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KINETICS OF UNDERGROUND
COMBUSTION

FINAL REPORT

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ABSTRACT

The University of Tulsa has been working on a contract with ERDA to study the kinetics of underground combustion. The purpose of the project was threefold - (1) to develop laboratory equipment and testing techniques for the study of reaction rates in forward underground combustion; (2) to perform enough tests to develop rate functions governing fuel laydown and fuel burnoff assuming an overall two-step chain reaction; and (3) to develop a realistic mathematical model of the forward combustion process based on these laboratory results that can be used to simulate petroleum reservoirs.

A high pressure fire flooding research facility has been assembled and tested in the laboratory of ~~the University of Tulsa~~. The main equipment was a gift from Sun Oil Research (Dallas). Since this apparatus was obtained after the initiation of the contract, original plans have been modified and a good deal of time and effort ~~was~~ spent getting the unit operational. Minor modifications have been made on the unit and several shake-down runs made. ^{The} Our next step will be to make the unit more versatile and with the capability of sampling fluid at any point inside the packed bed while combustion proceeds. This will provide data for the second phase - determination of rate data.

INTRODUCTION

The University of Tulsa has been working on a contract with ERDA to study the kinetics of underground combustion. The purpose of the project was threefold - (1) to develop laboratory equipment and testing techniques for the study of reaction rates in forward underground combustion; (2) to perform enough tests to develop rate functions governing fuel laydown and fuel burnoff assuming an overall two-step chain reaction; and (3) to develop a realistic mathematical model of the forward combustion process based on these laboratory results that can be used to simulate petroleum reservoirs.

The first of the three steps has been virtually accomplished with the acquisition of the in-situ combustion apparatus from Sun Oil Company and the subsequent installation in the petroleum engineering laboratory at the University of Tulsa. Based on preliminary test runs, only minor revisions in the equipment still remain before satisfactory data can be taken. Several test runs have been made to establish a standard operating procedure and an operating manual is being prepared for the use of future student operators.

APPARATUS

The laboratory equipment used for underground in-situ combustion is shown as a flow chart in Figure 1 with related pictures in Figures 2, 3 and 4. This equipment consists of four main components:

- A. The reactor assembly
- B. The flow control system
- C. The electronic control assembly
- D. The gas analysis system

To these one can add the supporting and auxiliary equipment.

A. The reactor assembly:

It consists of a high pressure jacket with a flange on each end. The jacket has a diameter of approximately 11 inches and an overall height of 50 inches. On the inside bottom flange 26 circular heaters are stacked and are individually connected to the electronic panel along with a thermocouple attached to the outside of each heater. The cylindrical void inside the stack is the location where the reactor tube is inserted through the top flange. The reactor tube has a thermocouple well running along the central axis through the entire length. When the tube is inside the reactor, thermocouples are inserted to the same level as the outside thermocouples. These are used to check

the temperature difference across the tube wall and maintain it to a minimum using the appropriate control on the heaters. On the upper part of the tube an electric igniter is installed and connected to a main switch through a power meter. The inlet fluids are injected at the top of the tube and the exit fluids come out at the bottom of the tube, go through a gas liquid separator (high pressure sight gage), then through a cooler and back to the flow control system. The annular space around the heaters is filled with insulation material and during the runs is pressurized with helium in order to maintain a minimum pressure drop across the tube wall. The inside thermocouples are connected to the electronic panel by lead wires going through the bottom part of the well. The jacket is equipped with two pipe connections for application or removal of helium pressure as needed.

B. The flow control system:

The flow control system is composed of several valves, regulators, gages, flow meters, air, nitrogen, helium cylinders. Each of these plays its own part in the relatively simple task of selecting, controlling or measuring the different flows and pressures of the injection and combustion fluids. Provision is made to direct different gases through or around scrubbers, thermal conductivity cells, oxygen analyzer and to the gas chromatograph. Two calibration gases are also provided. A small liquid pump with two tanks is connected to the system. They may be used for water injection.

Gages provide a visual means to check the pressure difference across the tube (inside tube pressure and jacket pressure) and the pressure drop across the sand pack (inlet versus outlet tube pressures).

C. The electronic control assembly:

An electronic cabinet contains most of the electronic devices that control and monitor the temperatures during the runs. Thirty voltage controllers (4 spares) are used to maintain equal temperatures across the reactor tube and are activated by the corresponding thermocouples in order to maintain an adiabatic system. Each controls a separate heater. The same cabinet houses the various switches (power supply, igniter) along with a digital voltmeter, a set of switches for manual operation of the heaters, a chassis for the TC cells, a clock chassis, a data printer and a switching chassis which scans all or selected thermocouples at preset time increments for print output.

D. The gas analysis system:

It consists of two calibration gas sources, a set of scrubbers with chemicals (drierite, MnO₂, Sodalime), three thermal conductivity cells (hydrocarbon, H₂S), and oxygen analyzer, different gas flow meters, and a gas chromatograph. Gases from the reactor can be directed through or around these components according to the desired analysis.

The auxiliary and supporting equipment consists of a vacuum pump, a high quality scale for material balance of the reactor tube, a calibration tube which contains thermocouples, several brackets for positioning and assembly of the sand pack, tools, spare parts, charts, etc.

The vacuum pump is used to evacuate the heater chamber to remove moisture. The calibration tube is used for instrument adjustments and setting of voltage controllers before a run.

TEST RESULTS

The first test run was made with the assistance of personnel of the Sun Oil Company laboratories. The run was performed by Mr. Omar Allag, graduate assistant on the project and was witnessed by Mr. Joe Parmley and Mr. Clarence Braun, consultants from Sun Oil Company who acted as advisors in operating the unit and adjusting controllers and recorders.

Prior to the run the charge for the combustion tube was prepared by thoroughly mixing the following materials in a large container:

Sand	45	pounds
Clay	2.5	pounds
Oil (28.0		
API crude)	5.9	pounds
Water	2.0	pounds

— This material was then put into the reactor tube a little bit at a time accompanied by thorough tamping in insure a uniform, tightly packed bed. The charged reactor was then placed inside the high pressure jacket and connected into the unit. To start the run, the electrical ignition element was turned on after establishing a flow of combustion air into the top of the reactor across the igniter. The air flow rate was 3.86 scf/hr which is 29.2 scf/hr. ft². A back pressure of 120 psig was maintained during the run. It takes from 24 to 72 hours to completely burn the charge but this initial test run only

lasted 5 hours. During the run, the position of the flame front can be determined by the thermocouple readings and as time progresses the maximum temperature moves slowly down the reactor. While this occurs, the heaters inside the jacket are controlled by temperature difference to maintain a nearly adiabatic condition at all points along the reactor length.

While the operation proved successful, the short duration of the run precluded any material balance measurements and gas analysis measurements indicated additional work required on the gas chromatograph equipment. Several thermocouples needed replacing and some of the heater controllers needed repair.

After making the necessary repairs several additional runs have been made. Figure 5 shows a typical temperature profile map. Each line represents a different time during the run. The first few inches and the first few hours are disturbed by end effects and start-up problems. Typical burning profiles occur after 3 hours and below the first 5 inches. Inspection of the curves shows that as the flame front moves forward the peak temperature rises slightly possibly due to a slow approach to a stable situation. This effect might also be due to a difference in character of the oil the flame front meets and the removal of water in place due to evaporation.

The temperature profile curve ahead of the peak is characterized by a drop in temperature. This occurs in the region when oil evaporation and thermal cracking is taking place. Further on there is a more pronounced drop in temperature below 700°F . In this region no thermal cracking and very little oil evaporation can occur. This pronounced dip in temperature is probably caused by evaporation of the water in the pores. In the neighborhood of 300°F the partial pressure of water vapor is below its vapor pressure and condensation of water occurs. This shows up as a flat in the temperature profile. Still further in advance of the front water is nearly all condensed and the temperature drops to the ambient temperature not showing any effect of the flame front.

Looking at it in another way we may consider a fixed point in the bed as the flame front passes. First it is at ambient temperature not having been affected by the heat. Then as hot gas moves by and conduction takes place the temperature starts to rise. When the temperature gets to the boiling point of water the rate of temperature rise drops to zero as the heat is taken up by vaporizing water. The temperature rises again but slows down above 700°F where vaporization of the oil starts to occur and at 900°F where

appreciable cracking starts to occur. The residual coke or heavy tar from cracking is finally burned providing heat for the reactions ahead of it at 950°F. The final result is clean, oil free sand at that point. If there is no igniter heat the temperature starts to drop off after this time.

In the system as it now exists, the gas is sampled after passing completely through the bed. The constituents of the gas are the results of thermal cracking at various temperature levels and combustion of various coke compositions. Not much can be told about reaction zones from this gas analysis. A typical analysis of this gas is as follows:

Component	Md Percent
H ₂	2.57
O ₂	1.03
N ₂	78.27
CH ₄	2.49
CO	5.33
CO ₂	10.31
Total	100.00

CONCLUSION

In order to get an in-depth view of the chemical reaction kinetics, it will be necessary to carry this project a step further and that is why we were encouraged at this point to try to modify the system in such a way as to be able to sample the fluids in the bed at different points while the combustion proceeds. That, basically, is the subject of a renewal of the research proposal submitted to ERDA this summer.

In this research proposal we show a moveable slip-tube which will be manually adjusted to sample any point in the reactor and actually follow the fluids as they pass through the bed. Thus instantaneous compositions will be available to allow calculation of reaction rates. A drawing of this tube installed in the reactor is shown in Figure 6.

Fig. 1 . Kinetics of Underground Combustion . Schematic Diagram of Test Apparatus for In Situ Combustion

PUBLICATIONS

A progress report was presented at the ERDA Symposium on Enhanced Oil and Gas Recovery held in Tulsa, Okla., September 4-5, 1975.

A second progress report was presented at the ERDA Symposium on Enhanced Oil and Gas Recovery held in Tulsa, Okla., September 8-9, 1976. This paper has been incorporated in the Proceedings of the Symposium.

FIGURE 5. Temperature Profiles in Sand Pack at Every Hour

Figure 2: Reactor Assembly

Figure 3: Bottom Flange with Heaters

Figure 4: General View of Front Panel with Controls

Fig. 6 SAMPLING DEVICE TO BE BUILT AT BOTTOM OF REACTOR