A Laboratory-Scale Experimental Study of In-Situ Combustion Processes

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A laboratory-scale experimental study of in-situ combustion for enhanced oil recovery is presented. The effects of oil saturation, preheating of the oil-sand bed, porosity of sand, and air-injection rate on both the time history of liquid yield and the total liquid yield have been determined. From the measured temperature profiles and charred length of oil-sand bed, the propagation rate of combustion front has been deduced. The volumetric concentrations of CO_2 and O_2 in the effluent gas have been measured. The rate of liquid yield is highest in the initial periods of in-situ heating or combustion. Air-injection rate, although it has an indirect influence on the temperatures achieved in the bed, exerts only a weak effect on the liquid yield. The increase in porosity of sand increases the liquid yield rate. The relative effects of air injection rate, oil saturation, and the porosity of sand under combustion conditions are simulated well by preheating the bed.

Introduction

Oil production from fields using conventional recovery methods is estimated to be only 35 percent (Boberg, 1988). There are two major reasons why over half of the oil in place in an average reservoir is unrecoverable by regular methods. First, only a fraction of the reservoir can be contacted by the displacement fluid. Second, heavier oils are too viscous to move to the production wells at rates sufficient to justify an economic operation. To overcome one or more of these limitations, enhanced oil recovery processes are employed. In-situ combustion is one such process.

In-situ combustion methods are generally classified under "thermal recovery" methods, which include hot-water injection, steam injection, and hot-gas injection. In-situ combustion methods are subgrouped as forward dry combustion, forward wet combustion, and reverse combustion processes. These processes generally involve injection of an oxygen-containing gas (air, oxygen, or oxygen-enriched air), ignition within the reservoir, and propagation of a combustion front through the reservoir. In dry combustion methods, oil is displaced by hot gases produced by combustion. In wet combustion processes, water is injected simultaneously with air to aid in the thermal drive process. All in-situ combustion methods suffer from the drawback of economically unjustifiable low rates of oil production. The low heat capacity of gases, low heat transfer rates, partial quenching, nonuniform propagation of flame front, and a lack of a systematic data base on the interactive effects of parameters hamper the use of in-situ combustion for enhanced oil recovery.

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The literature consists of several case histories of actual field runs (Boberg, 1988). However, the lab-scale experimental studies to delineate the roles of experimental parameters are limited. Penberthy and Ramey (1966) have developed an analytical model of the movement of a burning front along an oil-saturated sand pack in a cylindrical pipe accounting for the heat loss through the annular insulation. Martin et al. (1958) have studied the effects of air injection rate and operating pressure on combustion front advance rate in an oil-saturated sand pack. Parrish and Craig (1969) conducted an experimental study of the combination of forward combustion and water flooding (COFACAW) through an oil-saturated sandstone. They found the air requirement in the combined combustion and water flooding through the rock was markedly lower than in the dry combustion process. Showalter (1963) studied the relationship between the API gravity and the amount of air required in a sand bed. Vossoughi and his associates (1981, 1982) have studied the effects of clay content in the sand bed on in-situ combustion processes using a tube apparatus. They have found that the catalytic activity of clay on combustion processes was insignificant and a large surface area per unit mass of sand bed favors the establishment of a strong combustion front. Mehta and Karim (1990, 1992) have studied the ignition and combustion processes in fractured oil-sand samples in a lab-scale apparatus. They have noted from temperature measurements that combustion was occurring within the fracture rather than in the core itself. Abu-Khamsin et al. (1988) have observed in an experiment simulating in-situ combustion that pyrolsis of crude oil in porous media goes through three overlapping stages: distillation, mild cracking, and severe cracking. They also noted that clay minerals showed a catalytic effect on cracking reactions. Urban and Udell (1990) reported that in wet in-situ combustion, steam affects the low-

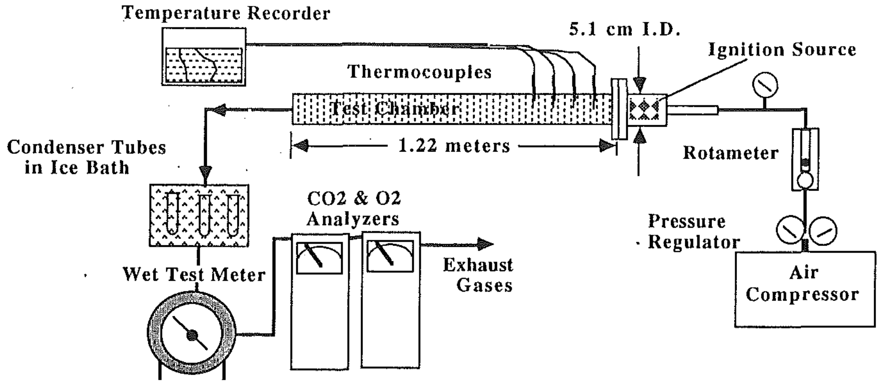

Fig. 1 Schematic diagram of the experimental apparatus

temperature oxidation and dramatically reduces the oxygen consumption, and attributed that observation to the participation of radicals in reactions.

A number of investigators (Coats, 1980; Vossoughi et al., 1982, 1985, 1989, 1990; Le Thiez and Lemonnier, 1990; Kumar, 1991) have developed numerical simulation models of in-situ combustion. All the models require some empirical inputs, such as kinetic data, a fluid mechanics model, and a heat loss model.

The aforementioned literature reveals that most of the lab-scale studies have been conducted to simulate the conditions of an actual field test. Many parameters are varied simultaneously, making the extraction of fundamental data on the individual effects of variables involved difficult. Also, the contribution of the combustion process per se on the oil yield rate is not isolated. This study focuses on experiments to resolve some of these issues.

Some key terms used in the subsequent discussions are defined as follows: sand porosity—the void volume as a percent of the total volume of the bed; bed saturation—the ratio of the oil volume in the bed to the volume required to completely fill the pores of the bed; liquid yield rate—the volume of oil collected from the bed; total liquid yield—the volume of oil collected until the time when the yield is not measurable (90 min in the experiments of this study).

Table 1 Experimental conditions

Inlet air pressure	125 kPa
Inlet air temperature	297 K
Outlet gas pressure	Ambient
Air injection flow rate per unit cross-sectional area of bed normal to flow	345, 652, 892 $m^3/(m^2h)$
Mass of sand	4.53 kg
Sand porosity (ϕ)	
Fine grade	27 percent
Coarse grade	33 percent
Sand size distribution Coarse grade	>500 μ........ 97 percent 500-420 μm.1.50 percent 420-297 μm.1.35 percent <150 μm ...0.15 percent
Fine grade	>500 μm ..... 26 percent 500-420 μm... 21 percent 420-297 μm... 40 percent <150 μm ..... 13 percent
Crude oil specific gravity	0.966 (15°API)
Oil saturation of bed (S)	10, 20, 30, 50 percent
Condenser temperature	273 K
Initial bed temperature	297, 327, 366, 411 K

Experimental Details

Apparatus. Figure 1 shows the schematic of the apparatus. A 5.1-cm i.d., 1.22-m long schedule 40 pipe capped at one end and flanged at the other end was used as the test chamber. The flanged end could be easily opened and closed with a quick disconnect system. Compressed air was supplied through the flanged end from an air compressor through a pressure regulator, and a calibrated rotameter. The efflux from the chamber was discharged through the capped end of the pipe. The efflux was first passed through a series of ice-chilled liquid traps (condenser) and a wet test meter. The amounts of water and liquid collected in the condenser were noted. The gas flow rate from the chamber efflux was measured by the wet test meter. A series of type K thermocouples were inserted radially into the chamber through sealed stainless steel tubes and compression fittings. The chamber was wrapped with 10-cm-thick fiberglass insulation. The chamber was heated during some experiments by wrapping it with two electrical heating tapes. The outside temperature of the chamber wall was measured by means of another set of type K thermocouples. The chamber was mounted horizontally on a metal stand. Three devices were tried to achieve the ignition of the oil-saturated sand: (*i*) an electrically heated wire, (*ii*) natural gas-air premixed flame formed at the exit of a 3.2-mm i.d. tube, and (*iii*) glowing charcoal briquettes. Since the third method produced a reliable ignition of the bed, it was employed for the study. To achieve reproducibility of results, in all experiments four briquettes of the same shape and size were used.

Details of Preparation of the Sand Bed and Achieving Its Ignition. First, the amount of oil required to saturate the sand was determined as follows: a known volume of sand (100 mL) was measured with a graduated cylinder. The oil was slowly added to the cylinder to displace the air in the pore volume between particles until the oil level was barely visible at the top surface of the sand bed, which was taken as the full saturation condition. The ratio of the volume of oil to the sand volume was later used in experiments to create the sand bed of required saturation. For each experimental run, a fresh oil-sand bed was prepared with the following procedure: a known volume, 2500 mL, of sand (with an approximate mass of 4 kg, depending on the sand grade) was mixed thoroughly in a pan with the required volume of oil to obtain the desired saturation. The sand was placed in the test chamber while slightly tilting it. In preheating experiments, the electrical heating coils were switched on until the desired bed temperature was recorded by a thermocouple. Tapping and continuously rotating the test chamber about its axis was necessary to minimize stratification of oil in the bed. No visual signs of coking were noticed while preheating the bed. The sand particle size distribution and the oil characteristics are included in Table 1.

Procedure. The experimental procedure consisted of the following steps: (*i*) preparation of the oil sand bed with the required degree of saturation; (*ii*) filling the chamber with the oil-sand mixture and preheating the chamber until the desired temperature was reached; (*iii*) starting combustion at the inlet

Table 2 Designators used to indicate experimental conditions

Designator 1	Sand grade	C = coarse F = fine
Designator 2	Initial oil saturation of the bed (percent)	
Designator 3	Air injection flux rate code	1: 9.58 mL/(s. cm^2) 2: 18.1 mL/(s. cm^2) 3: 24.8 mL/(s. cm^2)
Designator 4	Initial bed temperature (K)	

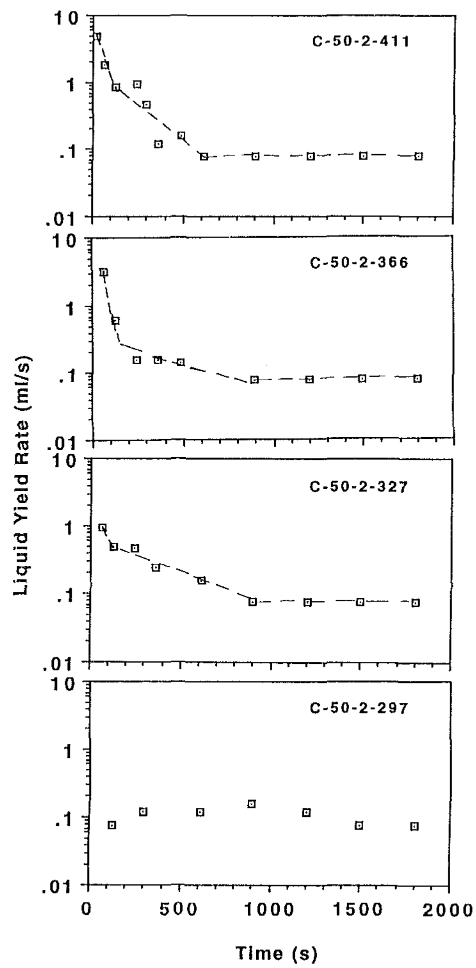

Fig. 2 Effect of the initial temperature of the bed on the time history of the liquid yield rate under noncombustion conditions (initial oil saturation = 50 percent; sand grade = coarse; air injection rate = 18.1 mL/(s.cm^2))

end of the pipe with the ignitor and sealing the flange of the chamber; (*iv*) starting air flow at the desired rate into the chamber; and (*v*) recording temperature readings from various thermocouples, the flow rate of inlet air, the flow rate of effluent gas, and the volumetric rate of collection of oil and water in the condensers. In nonburning ambient temperature experiments, preheating and ignition steps were omitted. In nonburning preheated sand-bed experiment, the ignition step was omitted. In some combustion experiments the exhaust gases were analyzed for the volumetric concentrations of O_2 and CO_2. Table 1 shows the experimental conditions and ranges of variables studied. Several experiments were conducted to determine the effects of sand grade, degree of saturation, air flow rate, and initial sand bed temperature. The classical experimental approach where one parameter was varied while keeping other parameters at fixed values was employed.

Table 2 gives the explanation of the abbreviations used to designate the experimental runs. Some experimental runs were repeated 3 times. The estimated uncertainties in the measurements of liquid yield rate, total liquid yield, and maximum temperatures, based on 95 percent confidence level, were 15, 5, and 2 percent, respectively.

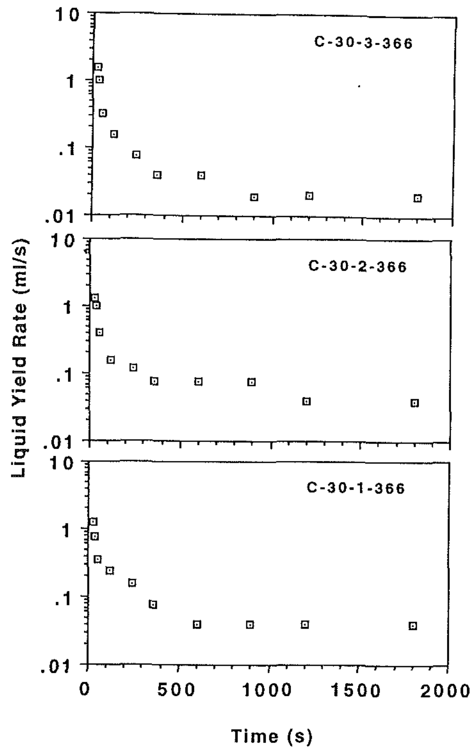

Fig. 3 Effect of air-injection rate on the time history of the liquid yield rate under noncombustion conditions (initial oil saturation = 30 percent; sand grade = coarse; initial bed temperature = 366 K)

Results and Discussion

Liquid Yield Rate. Figures 2–5 show the variation of liquid yield rate with time elapsed after the air flow through the sand bed was begun. All the results shown in these figures were obtained in experiments where combustion of the bed did not occur. It is noticed that in all runs, the liquid yield rate is maximum at the beginning of the experiment. In the initial period, the liquid yield rate falls steeply with time. In about 200 s the liquid yield rate drops to about 15 percent of the initial rate. After the first 200 s, the yield rate decreases gradually with time until 600 to 800 s have elapsed. Subsequently, the liquid yield rate varies asymptotically with time. For illustration, these three regions are shown by dotted lines with distinctly different slopes in the high-temperature experimental results of Fig. 2.

The effect of the initial temperature of the bed on time-history of liquid yield rate is shown in Fig. 2. The initial saturation of the bed, the bed porosity, and the air injection rate were maintained constant in this set of experiments. It is clear from the data in Fig. 2 that bed temperature affects only the liquid yield rate in the first and second stages. The effect of temperature is substantial in the first stage. The liquid yield rate in the third stage does not show a significant dependence on the initial bed temperature. At a temperature of 411 K, the liquid yield in the first minute was about 5 mL/s. At a temperature of 327 K, the liquid yield rate in the first minute drops to about 0.8 mL/s. At the ambient temperature, the liquid yield rate was negligibly small over the entire duration of the experiment. An increase in temperature of the bed can affect liquid yield rate in two ways: (*i*) the viscosity of liquid de-

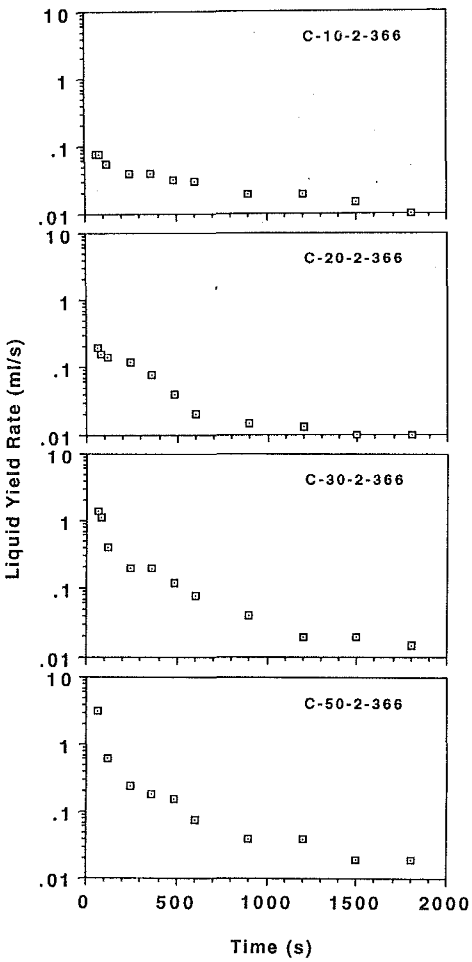

Fig. 4 Effect of initial oil saturation of the bed on the time history of the liquid yield rate under noncombustion conditions (sand grade = coarse; air injection rate = 18.1 mL/(s. cm^2); initial bed temperature = 366 K)

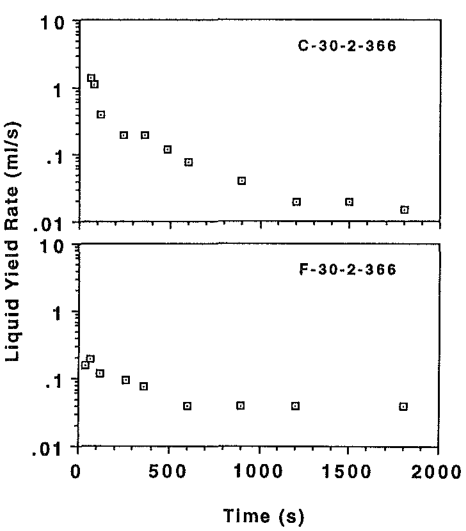

Fig. 5 Effect of sand grade on the time history of the liquid yield rate under noncombustion conditions (initial oil saturation = 30 percent; air injection rate = 18.1 mL/(s. cm^2); initial bed temperature = 366 K)

creases, and hence for a given pressure difference across the bed the liquid can flow faster; and (*ii*) some components of crude oil are evaporated and carried with the injected air and then converted back to liquid form in the condenser.

Figure 3 shows the effect of air injection rate on the liquid yield rate at an initial temperature of the bed equal to 366 K. The bed saturation and porosity were kept constant. It was observed that at a given bed temperature, the effect of air injection rate on liquid yield rate was much weaker than the effect of temperature. In the first stage, a higher air-injection rate produces somewhat higher liquid yield rate and the liquid yield continues for a longer duration. This slight increase is due to the increased driving force provided. Experiments were also conducted at the ambient temperature of the bed. For all flow rates, the liquid yield rate was negligibly small.

The effect of varying bed saturation on variation of liquid yield rate with time is shown in Fig. 4. Here, the bed saturation is defined as the volume of the liquid in the bed expressed as a percent of the volume of liquid needed to fill the pore volume. The sand bed porosity and air injection rate were kept constant in these experiments. The bed temperature was held at 366 K. It is noticed that higher saturations of the bed lead to higher yield rates as expected. When the bed saturation is decreased from 50 to 30 percent, the initial liquid yield rate decreases from 3 to 1.2 mL/s. For saturations of 20 percent and lower, the liquid yield rate was zero. At ambient temperatures, the liquid yield rate was negligible for saturations of 30 percent and lower. Even for a saturation of 50 percent, the liquid yield rate did not exceed 0.15 mL/s.

The effect of sand grade on the time history of liquid yield rate is shown in Fig. 5. The porosities for different sand grades are given in Table 1. The bed saturation, the air injection rate, and the initial temperature of the bed were held constant in this set of experiments. It is observed that the coarse sand bed gives the highest initial liquid yield rate for crude oil. The number of pores and the total pore area for a given cross section increases with the increase in fineness of sand. However, the size of individual pores decreases with the decrease in the sand particle size. These results suggest, for high-viscosity liquids, individual pore size dictated the liquid yield rate.

Total Liquid Yield. In the experiments where combustion of the bed was initiated, the liquid yield rates in the initial stages were too large to be accurately measured. Also, the transient conditions involved in the ignition process made the measurement of the liquid yield rate in the first stage not only difficult, but also unrepeatable. Hence, only the total liquid yield rates were determined in the combustion experiments. For consistency and comparison with combustion experiments, the results of the noncombustion experiments are also shown in terms of total liquid yield. Figure 6 shows the effect of different variables on the total liquid yield in nonburning tests. The results of tests in which combustion of the oil/sand bed was initiated are compared with the results of noncombustion tests in Fig. 7. In all these graphs, the total liquid yield corresponds to the amount of liquid collected in the condenser for a period of 90 min, which was much longer than the period for the flow rate to become negligible. The fraction of the original amount of oil in the bed that was recovered in this process is also marked in all graphs.

In Fig. 6, it is noticed that the total liquid yield rate increases with (*i*) the increase of bed temperature, (*ii*) the increase in air injection rate, (*iii*) the increase in saturation of the bed, and (*iv*) the increase in sand porosity. In Fig. 7, it is also noticed that both preheating the bed and combustion increase liquid yield. However, preheating seems to produce more liquid yield than combustion. The fact that some of the crude oil is vaporized and is burned in the combustion experiment accounts for this difference. It is noticed that this comparison is maintained even when the bed saturation, air-injection, and sand porosity are changed. It is clear that in-situ combustion results in an increase of liquid yield compared with ambient experiments. Experiments in which the bed is preheated can be conducted to simulate the effects of in-situ combustion to explore the relative effects of bed and fluid parameters.

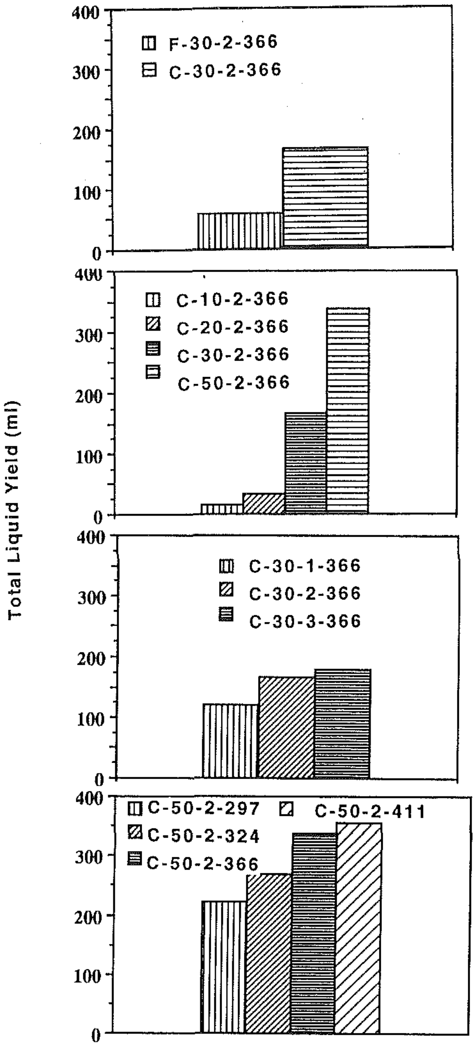

Fig. 6 Effect of the initial temperature, air injection rate, initial oil saturation, and sand grade of the bed on the total liquid yield under noncombustion conditions (conditions that were kept constant are indicated by the designators shown on each figure)

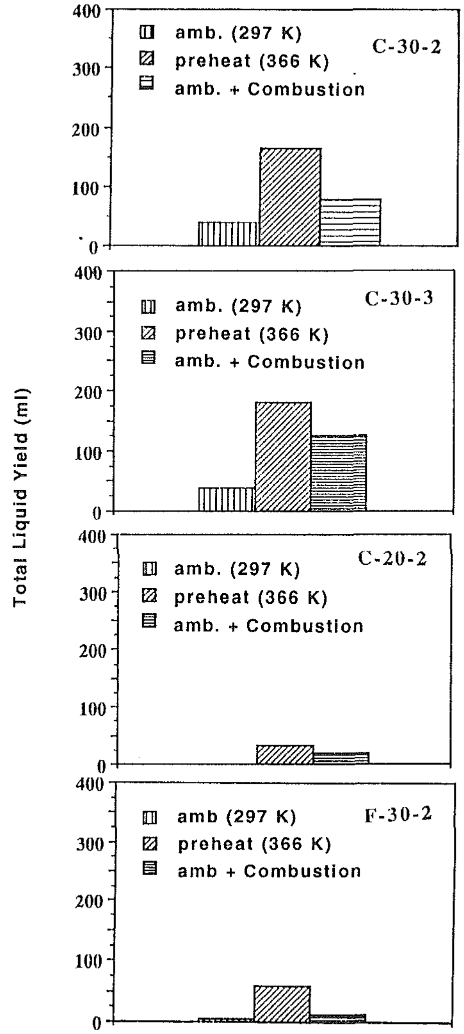

Fig. 7 Comparison of total liquid yield at nonheated, preheated, and combustion conditions (conditions that were kept constant are indicated by the designators shown on each figure)

Temperature Profiles. Figure 8 shows the temperature variation with elapsed time recorded by four thermocouples inserted in the bed. The hot junctions of thermocouples were located at the center of the tube. Four thermocouples were placed at 2.54-cm intervals starting from the ignition end of the bed. It is noticed temperatures at all locations increase gradually with time, and after a certain instant decrease gradually. The peak temperatures recorded were in the range of 673–873 K. These temperatures are in conformity with the values recorded in lab-scale experiments reported by Martin et al. (1958) and Wilson et al. (1963). The temperature at each location of the bed increases when the hot gases generated by the ignition source and burned oil pass through it. The increase continues until the flame front passes over the region where the thermocouple is located. When the combustion front has passed and injected ambient temperature air begins to arrive, the temperature at that location begins to decrease. From the time required for the peak temperature zone to travel between two thermocouples whose separation distance was known a priori, the rate of flame front propagation could be calculated.

Temperature profiles in this study exhibit single peaks in contrast to the double-peak structure found by Martin et al. (1958). The discrepancy between the two studies may be attributed to the difference in the air-injection rate procedure. In the study by Martin et al., the injection rate of air was first

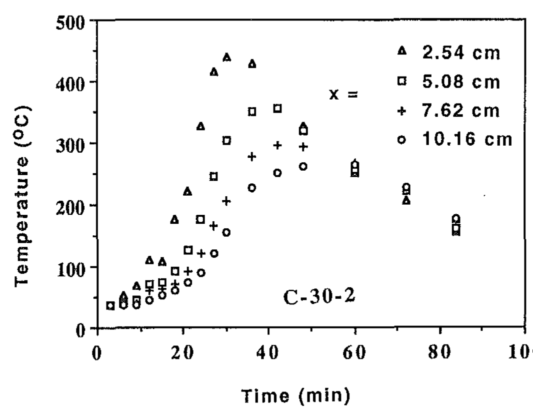

Fig. 8 Temperature-time profiles at different locations of the bed under combustion conditions (sand grade = coarse; initial oil saturation = 30 percent; air injection rate = 18.1 mL/(s. cm^2); initial bed temperature = 366 K)

maintained at a low value until the ignition source gains strength. During that period, the temperature at the downstream locations increased because of convection of hot gases from the ignition source. The air-injection rate was subsequently increased to cause the combustion front to propagate through the bed, causing a second peak in temperature profiles. In the present study, the air-injection rate maintained high enough excess to initiate the combustion front propagation from the beginning of the experimental run, and hence only single peaks are observed. To ensure that the temperature peaks were due to combustion front, experiments were performed with a dry sand bed and the same ignition source. The peak temperature values so obtained in the dry sand bed, which were only due to convective flow from the ignition source, were an order of magnitude smaller than the temperatures during oil-sand bed tests. The peak values of temperature and the trends of profiles are somewhat similar to those recorded by Mehta and Karim in oil-sand samples (1992).

From the temperature profiles shown in Fig. 8, it appears that, except between $x = 5.08$ and $x = 10.16$ cm (thermocouples 2 and 3), the flame propagated at approximately uniform rate. The nonuniform propagation could be caused by the uneven distribution of sand, saturation, and voids in the bed. Considering the combustion front propagation between thermocouple locations 1 and 2, and 3 and 4, the average rate of propagation of the combustion front was calculated to be about 14 cm per h (3.35 m per d). This value is in the range of measurements by Martin et al. (1958) and predictions of Wilson et al. (1963).

Char Front Propagation. A further confirmation of the occurrence of oil combustion in the sand bed was obtained by measuring the length of charring of sand from the ignition point at the end of each test. When the sand bed was examined after each combustion run, a portion of the bed close to the ignitor end appeared brown, similar to the original color of the sand particles. Subsequently, another part of the bed appeared as a solid material where the sand particles had adhered to one another and appeared black. The first part was a consequence of complete combustion as the bed was exposed to fresh injected air. The second part indicated an incomplete combustion, probably due to coking of the fuel and the flow of vitiated combustion products. The downstream edge of this charred part was fairly well defined. Although the value of char front propagation rate is not a reliable indication of combustion front propagation rate because of the uncertainties in charring characteristics of oil and the time over which it occurs, the measurement of char front nonetheless provides an indication of the attainment of liquid-phase pyrolysis at a given location of the bed. The measured char lengths were approximately 10.2 cm from the ignition end. Considering the time required for the attainment of peak temperature at the last thermocouple location, the char front propagation rate is about 12.7 cm per h (3.05 m per d).

Effluent Gas Composition. The volumetric concentrations of CO_2 and O_2 in the effluent gas were measured at different times, starting from the instant of ignition. The concentration of CO_2 varied from 7.4 percent at 600 s after the test was begun to 2.2 percent after 3000 s. The corresponding values of O_2 concentration were 12.5 and 17.4 percent. Probably the ignition source contributed to some part of the initial high concentration of CO_2 and low concentration of O_2. A comparison of these values with the measurements of Martin et al. (1958) indicate that the air injection rate in the present tests were such that combustion in the study of Martin et al. occurred under much higher O_2 deficient conditions.

Conclusions

This experimental study has shown that the bed temperature has the strongest effect on the rate of liquid yield and the total liquid yield from oil-sand beds. The rate of liquid yield is highest in the initial periods of in-situ heating or combustion methods of oil extraction. Air-injection rate, although having an indirect influence on the temperatures achieved in the bed, exerts only a weak effect on the liquid yield. The increase in porosity of sand increases the liquid yield rate. Laboratory-scale experiments in which the oil-sand bed is preheated can be employed to simulate the relative affects of air injection rate, oil saturation, and sand porosity.

Acknowledgments

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References

Abu-Khamsin, S. A., Brigham, W. E., and Ramey, Jr., H. J., 1988, "Reaction Kinetics of Fuel Formation for In-Situ Combustion," *Society of Petroleum Engineers Transactions*, Vol. 285, pp. 1308–1316.

Boberg, T. C., 1988, *Thermal Methods of Recovery*, John Wiley and Sons, New York, NY.

Coats, K. H., 1980, "In-Situ Combustion Model," *Society of Petroleum Engineers Journal*, Dec., Vol. 20, pp. 533–554.

Kumar, M., 1991, "A Cross-Sectional Simulation of West Heidelberg In-Situ Combustion Project," *Society of Petroleum Engineers Transactions*, Vol. 291, pp. 46–54.

Le Thiez, P. A., and Lemonnier, P. A., 1990, "An In-Situ Combustion Reservoir Simulator With a New Representation of Chemical Reactions," *Society of Petroleum Engineers Transactions*, Vol. 289, pp. 285–292.

Martin, W. L., Alexander, J. D., and Dew, J. N., 1958, "Process Variables in In-Situ Combustion," *Petroleum Transactions*, Vol. 213, pp. 28–35.

Mehta, S. A., and Karim, G. A., 1990, "High Pressure Ignition of Oil Sand Samples in Oxygen Atmospheres Containing Various Concentrations of Diluents," ASME Journal of Energy Resources Technology, Vol. 112, pp. 264–267.

Mehta, S., and Karim, G. A., 1992, "An Experimental Investigation of the Transport and Combustion Processes Within Fractured Oil Sand Beds," *Emerging Energy Technology Symposium*, ASME-Vol. PD-41, ed., S. R. Gollahalli, pp. 1–8.

Parrish, D. R., and Craig, Jr., F. F., 1969, "Laboratory Study of a Combination of Forward Combustion and Water Flooding—The COFCAW Process," *Journal of Petroleum Technology*, Vol. 21, June, pp. 753–761.

Penberthy, W. L., and Ramey, H. J., 1966, "Design and Operation of Laboratory Combustion Studies," *Society of Petroleum Engineers Journal*, June, Vol. 6, pp. 183–198.

Saim, S., and Vossoughi, S., 1989, "In-Situ Combustion Simulation Using TGA/DTG Experimental Curves," *Journal of Petroleum Science and Engineering*, Vol. 3, pp. 161–172.

Saim, S., and Vossoughi, S., 1990, "A TG/DTG Kinetic Model and Its Application in an In-Situ Combustion Reservoir Simulator," *Thermochimica Acta*, Vol. 166, pp. 219–230.

Showalter, W. E., 1963, "Combustion-Drive Tests," *Society of Petroleum Engineers Journal*, Mar., Vol. 3, pp. 53–58.

Urban, D. L., and Udell, K. S., 1990, "The Effects of Steam on the Combustion of Oil on Sand," *Society of Petroleum Engineers Transactions*, Vol. 289, pp. 170–176.

Vossoughi, S., and Willhite, G. P., 1981, "Effect of Clay on Crude Oil In-Situ Combustion Process," *Society of Petroleum Engineers*, Paper No. 10320.

Vossoughi, S., Bartlett, G. W., and Willhite, G. P., 1982, "Effect of Sand Grain Specific Surface Area on the Performance of the Tube In-Situ Combustion Process," *Society of Petroleum Engineers*, Paper No. 11072.

Vossoughi, S., Bartlett, G. W., and Willhite, G. P., 1982, "Development of a Kinetic Model for In-Situ Combustion and Prediction of the Process Variables Using TGA/DSC Techniques," *Society of Petroleum Engineers*, Paper No. 11073.

Vossughi, S., Bartlett, G. W., and Willhite, G. P., 1985, "Prediction of In-Situ Combustion Processes by Use of TGA/DSC Techniques and the Effect of Sand Grain Surface Area on the Process," *Society of Petroleum Engineers Journal*, Oct., Vol. 25, pp. 656–664.

Wilson, L. A., Reed, R. L., Reed, D. W., Clay, R. R., and Harrison, N. H., 1963, "Some Effects of Pressure on Forward and Reverse Combustion," *Society of Petroleum Engineers Journal*, Vol. 3, pp. 127–137.