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CHARACTERIZATION OF THE WRI ENTRAINED-FLOW REACTOR

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TABLE OF CONTENTS

	<u>Page</u>
LIST OF TABLES AND FIGURES.....	iii
SUMMARY.....	iv
INTRODUCTION.....	1
REACTOR DESIGN.....	1
Solids Feeder.....	3
High-Temperature Reactor.....	3
Isothermal Reactor.....	10
Product Recovery System.....	10
Instrumentation.....	13
Pressure Shell.....	14
REACTOR PERFORMANCE.....	15
Solids Feeder.....	15
High-Temperature Reactor.....	15
Product Recovery System.....	18
CONCLUSIONS.....	20
ACKNOWLEDGEMENT.....	21
DISCLAIMER.....	21
REFERENCES.....	21

LIST OF TABLES AND FIGURES

<u>Table</u>	<u>Page</u>
1. High-Heating-Rate Experiment Conditions.....	16

<u>Figure</u>	<u>Page</u>
1. High-Heating-Rate Reactor System Block Diagram.....	2
2. Reactor Process Diagram.....	4
3. Solids Feeder.....	5
4. Modified Free-Jet Assembly.....	6
5. Molybdenum-Wound Heater.....	7
6. High-Heating-Rate Reactor and Upper Pressure Shell.....	9
7. Isothermal Heater and Lower Pressure Shell.....	11
8. Product Recovery System.....	12
9. Reactor Temperature Profiles for Runs 13 and 14.....	19

SUMMARY

A high-heating-rate, entrained-flow reactor has been designed, constructed, and operated. Design goals for this system were to achieve heating rates of $>10^4$ °C per second ($>2 \times 10^4$ °F/s) for a uniform mixture of gas and particles at 500 psig. This objective has been met with a reactor system capable of heating 20 to 150 grams of solid per hour at heating rates up to 3×10^4 °C per second (6×10^4 °F/s) to temperatures up to 870°C (1600°F). Problems with the reactor system are high-temperature-heater survival and capture efficiency of the liquid-product recovery system.

INTRODUCTION

There is substantial experimental evidence that high-heating-rate pyrolysis of oil shale produces higher yields of oil than typical low-heating-rate processes such as Fischer assay (Wallman et al. 1980; Richardson et al. 1982; Forgac 1984; Carter 1986). Typically, studies show an improvement of 5 to 15% for western shale and 50 to 100% for eastern shale over Fischer assay oil yields. Pilot-scale fluid-bed tests have also produced enhanced oil yields. Typically, these have been about 110% of Fischer assay for western shale and 120 to 130% for eastern shale (Braun and Burnham 1986; Merriam and Cha 1987; Rubel et al. 1987). Obviously, heating rates in fluid-bed systems are sufficiently high to obtain enhanced product yields.

Besides operating at high heating rates, there are other characteristics of fluid-bed systems that may improve shale retorting efficiency. Small particle sizes typical of fluidized beds reduce heat and mass transfer diffusion resistances, minimizing intraparticle product coking and cracking losses. Also, the high gas rates in a fluid bed reduce the product residence time in the heated region of the reactor, reducing secondary oil cracking losses. Unfortunately, poor material balances, unknown sample residence times, and product dilution are also typical of fluid-bed systems and make kinetic and stoichiometric studies difficult.

The ultimate goal of the current research has been to obtain kinetic and stoichiometric data on the high-heating-rate pyrolysis of a western oil shale. To accomplish this, a reactor system had to be chosen that could attain the high heating rates observed in fluid beds, but avoid some of their limitations. One of the most favorable high-heating-rate systems for accurate reaction research is an entrained-flow reactor. With proper design, heating rates can equal and surpass those observed in fluid-bed reactors, and product recovery is simpler and more efficient. To obtain the larger amounts of solid and liquid products needed for detailed chemical and physical analyses, the system need only be run for a longer time.

Western Research Institute (WRI) has designed, constructed, and begun operating a high-heating-rate, pressurized, entrained-flow reactor system. This reactor system was developed to provide kinetic and stoichiometric data on the high-heating-rate pyrolysis of oil shale (Western Research Institute, 1988) and to optimize operating conditions for the scale-up of a proprietary commercial process. This report describes the reactor system and its performance characteristics.

REACTOR DESIGN

The high-heating-rate, entrained-flow reactor system is constructed around five basic subsystems (Figure 1) and a high-pressure housing. The solids feeder/entrainer combines the bulk solids and gas feed into a uniform, diffuse entrained flow. A high-temperature reactor heats the entrained material rapidly to a desired exit temperature. Hot materials exiting the high-temperature reactor enter an isothermal reactor, which

Figure 1. High-Heating-Rate Reactor System Block Diagram

holds the materials at a constant temperature for a predetermined residence time. A system diagram is shown in Figure 2. The product recovery system separates char and ash from liquid products and provides access for online gas sampling. An instrumentation subsystem monitors temperatures, pressures, and flows in the reactor system.

Solids Feeder

The feed to an entrained-flow reactor must be a constant uniform mixture of solids and gas. Significant variations in this mixture will cause temperature transients in the reactor. However, gas flow rates, solids loading, and total solids feed rates must be reasonably flexible to allow variation in reactor operating conditions. The feeder must also be able to function over the same pressure range as the reactor.

The design of the solids feeder presents three problems. The first is obtaining a uniform feed of finely ground material. This is accomplished using a vertical, 0.24-inch-diameter auger feeding out of a cone-shaped solids reservoir (Figure 3). Two flexible stirrers keep solids agitated in the reservoir while a small wire stirrer ensures uniform auger loading. The reservoir holds up to 300 grams of solids.

A second problem is getting solids entrained in small-diameter tubing. This problem has been addressed by attaching a modified free-jet to the bottom of the vertical auger (Figure 4). Solids dropping from the auger pass into an 0.125-inch gap between the high-velocity gas inlet jet (0.020-inch i.d.) and the slightly flared, larger diameter outlet tube (0.085-inch i.d.). The jet has sufficient velocity that makeup gas must be supplied from the side of the assembly. Solids are entrained by the makeup gas and the jet and are carried out of the feeder in the outlet tube.

To address the third problem, operation at pressure, the auger and solids reservoir are fitted into an Autoclave Engineers autoclave that has been modified to allow the auger to be driven by a magnetically coupled external electric motor. The autoclave is rated for operation at pressures up to 3000 psig, well above the limits of the entrained-flow reactor system. The autoclave can also be heated to thermally pretreat the feed material if desired.

High-Temperature Reactor

The high-temperature heater provides the temperature necessary to heat solids at the desired rate to the desired exit temperature. To obtain gas-solid exit temperatures in the range 800-900°C (1470-1650°F), the heater must be capable of reaching temperatures between 1100 and 1650°C (2000-3000°F). This limits the choice of construction materials for the heater to ceramics. Unfortunately, the high-density, high-temperature ceramics available have poor thermal stress resistance resulting in short heater lifetimes.

Each high-temperature heater is custom built using a 99.9% alumina core wound with molybdenum wire (Figure 5). The alumina has a maximum use temperature near 1900°C (3450°F), whereas the molybdenum wire has a

Figure 2. Reactor Process Diagram

Figure 3. Solids Feeder

Figure 4. Modified Free-Jet Assembly

Figure 5. Molybdenum-Wound Heater

melting point greater than 2600°C (4700°F). Typically, the alumina core has an outside diameter of 0.5 inch and an inside diameter of 0.25 inch. The length of the core varies depending on the particular experiments being conducted. A typical core may be 13 inches long with 10 inches of the length wrapped with a double strand of 0.02-inch-diameter molybdenum wire. The spacing between adjacent windings is maintained at 0.04 inch by coating the outside of the core and windings with two layers of Ceramabond 503 adhesive. This adhesive has alumina as its major constituent, bonds well with both the alumina core and the molybdenum, and will withstand temperatures to 1650°C (~3000°F). The molybdenum winding wire is cut to leave approximately 18 inches of double strand at each end of the heater. These ends are folded in half twice to form the heater leads. Multiple wraps of molybdenum wire anchor the bases of the leads and provide stress relief.

Each high-temperature heater is instrumented with three Inconel-sheathed, 0.0625-inch-o.d., type-K thermocouples. The thermocouple junctions are placed 1.5 inches from each end and in the middle of the wrapped section on the outside of the heater. A 0.125-inch-o.d. by approximately 2-inch-long alumina tube holds each thermocouple in position. Molybdenum wire strung with alumina beads holds the ceramic tubes onto the outside of the heater.

Proper installation of the high-temperature heater requires that both the top and bottom of the heater seal tightly to the stainless steel tubing used in the rest of the system. At the top of the reactor, the 0.125-inch feed line must be mated to the 0.5-inch-o.d. by 0.125- or 0.25-inch-i.d. heater. This is accomplished using a modified Swagelok 0.5-inch by 0.125-inch reducing union. The 0.5-inch end of the reducing union is attached to the heater by replacing the compression ferrules with graphite tape. The tape deforms and seals as the fitting is tightened. The 0.125-inch end of the reducing union is drilled out to allow 0.125-inch tubing to slide all the way through the reducing union. The 0.125-inch feed tube is adjusted so that the feed material will exit the tube at the top of the wrapped section of the heater. A Swagelok nut and ferrule hold the tube in place. The bottom of the heater is attached to 0.25-inch tubing with a 0.5-inch by 0.25-inch reducing union. Graphite tape is again used on the 0.5-inch end of the union. The other end is fitted to the rest of the system with a standard 0.25-inch nut and ferrule. The bottom reducing union is modified to allow a 0.0625-inch-o.d. thermocouple to be inserted at the bottom of the ceramic heater core.

Heater installation must provide for thermal insulation to protect the high-pressure shell and reduce heat losses (Figure 6). It must also provide electrical insulation at high temperatures between the heater leads and the steel tubing and pressure shell. The heater is thermally shielded with multiple wraps of A.P. Green INSWOOL-HP high-temperature insulation. The outside diameter of the wrapping is typically 6-7 inches and is held in place with Nichrome wire ties. The heater leads are insulated with ceramic beads and attached to nichrome extension wire with electrical clamps. The extension wire is insulated with a combination of glass sheathing material and wraps of INSWOOL-HP and is connected with clamps to Teflon-coated copper wire that passes through the pressure shell.

Figure 6. High-Heating-Rate Reactor and Upper Pressure Shell

The power for the high-temperature heater is supplied by a 0-140 volt autotransformer. The temperatures at the three heater thermocouples are monitored while the transformer is slowly turned up. Gas flow through the heater is also increased slowly. The objective is to reach experiment temperature and flow rate at nearly the same time. Because of the poor thermal shock properties of the alumina core, heating and cooling rates for this heater should be below 140°C (250°F) per hour. Greater heating rates may be tolerated, but rapid cooling causes the heater to break.

Isothermal Reactor

The isothermal reactor is located below the high-temperature reactor and below the quench point. This reactor holds the product stream at a constant temperature for a predetermined time. A quench gas can be added above the heater if the isothermal reactor is to be operated at a lower temperature than that of products exiting the high-temperature reactor.

The isothermal furnace is constructed with four levels of 10-inch-high by 4-inch-o.d. by 3.5-inch-i.d. Nichrome heaters (Figure 7). Each heater is assembled from two half-shell elements and is controlled separately. The four heaters are imbedded in A.P. Green VSL 50 insulating, castable refractory. This is a low-iron refractory with a maximum use temperature of 1260°C (2300°F). A vertical tube cast into the refractory provides passage for the heater power leads, which then pass through a Conax fitting at the bottom of the pressure shell. The whole furnace assembly rests on a cast refractory base inside the pressure shell and is surrounded by a layer of vermiculite fill. A stainless steel thermowell inside the furnace contains the four control thermocouples for the heaters.

The reactor vessel inside the isothermal furnace currently consists of 0.25-inch stainless steel tubing. However, there is sufficient room for either larger diameter tubing or coiled tubing if long residence times are desired.

Product Recovery System

Materials exiting the entrained-flow reactor are separated in the product recovery system. This system is constructed with two identical recovery trains in parallel. By turning valves to open the second train and close the first, a second experiment can be performed before vessels must be emptied. The following description is of one train of the system.

The exit stream from the isothermal reactor carries solids, gases, and entrained liquids. Products are separated from this stream in three stages (Figure 8). The first of these stages inertially separates entrained solids out of the product stream. It consists of a heated vessel with a particle disengaging region and a filter. The particle disengaging region is formed by directing the gas/particle mixture at an angled surface. The combination of particle slowing due to impact with the surface, changing flow direction in the region, and the rapid

Figure 7. Isothermal Heater and Lower Pressure Shell

Figure 8. Product Recovery System

decrease in gas velocity results in particulate disengagement. A filter formed from rolled Inswool captures any remaining entrained particles. The main body of the char receiver is made of schedule 80, 2-inch stainless steel pipe. An iron-pipe cooling jacket is welded to the outside of the char receiver body. The vessel is heat-taped to prevent condensation. Typically, the vessel temperature is kept above 260°C (500°F) during an experiment, but it is cooled rapidly at the end of the experiment by introducing water flow to the cooling jacket.

The second stage of the product recovery system is the hot-oil separator. This is a stainless steel bomb made from 2-inch steel pipe approximately 15 inches long. A heated sand pack around the bomb keeps the temperature near 180°C (360°F). The last stage of the recovery system is the cold trap, which is kept near 0°C (32°F) by an ice bath. An ice-cooled coil just downstream from the cold trap ensures that the gas going to the back-pressure regulator is cool.

Instrumentation

The entrained-flow reactor system has temperatures, pressures, flows, and heater power that must be monitored throughout each experiment. This is accomplished with an Omega 900 series data-acquisition system. The Omega system is configured to monitor 16 thermocouples, four pressures, four flows, heater voltage, and heater current. The Omega 900 unit is attached to a microcomputer, which displays and stores the collected data. Data are collected, displayed, and stored at 10-second intervals during an experiment. In addition, gas analyses must be performed and related to the ongoing data acquisition.

Temperatures at critical points in the reactor system are monitored with type-K thermocouples. All thermocouples are sheathed with stainless steel except for the three on the outside of the high-temperature heater, which are Inconel sheathed. Thermocouples with junctions in the process stream are installed through drilled-out Swagelok fittings. Thermocouple extension wires for those thermocouples inside the pressure shell exit the shell through Conax compression fittings. Readings from the high-temperature-heater and exit thermocouples are displayed graphically on the data acquisition computer.

Transducers measure system pressures at four locations. Both the jet flow stream and the makeup gas line to the solids feeder are monitored. The pressure in the pressure shell and the pressure upstream of the high-temperature reactor are also monitored.

Four mass flow meters monitor gas flow into the reactor. The flow meter/gas manifold is configured to allow a mixture of two gases (commonly hydrogen and nitrogen) to be fed to the solids feeder and reactor system. A mass flow meter measures the flow rate of each gas. This stream is then split with part of the flow going to the feeder jet and part being the feeder makeup gas. The makeup gas flow rate is monitored by another mass flow meter. The flow rate through the jet is calculated by difference. The fourth flow meter is used to measure the quench-gas flow rate.

Leeds and Northrup temperature controllers and SCRs (silicon-controlled rectifiers) maintain desired temperatures in the isothermal reactor and in the char separator. The four heater sections in the isothermal reactor have separate controllers and, if necessary, can be set to different temperatures. The char separator is heated with three heat tapes, each of which has its own control thermocouple and controller.

A Hewlett-Packard 5890 Series II gas chromatograph analyzes the product gas stream from the reactor system. A small amount of product gas is diverted to the gas chromatograph from the product lines just upstream of the char receivers. A small filter pack eliminates particles, and two dry-ice traps condense moisture and heavy hydrocarbons. A needle valve upstream of the first dry-ice trap drops the line pressure and, thus, speeds the gas to the gas chromatograph. A water bubbler ensures that the gas stream entering the chromatograph sample loops is always at the same pressure.

The gas chromatograph is fitted with an auxiliary sampling system consisting of an electrically actuated, multiposition valve with 16 sample loops. The gas chromatograph is operated continuously online during an experiment, but halfway through each analysis, one of the auxiliary sample loops is loaded. When the experiment is completed, the samples stored in the auxiliary loops are analyzed. The results of all the gas analyses are then shuffled together in the proper time sequence. This analytical system allows twice as many gas samples to be obtained during an experiment than is otherwise possible.

A 0.125-inch-o.d. by 6-foot-long Poropak N column is used with temperature programming to separate hydrogen, nitrogen, carbon monoxide, methane, carbon dioxide, ethene, ethane, C3s, isobutane, and normal butane. An argon carrier gas enhances the resolution of hydrogen on a thermal conductivity detector (TCD). A flame ionization detector (FID) in series with the TCD provides good sensitivity for the hydrocarbon species.

Pressure Shell

The pressure shell allows the high-temperature portions of the reactor system to be operated with low differential pressures. The shell is filled with nitrogen at a pressure slightly higher than that inside the reactor tubing. Any breaks in the tubing result in nitrogen flooding into the reactor, cooling the system rapidly, and protecting against release of hydrogen.

The shell is constructed in three pieces of 8-inch, schedule 80 pipe joined with 1500-pound, stainless steel, ring-seal flanges (Figures 5 and 6). The bottom section of the shell consists of a steel dome with ports for the isothermal heater leads, a steam line, and the reactor product exit line. The middle section encloses the isothermal furnace and reactor tubing and has the access ports for flows, thermocouples, and power leads for the high-temperature heater. The top shell section can be unbolted and lifted out of the way to provide access to interior fittings, wiring, and the high-temperature heater. It has an emergency pressure-release valve and a vent line attached at the top. The shell has been hydrostatically tested to 2000 pounds pressure.

REACTOR PERFORMANCE

The three most critical elements in the operation of an entrained-flow reactor are the solids feed system, the high-temperature heater, and the product recovery train. It is not surprising that the first two elements also cause the most operational problems. The feeder causes problems because entraining particles in small-diameter tubing is difficult, and the heater causes problems because of the high thermal stresses on the reactor materials. The product recovery system is important for calculating material balances.

Solids Feeder

The solids feeder is a critical element in a successful entrained-flow reactor system. Deviations from uniform flow through the reactor result in temperature and residence-time swings that, at best, complicate interpretation of the results. In the worst case, reactor components fail, and the experiment is aborted.

The solids feeder was designed to feed small material (70% passing 200 mesh) material at a uniform rate of approximately 100 grams per hour. Early experiments with the current feeder design were only intermittently successful. The feeder operated acceptably in dry runs but plugged during high-heating-rate experiments. Plugging interrupted flow to the high-temperature heater causing rapid temperature changes in the heater. The resulting thermal stresses commonly fractured the heater. We solved the plugging problem with two modifications. The feed material was screened to remove any +100-mesh particles, and a vibrator was installed on the feed line downstream of the solids feeder. With these modifications, flow rates from 20 to at least 150 grams per hour are possible.

Most successful experiments have been performed when the gas velocity through the 0.020-inch-i.d. jet is approximately 171 feet per second. The balance of the feed gas must come from the makeup gas port on the side of the free jet. Typical makeup-gas flow rates are 1.5 to 4 times the jet flow resulting in gas and particle velocities in the 0.085-inch-i.d. tubing between 22 and 45 feet per second.

High-Temperature Reactor

Run conditions for 20 early high-heating-rate reactor experiments are listed in Table 1. The inlet and exit temperatures are measured in the reactor gas stream above and just below the high-temperature heater. The quench temperature is calculated from the temperatures, heat capacities, and enthalpies of the feed and quench gases. We assume the effect of solids on the quench temperature is small, and it is ignored. The isothermal temperature is the setpoint temperature of the isothermal heaters.

Flow rates for feed and quench are average values over the duration of the experiment. In all cases, the quench gas is 100% hydrogen. The reactor pressure is also averaged over the duration of the test.

Table 1. High-Heating-Rate Experiment Conditions

Run Number:	1	2	3	4	5	6	7	8	9	10
Inlet Temperature, °C	147	234	224	208	228	218	114	111	114	125
Exit Temperature, °C	875	843	843	816	788	843	579	538	746	704
Quench Temperature, °C	482	506	404	394	252	270	366	366	457	376
Isothermal Temperature, °C	538	538	371	371	371	371	371	371	371	371
Hydrogen Flow Rate, slpm ¹	13.8	20.8	25.5	25.6	25.4	31.4	27.0	27.0	24.0	22.0
Nitrogen Flow Rate, slpm ¹	14.2	21.5	26.8	26.8	26.8	32.6	26.9	26.9	56.5	37.4
Quench Flow Rate, slpm ¹	26.1	32.0	65.9	65.0	137.1	166.5	36.2	29.1	58.0	60.3
Av. Reactor Pressure, psig	515	516	510	503	518	499	504	497	509	496
Heater i.d., inch	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125
Heater Length, inch	10	10	10	10	10	10	10	10	10	10
Residence Time, ms	57	36	29	30	31	24	37	37	22	29
Heating Rate, °C/s	1.3E+04	1.7E+04	2.1E+04	2.1E+04	1.8E+04	2.7E+04	1.3E+04	1.1E+04	2.9E+04	2.0E+04
Total Feed Time, min	67.5	63.2	71.2	66.5	69.2	61.0	61.2	65.5	61.0	23.7
Material Fed (dry), g	94.9	105.9	132.3	107.5	95.3	96.4	84.1	67.8	87.6	28.7

¹ slpm = standard liters per minute (1 atmosphere and 25°C).

Table 1. High-Heating-Rate Experiment Conditions (continued)

Run Number:	11	12	13	14	15	16	17	18	19	20
Inlet Temperature, °C	67	68	70	68	76	150	144	123	224	227
Exit Temperature, °C	546	627	629	552	845	822	752	539	910	994
Quench Temperature, °C	351	344	377	349	454	336	333	539	346	377
Isothermal Temperature, °C	371	371	371	371	371	371	371	538	371	371
Hydrogen Flow Rate, slpm ¹	27.1	27.0	28.5	27.2	48.8	24.0	23.9	54.5	13.5	13.5
Nitrogen Flow Rate, slpm ¹	26.8	26.9	28.4	28.4	49.6	23.9	23.9	53.5	13.4	13.4
Quench Flow Rate, slpm ¹	34.6	51.9	44.0	37.5	97.3	82.1	71.1	0.0	52.0	52.0
Av. Reactor Pressure, psig	504	502	502	507	504	505	497	506	496	503
Heater i.d., inch	0.25	0.25	0.25	0.25	0.25	0.125	0.125	0.125	0.125	0.125
Heater Length, inch	10	10	10	10	10	10	10	10	10	10
Residence Time, ms	156	145	137	152	68	34	35	174	53	51
Heating Rate, °C/s	3.1E+03	3.8E+03	4.1E+03	3.2E+03	1.1E+04	2.0E+04	1.7E+04	2.2E+04	1.3E+04	1.5E+04
Total Feed Time, min	65.0	60.0	60.0	60.0	9.2	57.7	55.8	50.0	60.0	60.0
Material Fed (dry), g	53.9	56.6	54.0	52.1	12.3	40.9	na	na	na	na

¹ slpm = standard liters per minute (1 atmosphere and 25°C)

Occasionally, an upset required us to stop the solids feed for a short time during an experiment. The flow and pressure averages include only the time during which the solids feeder was operating.

The most often quoted characteristics of high-heating-rate reactors are the solids residence times and the solids heating rates. For this report, we have made first-order approximations for these parameters. Experiments were conducted with the high-temperature heater in 0.25-inch-i.d. and 0.125-inch-i.d. configurations. In all tests, the wound (heated) length of the heater was 10 inches long. The residence time is calculated assuming the following: (1) the average particle and gas temperatures in the high-temperature reactor are the same as the average of the inlet and exit temperatures and (2) the particles move at the same velocity as the gas. The effects of pyrolysis-gas formation are not included in this approximation. The particle residence times varied from 22 to 174 milliseconds. Although longer residence times are possible, 22 milliseconds is close to the minimum residence time possible for the current reactor configuration. Shorter times require higher gas flows and more thermal stress for the high-temperature heater.

As a first approximation, the calculated heating rate is the difference between inlet and exit temperatures divided by the residence time. No correction is made for heats of reaction or pyrolysis gas evolution. Values range from 3100°C/s (5600°F/s) for a long-residence-time experiment to 29,000°C/s (52,000°F/s) for the shortest residence-time (22 ms) test. The heating-rate calculations are obviously not rigorous, but they do show performance in the desired heating-rate regime. The temperature profiles for experiments 13 and 14 are shown in Figure 9. The top, middle, and bottom labels refer to the external location of the thermocouples on the heater. Because these three thermocouples are not in the gas stream, actual gas temperatures are probably more like those shown with the dotted line.

The bottom two items in Table 1 show the total time during which the solids feeder was operating and the weight of material fed during that time. Intermittent plugging occurred during tests 1 through 5 and test 7. We then modified the screening procedure to remove +100-mesh material. Most of the remainder of the tests were completed with little or no problems. Only tests 10 and 15 were terminated early because of operating difficulties.

Product Recovery System

The first stage of the product recovery system, the solids receiver, performs well. Only a small amount of particulate material is ever found downstream, typically this was caused by minor channeling along the receiver's filter pack. Much of the particulate material lies loose inside the receiver, but a small fraction is embedded in the receiver filter pack. There have been no visible signs of product oil contamination of the particulates.

The materials passed through the high-heating-rate reactor thus far have not produced significant amounts of tar or oil. We found small volumes of oil in both the hot-oil separator and the cold trap. The amounts trapped have been consistent with material balance expectations.

Figure 9. Reactor Temperature Profiles for Runs 13 and 14

The recovery system has proven unsatisfactory for collecting product moisture. Almost all the water produced during high-heating-rate reactor operation passes through the product recovery system. When dry ice is used to cool the cold trap, plugging is invariably the result.

CONCLUSIONS

The high-heating-rate reactor system is capable of heating approximately 100 grams of solid material per hour to temperatures up to 1000°C (1800°F) at heating rates approaching 30,000°C per second (54,000°F/s). The solids feeder performs well, and the product recovery system efficiently separates particulates and traps product oils.

Weaknesses in the current reactor design include a short operational lifetime for the high-temperature heater and inefficient product water trapping. To extend the lifetime of the high-temperature heater, a portion of the reactor inlet gas will be diverted through an inline heater. This preheated gas will then be mixed with the smaller flow carrying the solid at the top of the high-temperature heater. The resulting gas-solid temperature entering the heater can be as high as 800°C (1500°F). The change in temperature over the length of the high-temperature heater is then relatively small as is the thermal stress on the ceramic. Also, because the high-temperature heater will no longer need to provide as much of the temperature change for the feed material, temperatures inside the heater can be low enough to allow a metal liner to be inserted into the heater. This will provide extra strength and disperse the temperature more evenly along the heater.

The inefficient trapping of product water in the product recovery system causes problems with obtaining a reliable material balance. This problem will ultimately be addressed by redesigning the cold-trap system to prevent plugging at dry-ice temperatures. The modification necessary may be as simple as heating the cold-trap inlet line. This might carry enough heat into the trap to prevent plugging on the inlet tubing.

The high-heating-rate, entrained-flow reactor system operates in the heating-rate, residence-time, and temperature ranges required to mimic fluid-bed systems. Further studies on the system will provide valuable information on the high-heating-rate pyrolysis of fossil fuels.

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DISCLAIMER

Mention of specific brand names or models of equipment is for information only and does not imply endorsement of any particular brand.

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