FEASIBILITY OF IN-SITU COMBUSTION OF TAR FROM A TARMAT RESERVOIR

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ABSTRACT

Combustion-tube tests were conducted on a tar of physical and chemical characteristics similar to a natural reservoir tar. Ottawa sand of 20-30 mesh size was used to prepare tar-sand mixtures of about 37% porosity, 19 to 25% water saturation and 21 to 32% tar saturation. In runs with distilled water, a combustion front was successfully initiated and moved into the sand pack. Later, however, the front's temperature dropped below 500 °C causing the front to stagnate and become extinguished a short distance away from the tube's inlet. When ferric nitrate was added to the water, sustained combustion was achieved with front temperatures maintained above 500 °C and high oxygen utilization. It appears that a minimum iron concentration in the water of about 2700 ppm is required for stable combustion. Concentrations above 4200 ppm did not enhance combustion performance.

INTRODUCTION

Tarmat is a loosely defined term ascribed to a layer of very viscous tar or

bitumen that exists around the periphery of some oil reservoirs, usually at the

oil/water contact. Problems posed by this phenomenon and techniques proposed to breach the tar layer were discussed in a previous article (Abu-Khamsin, 2001). In that article, oxidation kinetics of tar were studied as a preliminary step before feasibility of in-situ combustion as a tar-dissipation technique could be established. The main finding of that study was that high-temperature oxidation (HTO) of tar peaked at temperatures above 500 °C and the reaction's activation energy was about 100 kJ/mol. Since such a temperature is difficult to mainatain under ordinary combustion-drive conditions, the tar appeared incapable of supporting sustained in-situ combustion. To confirm this hypothesis, it was decided to run combustion-tube tests on the tar.

Two factors play crucial roles in the performance of in-situ combustion; these are availability and reactivity of the fuel. Insufficient fuel deposition ahead of the combustion front deprives the front of the heat necessary to sustain the process leading to premature extinction. Since medium and heavy crudes usually satisfy the fuel requirement (Alexander et al., 1962), this factor is not expected to be of concern with the tar. Fuel reactivity, on the other hand, controls the rate at which combustion heat is released. If HTO of the fuel is fast, convective and conductive heat losses from the combustion zone become small compared with the rate of heat release. This leads to fast accumulation of heat and, hence, rapid heating of cooler reservoir rock ahead of the front propelling this rock to combustion temperatures.

As specified by reaction kinetics, the rate of HTO is computed by:

$$R_{HTO} = k_{HTO} P_O{}^m C_f{}^n \tag{1}$$

Where R_{HTO} is the rate of HTO of fuel (g per cm^3 of rock per s), k_{HTO} is HTO reaction rate constant (consistent units), P_O is partial pressure of oxygen (Pa), C_f is fuel concentration (g per cm^3 of rock), m is reaction order with respect to oxygen, and n is reaction order with respect to fuel. k_{HTO} is dictated chiefly by the reaction's activation energy (E_{HTO}, kJ/mol) and temperature (T, °K) as governed by Arrhenius law:

$$k_{HTO} = A \exp[-E_{HTO}/(RT)] \tag{2}$$

Where A is a frequency factor (consistent units) and R is the universal gas constant. If ample fuel and oxygen are available, rate of HTO would be set by k_{HTO}. Should the nature of the fuel necessitate a large E_{HTO}, a higher temperature would be required for the reaction to proceed at the rate needed to generate enough heat to maintain such temperature. Achieving this thermal-kinetic balance is the prerequisite for a sustained combustion front, which, given the large E_{HTO} of the tar, appears rather difficult.

EXPERIMENTAL WORK

Materials

Due to the scarcity of reservoir tar samples, the tar used in this study was prepared by distilling Ghawwar Arab-D crude to yield a residue of physical and chemical properties similar to the reservoir tar. Justification for this approach as well as properties of the prepared and reservoir tars are found elsewhere (Abu-

Khamsin, 2001). Some properties of the prepared tar are repeated in Table 1 for reference.

Table 1: Physical and Chemical Properties of Prepared Tar.

Density @ 15 ^{o}C, g/ml	0.922
Viscosity @ 15 ^{o}C, cP	10322
Atomic Hydrogen/Carbon ratio	1.73
Saturates, wt%	32.8
Aromatics, wt%	32.4
Resins, wt%	9.0
Asphaltenes, wt%	25.8

Ottawa sand of 20-30 mesh size was used. The sand was mixed with about 5 wt% mortar clay to enhance combustion.

Setup

Figure 1 shows a schematic of the apparatus, which consisted of gas supply and control, combustion tube and pressure jacket, effluent gas and liquid separation and metering, effluent-gas analysis instruments, sand-pack temperature monitoring, and data acquisition system.

The combustion tube (Fig. 2) was made of a thin-walled, stainless-steel tube measuring 99 cm (length) x 7.6 cm (diameter) x 0.4 mm (wall thickness). Two stainless steel thermowells were fitted along the axis of the tube. The larger thermowell (3.2 mm OD) housed a bundle of thermocouples whose tips were spaced at 10 cm intervals. These provided temperature readings at fixed locations within the tube. The smaller thermowell (1.6 mm OD) housed a thermocouple that could be moved along the length of the tube for tracking the
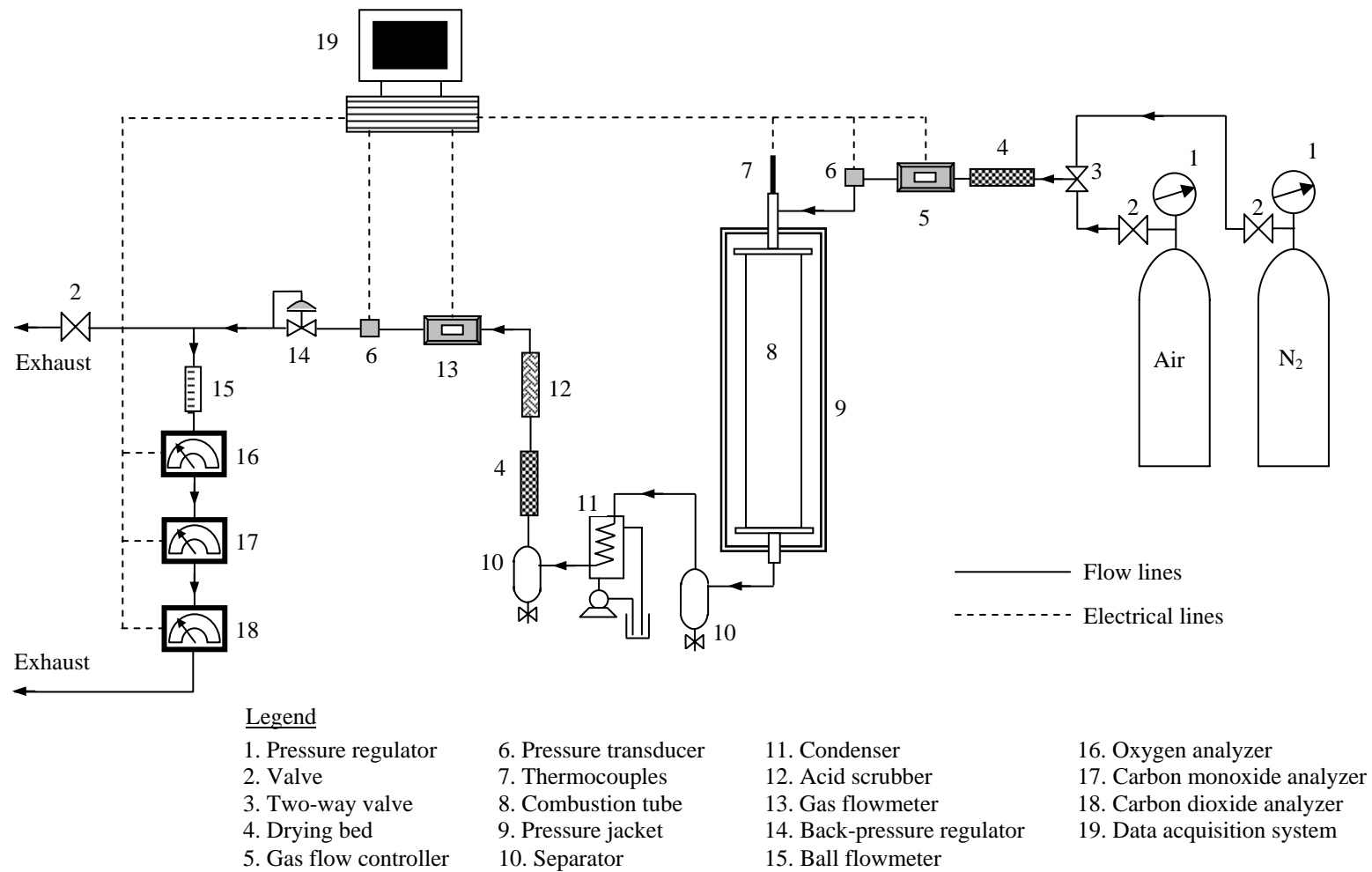
Legend

1. Pressure regulator	6. Pressure transducer	11. Condenser	16. Oxygen analyzer
2. Valve	7. Thermocouples	12. Acid scrubber	17. Carbon monoxide analyzer
3. Two-way valve	8. Combustion tube	13. Gas flowmeter	18. Carbon dioxide analyzer
4. Drying bed	9. Pressure jacket	14. Back-pressure regulator	19. Data acquisition system
5. Gas flow controller	10. Separator	15. Ball flowmeter	

Fig. 1: Schematic of Combustion-tube Apparatus
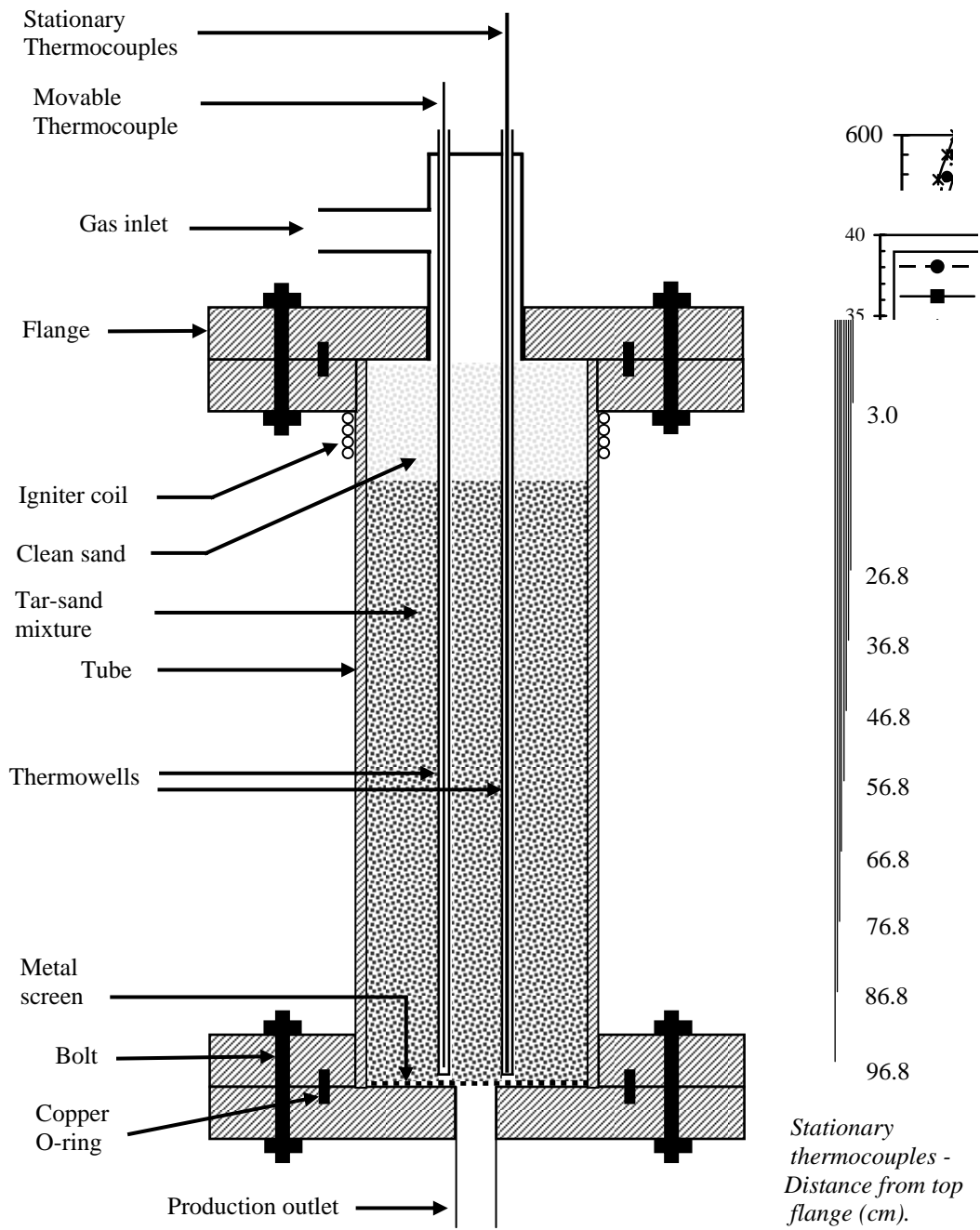
Fig. 2: Details of the Combustion Tube.

exact location of the combustion front and provide finer details on its temperature profile.

Procedure

A typical run began by preparing a mixture of tar, sand, clay and water that would yield the desired porosity and fluid saturations once packed in the tube. After the tube is filled with the mixture, assembled, flushed with nitrogen and pressure tested at 1135 kPa (150 psig), it was mounted inside the pressure jacket. The jacket was then filled with Vermiculite for insulation and sealed, and jacket heaters were turned on and set at 80 °C (Arab-D reservoir temperature). The tube assembly was then left to warm up overnight. Ignition was initiated at the top by first heating the tube's inlet to 500 °C with high-output, external electric heaters then air flow was started at 3 std. liters/min. The tube's outlet pressure was kept at 790 kPa (100 psig). Once a combustion front was detected, temperature profiles were taken at 20-30 minute intervals.

For successful runs, which usually required 8-10 hours, the combustion front was driven to the bottom of the tube. Runs that were destined to fail were terminated by flushing the sand pack with nitrogen and, after cooling, the sand pack was excavated, weighed and analyzed.

Liquids accumulating in the separators were collected periodically and saved for later analysis.

Preliminary Runs

Table 2 lists the initial conditions of the first 2 runs (ST1 and ST2), which had distilled water as the aqueous phase. These runs failed to sustain stable combustion fronts even though such fronts were successfully initiated.

Table 2: Initial Conditions of Preliminary Runs.

Run	S_{wi} [a] (%)	S_{oi} [b] (%)	Porosity (%)	Sand-Pack Depth [c] (cm)
ST1	21.1	23.6	35.7	10.6
ST2	18.9	31.6	38.3	8.8

[a] Initial water saturation (percent of sand-pack pore volume).
[b] Initial tar saturation (percent of sand-pack pore volume).
[c] Sand-pack depth from top flange of combustion tube.

Figure 3 shows concentrations of O_2, CO_2 and CO in the effluent gas versus time for run ST1. As Fig. 3 illustrates, ignition was achieved in run ST1 shortly after air flow was started with near total oxygen utilization. The temperature profiles for this run (Fig. 4) showed a combustion front emerging and moving down the tube. However, once the ignition heaters were switched off after about 50 minutes of air injection, a sudden rise in effluent O_2 concentration was immediately noticed and the combustion front began cooling down. Thereafter, O_2 concentration continued to increase accompanied by gradual decline in CO and CO_2 concentrations. The front seemed to have remained stationary at 26 cm and started losing its sharp definition. It also seemed that the combustion front stopped advancing once its temperature dropped below 500 $^{\circ}$C.

Post-burn analysis of the sand pack revealed the presence of a solid carbonaceous residue at a small concentration (about 1% by weight of sand) in the
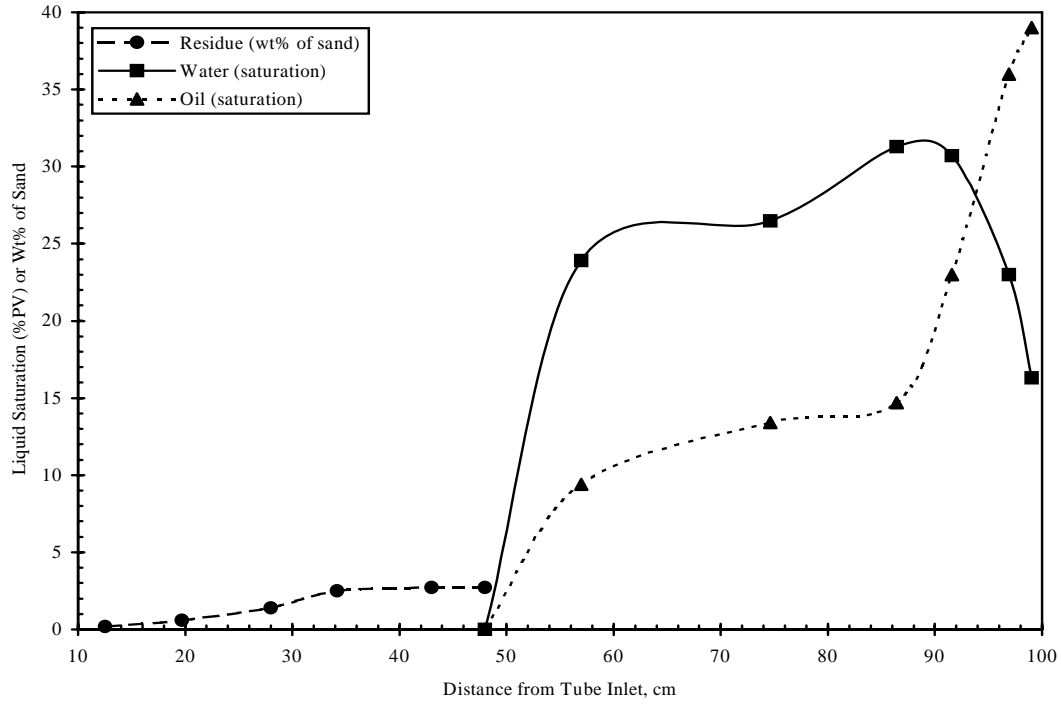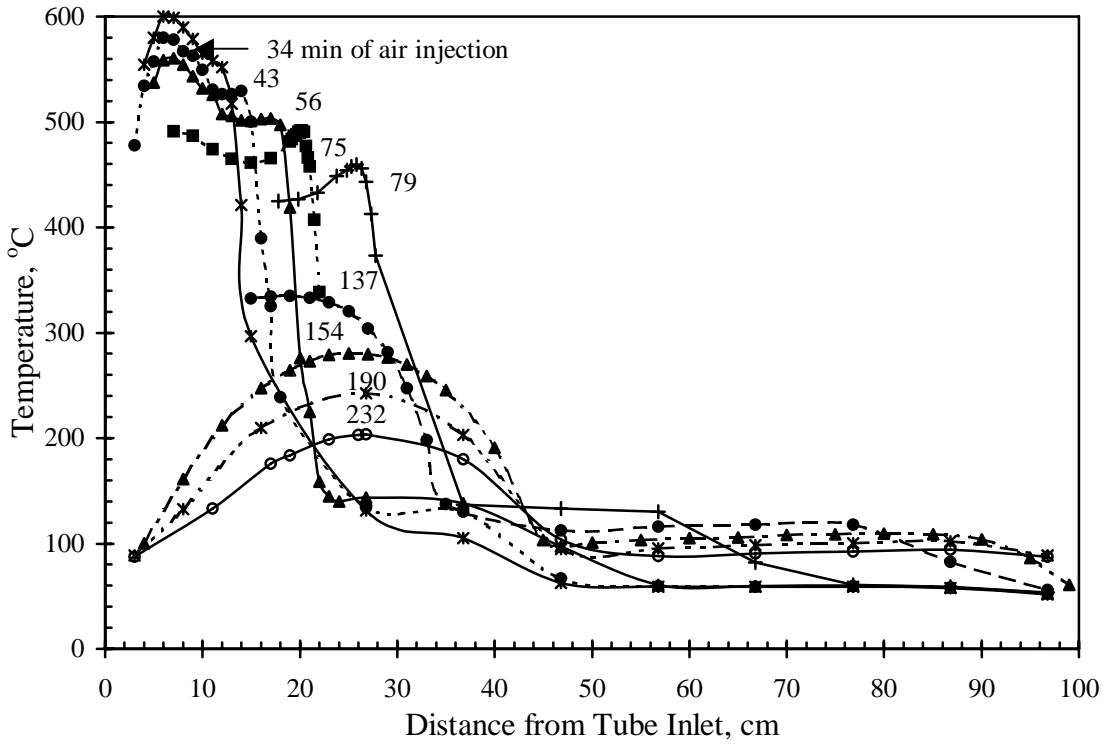
Fig. 3: Composition of Effluent Gas – Run ST1.

Fig. 4: Temperature Profiles in Sand Pack – Run ST1.

portion swept by the front (up to 26 cm). Beyond that point, the residue increased rapidly to 3 wt% between 30 and 48 cm then disappeared rather abruptly. The rest of the pack contained both water and heavy oil. Figure 5 shows post-burn residue concentration and fluid saturations where a water bank and the trailing end of an oil bank are visible. In this run, nearly half of the original tar was produced in the form of lighter and less viscous oil.
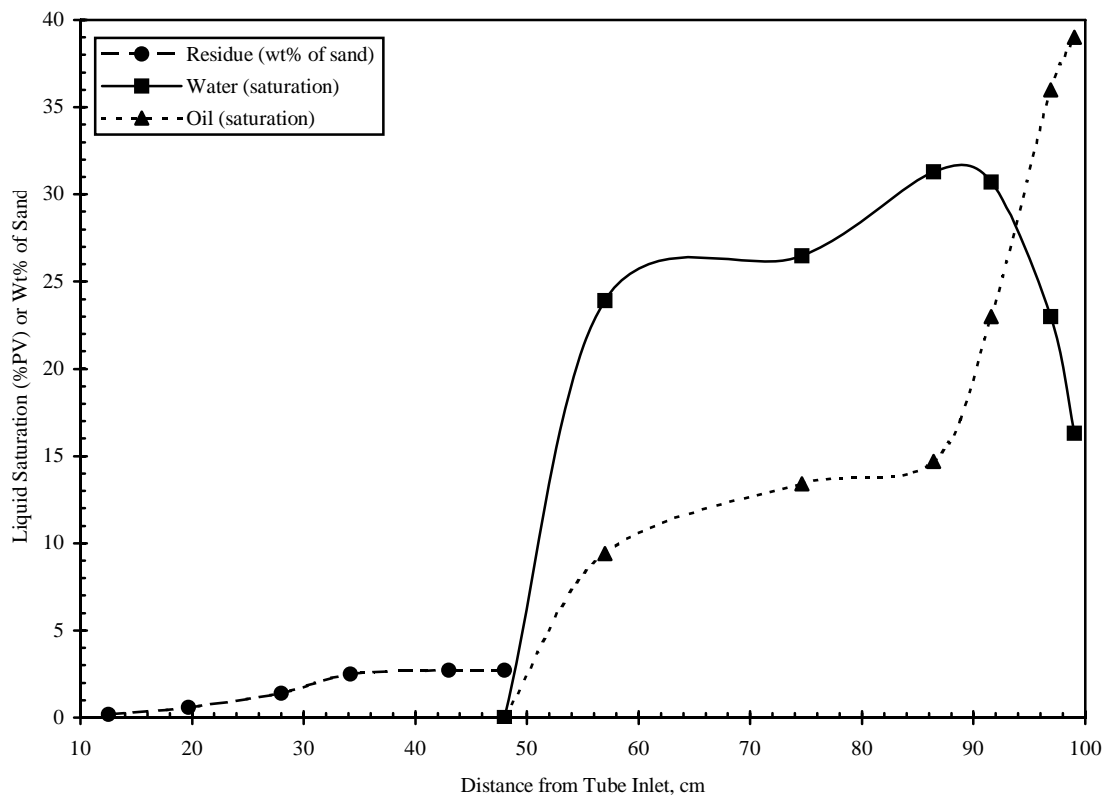

Fig. 5: Post-Burn Residue and Fluid Saturations in Sand Pack – Run ST1.

Since the residue concentration found immediately ahead of the extinct front in run ST1 was equivalent to about 51.3 kg per m^3 of bulk sand, lack of fuel was ruled out as the cause of failure. In most successful field combustion projects, fuel

concentrations ranged between 10 and 35 kg per m^3 of rock (Farouq Ali, 1972, Brigham et al., 1980). Therefore, initial tar saturation was increased in the second run (ST2) to impede tar displacement by the front and, hopefully, allow some of the tar to burn along with the residue. This should improve the overall kinetics of the HTO reaction even though the fuel load could increase. Steady combustion also failed in ST2. Residue concentration ahead of the front was nearly the same as ST1 and 500 ^{o}C also appeared to be the threshold stability temperature of the front. At this point, it was concluded that fuel quality and laydown were not affected much by initial tar saturation, and, for sustained combustion, k_{HTO} should be improved by some form of catalyst.

Runs with Ferric Nitrate

Heavy metals in the form of oxides, chlorides or nitrates have been found to improve combustion performance whether they were present in the oil or in the porous medium (Burger and Sahuquet 1972). Their main effect is promoting cracking and coking reactions leading to increased fuel laydown (Shallcross et al., 1991) and lowering of oxidation activation energy (Burger and Sahuquet 1972). During oxidation kinetics experiments, heavy metals, especially iron, were observed to reduce HTO peak temperature significantly (Drici and Vossoughi 1987, Shallcross et al., 1991). Such effect was attributed to increase in the frequency factor of HTO rate constant rather than decrease in reaction activation energy.

Four combustion tube runs were conducted with solutions of ferric nitrate nonhydrate (Fe(NO$_3$)$_3$.9H2O) as the aqueous phase. Solution concentrations ranged between 0.6 to 12% by weight of solution. (830 to 16600 ppm iron). Table 3 lists the initial conditions of these runs. Run ST3, with the least iron concentration, failed

showing the same characteristics of residue concentration, liquid saturations and front temperature trends as the previous two runs.

Table 3: Initial Conditions of Runs with Ferric Nitrate.

Run	S_{wi} (%)	S_{oi} (%)	Porosity (%)	Sand-Pack Depth (cm)	Wt% Ferric Nitrate in Water
ST3	19.8	22.1	37.2	9.2	0.6
ST4	25.5	21.7	38.2	11.0	12.0
ST5	23.0	26.4	38.0	7.2	6.0
ST6	21.6	24.8	39.4	8.9	3.0

Run ST4 was the first successful run with the Saudi Arabian tar. The sand pack burned efficiently and completely down to the tube's bottom flange. Figures 6 and 7 show effluent gas composition and temperature profile history, respectively, for this run. Fluctuations in the curves of Fig. 6 are caused by periodic draining of the separators.

The two figures indicate very efficient combustion at a stable front temperature of about 500 ^{o}C and a front velocity of 12 cm/hr. Using this velocity and the production rates of CO, CO_2 and O_2, computed instantaneous fuel concentration was found to be nearly constant at about 40 kg/m^3 of sand, which represented an equivalent tar saturation of 11.4%. The atomic hydrogen/carbon ratio of the fuel averaged 0.4 indicating a very carbonaceous residue.

The last 2 runs (ST5 and ST6) were aimed at estimating the minimum iron concentration with which sustained combustion could still be achieved. Both runs produced results similar to run ST4 in front temperatures (about 500 ^{o}C), front velocities (12 to 13.6 cm/hr), fuel concentrations (40 and 43 kg/m^3) and fuel H/C ratios (0.3 to 0.4). From the 3 successful runs with ferric nitrate, it appears that a
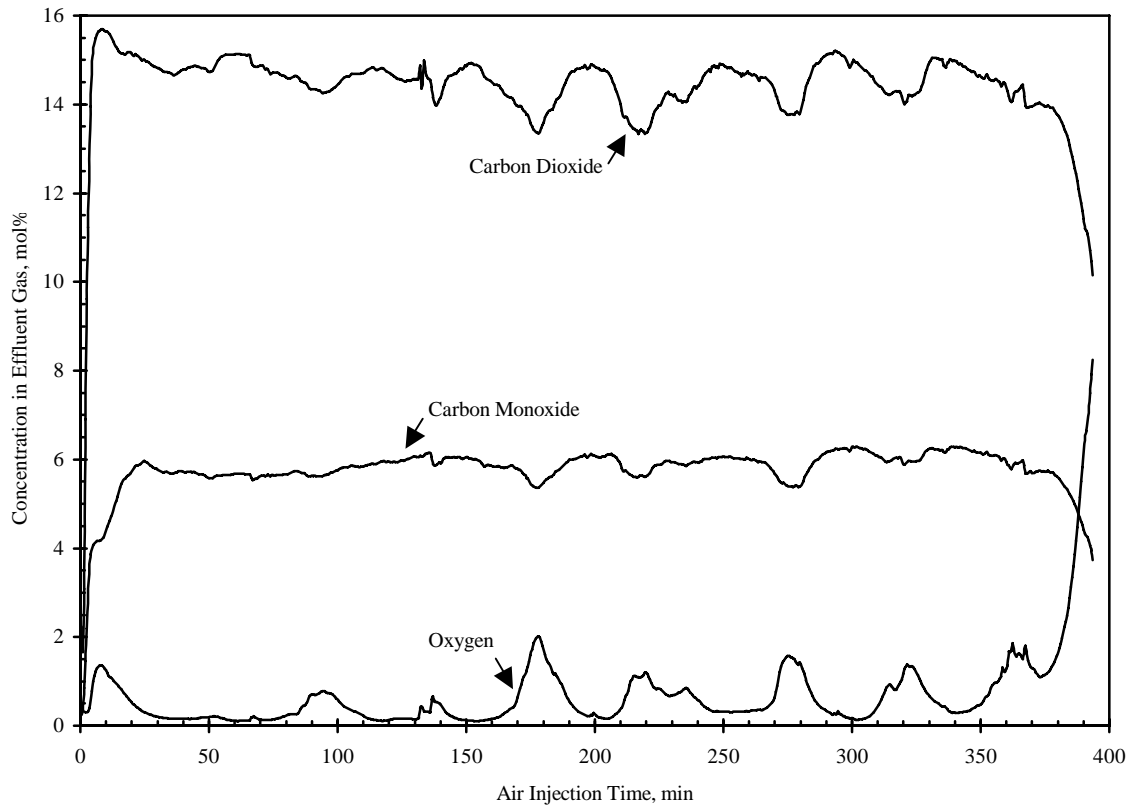
Fig. 6: Composition of Effluent Gas – Run ST4.

minimum iron concentration of about 2700 ppm is needed to achieve sustained combustion with the tar.

It is interesting to note that during the period (30 to 50 min) when a combustion front was propagating through the sand pack of failed run ST1 front velocity as well as fuel concentration and H/C ratio were nearly identical to those of run ST4. It appears, therefore, that the iron additive did not alter any of the combustion process parameters for the tar; it only enhanced the HTO reaction rate.
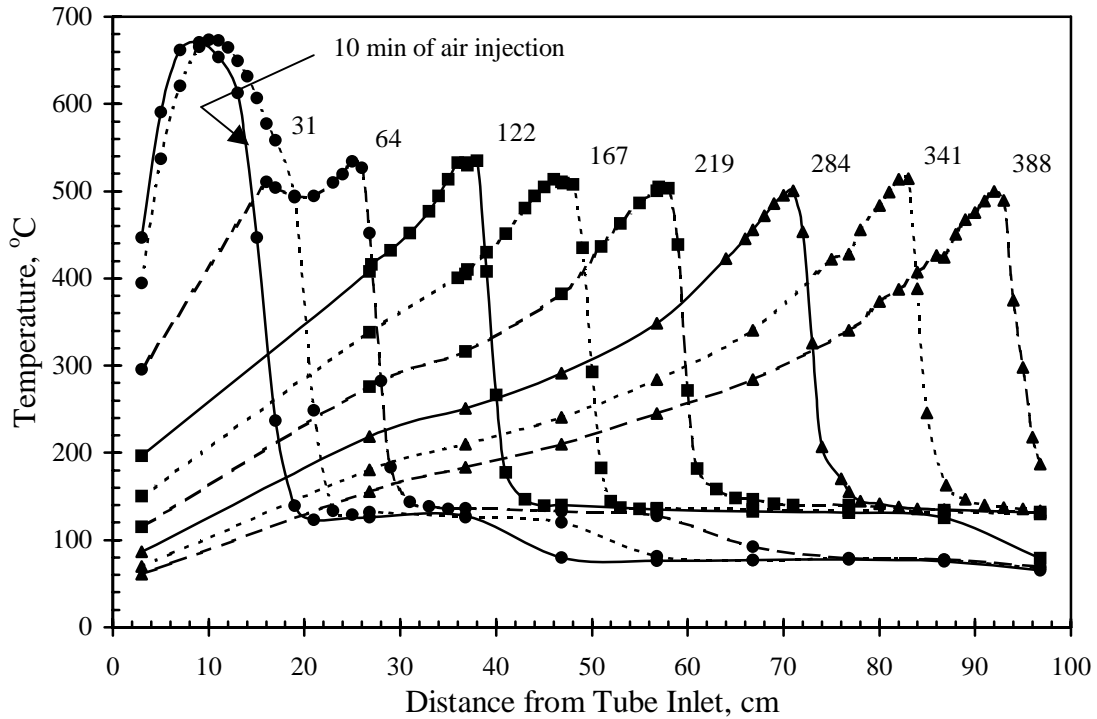
Fig. 7: Temperature Profiles in Sand Pack – Run ST4.

CONCLUSIONS

Based on the results of this study, the following conclusions can be made:

(1) A tar with physical and chemical characteristics similar to those of a Saudi Arabian reservoir tar was prepared from heavy Arab-D reservoir crude.

(2) The tar can burn smoothly above 500 ^{o}C, but its oxidation characteristics render it difficult to sustain a combustion front through a tar-saturated sand pack.

(3) With about 4200 ppm iron in the aqueous phase, a 500-^{o}C combustion front can be propagated steadily through the tar-saturated sand pack. Larger iron concentrations do not appear to enhance combustion performance.

(4) A minimum iron concentration of about 2700 ppm is needed to facilitate combustion of the tar.

(5) The iron additive appears to affect HTO reaction rate only without altering combustion process parameters.

(6) As low as 22% initial tar saturation can sustain combustion. At this saturation nearly 52% of the initial tar was burned.

(7) Iron additives could be a promising remedy to initiate and sustain in-situ combustion through the tar zone of a tarmat reservoir.

<u>ACKNOWLEGEMENT</u>

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