050 and 9400 KPa

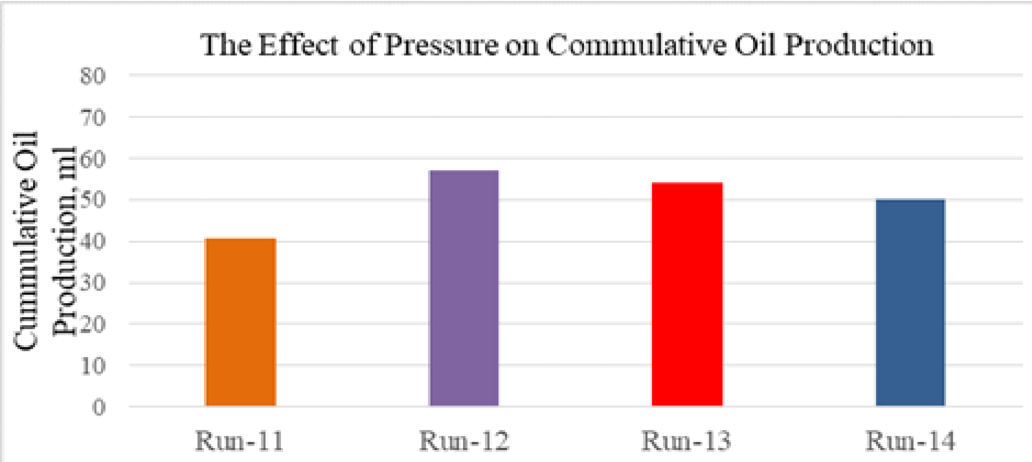

Fig. 9. Cumulative oil production at different pressures of 6900, 7300, 8050 and 9400 KPa

4. Conclusions

In Pakistan's X field, a combustion cell was designed to evaluate the efficiency of air injection into medium oil reservoirs. The reservoir medium oils and unconsolidated core are used in all of the thorough analyses (sand pack). With an average percentage of gas composition of 7% CO_2, 4% CO, and balanced unreacted oxygen, the production of combustion gases at high temperatures was quite effective in carbon oxides. The consumption of oxygen, as well as characteristic combustion parameters, were studied. The consumption of oxygen by about 90 percent was investigated using flue gas analysis.

A significant amount of oil was recovered, ranging from 65 to 81.5 %. It was discovered that increasing air flux and heat input increased oxygen consumption rate. We observed that entrapped hydrocarbons in porous media affect the sand pack mesh size, causing the medium temperature oxidation effect in the formation. The effect of three distinct air fluxes of 7.65, 11.391, and 15.20 Sm3/m2-hr on crude oil oxidation was investigated. Over the temperature range studied, increasing air flux resulted in somewhat higher rates of oxygen consumption. The heaters extended from one to three increased the rate of reaction. High oil recovery of medium oil was observed under medium pressure when compared to low and high pressure. At a pressure of 7300 KPa, the highest recovery of 81.5% of the original oil in place was observed.

5. Acknowledgment

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