Experimental research on smoldering combustion for oily sludge

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Abstract. Petroleum contaminants like oily sludge and oily spills cause a great damage to the environment. Compared to the conventional treatments to remove the oily contaminants of the soil, smoldering combustion can satisfy the further treatment of contaminants with low oil content. This paper presents the experimental research of smoldering combustion for oily sludge with low oil content. Experimental results showed that petroleum contaminants could be further removed with the condition of continuous heating. However, without external heating, smoldering would not be self-sustaining. Experimental results show that smoldering has the potential to further remove petroleum contaminants in low oil content oily sludge which cannot be treated by other methods.

1. Introduction

Oily sludge is one of the main pollutant in petroleum and petrochemical industry, it can not only cause environmental damage, but also waste resources. At present, various conventional methods like land filling, incineration, air splurging, etc. have been applied since early times for remediation of oily waste. It is observed that none of the conventional methods is environment friendly solution. The common drawback is that they are not the permanent solution for the environmental pollution and sometimes they are not cost effective[1-2]. On the other hand, smoldering combustion is an international burgeoning technology which can make up for the shortcomings of the above traditional methods[3]. In Canada and United States, laboratory research results of smoldering combustion have also been successfully applied to engineering and obtained considerable removal efficiency[4-5].

Similar to the "combustion triangle", smoldering combustion also needs to meet the "smoldering triangle", that is, fuel, oxidant (air or oxygen) and ignition point[6-7]. Different from the combustion triangle, when the fuel reaches the ignition point, the heat supply is stopped[8]. Energy balance between the heat released by the smoldering and the heat transferred outwards is established, and the smoldering combustion starts to self-sustainably spread forward[9-10]. Concept of smoldering triangle was showed in Figure 1.

In this work the potential of oily sludge smoldering as a remediation technology was evaluated and quantified in a systematic manner through a suite of laboratory experiments. By sorting out the temperature data in the experimental process, the relevant temperature curves was used to reflect the ignition process and the advance process of smoldering.
2. Material and method

2.1. Overall Device

A dismountable experimental system which was able to measure the temperature in three dimensions as well as purifying tail gas was designed to conduct laboratory experiments, shown as Figure 2. The system includes: longitudinal thermocouple socket, transverse thermocouple socket, steel tube, cast copper heating plate, air dispersion plate, temperature control box, glass rotameter, air compressor, air heat exchanger, gas liquid separator and activated carbon treatment box. The main body of smoldering furnace was made of steel tubes (D200*5mm, H=500mm). The temperature control box was connected with the casting copper heating plate, of which the heating temperature was preset by using the principle of PLC automatic control and could be monitored in real time. The top cover was designed to be inclined conical. Tail gas collection pipe was connected to the tip of the inclined conical top to collect tail gas generated by smoldering. A large hole was cut at the center of the inclined cone as a longitudinal thermocouple socket, so that a set of longitudinal measuring points could be set on the center of the cone. There were 6 holes evenly opened around the inclined cone as the transverse thermocouple sockets. The purpose was to place a set of transverse measuring points on the same horizontal surface. Air dispersion plate with compact holes could make the air flowing into the reactor evenly distributed, so that the airflow into the smoldering area becomes more stable.

Figure 2. Overall Device of smoldering system.
2.2. **Oily sludge configuration**
Crude river sand with an average particle size of 3-5mm mixed with crude oil was used to approximately replace real oily sludge. In engineering, oily sludge is often mixed with coarse sand or blinding in order to increase the porosity of oily sludge so as to enlarge the surface area of contact between air and oily sludge. The proportion of crude oil and coarse sand was controlled in 38g/kg.

2.3. **Temperature measurement and controlling device**
In this experiment, a k-type thermocouple with a diameter of 5mm, a probe length of 500mm and a maximum bearing temperature of 1000°C was adopted. Thermocouple thermometers with 4 channels were connected to the thermocouples to record the temperatures inside the smoldering furnace. The temperature of the cast copper heating plate can be adjusted through the temperature control cabinet, with an accuracy of 1°C and a maximum of 650°C.

2.4. **Air supply and metering device**
The air supply device adopted air compressor, of which the motor power was 1600W, the maximum pressure was 0.8mpa, the tank capacity was 50L, shown as Figure 3. The glass rotameter was used to measure the air sent into the smoldering furnace, of which the measuring range was 1.2-12m³/h.

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**Figure 3.** Air compressor.

3. **Experimental process and results**
Stepwise heating and stepwise cooling were used in the experiment. The heating temperature gradually increased from 400°C, 450°C, 480°C to 500°C. Cooling temperature gradually reduced from 500°C, 480°C to 450°C. When the heating plate temperature dropped below 450°C, the smoldering front gradually extinguished. Figure 4 showed the temperature distribution curves of smoldering furnace at different positions during the experiment. 0cm means that the position recorded by the curve is on the contact surface between the cast copper heating plate and the oily sludge, 2cm means that the position recorded by the curve is 2cm from the radial height of the cast copper heating plate.

During the experiment, in order to verify that smoldering reaction did occur in the smoldering furnace, the air input was suspended within 203 to 208 minutes. At this time, the temperature curves of 0cm and 2cm showed an obvious downward trend. This indicated that the smoldering front was in the position of 0-2cm, the air input is stopped, and the smolder is gradually extinguished. At 208 min the air was reintroduced and the smoldering reaction begins again. Furthermore, the cast copper heating plate closed at 239 minutes. After that, despite the air input, the temperature curve decreased significantly. It indicated that in the case of low oil content, the smoldering requires stable external heating, so that the sum of the heat generated by smoldering and the heat supplied by the heating plate is equal to the heat released from the whole system to the external environment.
Figure 4. Temperature distribution curves at different positions in smolder experiments.

The oily sludge samples before and after treatment were analyzed, as shown in Figure 5. The sampling location was 2cm above the cast copper heating plate. The oil content of oily sludge further decreased after smolder treatment.

Figure 5. Samples before and after smoldering treatment.

Naturally, petroleum products are hydrocarbons containing carbon and hydrogen in chemical compounds like methane, propane, butane, benzene, etc. All these molecules are having C-C, C-H bonds, etc. as major constituents. It will be characterized by analyzing the FT-IR spectra of molecules. The detailed parameters of the infrared spectrometer used in the experiment were shown in Table 1.

Table 1 Detailed parameters of the infrared spectrometer,

| Model        | Manufacturer        | Technical parameters                  | Main accessories                        |
|--------------|---------------------|---------------------------------------|-----------------------------------------|
| NEXUS FT-IR  | Nicolet Corporation, USA | Wave number range: 4000-10000p       | Diffuse reflectance accessory           |
|              |                     | x-1 Accuracy of wave number: 0.25px-1 | High temperature diffuse reflection in situ system |
|              |                     | Resolution ratio: better than 2.25px-1|                                         |

FTIR analysis of petroleum hydrocarbon exists on the samples had been recorded and given in Figure 6.
Figure 6 FTIR Spectra of samples before and after treatment

For petroleum pollutants, the peak of the infrared spectrum was between 1000-3000. Two samples of the same quality were used for testing. The absorption peak of the sample after treatment was found to be significantly reduced in the range of 1000-3000. The result showed that smolder consumed part of petroleum pollutants and further verified the feasibility of smoldering treatment of oily sludge.

4. Conclusion
When the oil content of oily sludge is relatively low, smoldering can be generated and promoted by auxiliary heating with an external heat source. The ignition temperature is about \(344^\circ C\) and the maximum temperature is about \(400^\circ C\). The energy balance is that the sum of the heat emission from the external heat source and smoldering reaction is greater than (or equal to) the energy required to ignite the unburned part, and the reaction can advance self-sustainably. Remove the external heat source, since the heat release of smoldering reaction cannot meet the energy required to ignite the unburned part, the smoldering front cannot advance self-sustainably. At this time, the energy balance is that the heat release of smoldering reaction is less than the energy required to ignite the unburned part.

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Reference
[1] Rajendiran T, Vijayakumar R, Ganakumar G 2016 Experimental Analysis of Smoldering Combustion as a Remediation Technology for Treating Petroleum Products Contaminated Soil [J]. Middle-East Journal of Scientific Research 24(S1) 240-244 10.5829/idosi.mejsr.2016.24.S1.49
[2] Silva LJ, Alves FC, França FP 2012 A review of the technological solutions for the treatment of oily sludges from petroleum refineries [J]. Waste Management & Research 30(10) 1016-1030 10.1177/0734242x12448517
[3] Salman M, Gerhard JJ, Major DW, et al. 2015 Remediation of trichloroethylene-contaminated soils by STAR technology using vegetable oil smoldering [J]. Journal of Hazardous Materials 285 346-355 https://doi.org/10.1016/j.jhazmat.2014.11.042
[4] Scholes, GC, Gerhard JI, Grant GP, et al 2015 Smoldering Remediation of Coal-Tar-Contaminated Soil: Pilot Field Tests of STAR [J]. *Environmental Science & Technology* **49**(24) 14334-14342 10.1021/acs.est.5b03177

[5] Wang T-Y, Jiang W-M, Liu Y 2020 Research and Progress of Smoldering Combustion Technology for Oily Sludge [J]. *CIESC Journal* **71**(4) 1411-1423 10.11949/0438-1157.20191085 (in Chinese)

[6] Huang X, Rein G 2014 Smoldering combustion of peat in wildfires: Inverse modelling of the drying and the thermal and oxidative decomposition kinetics [J]. *Combustion and Flame* **161**(6) 1633-1644 10.1016/j.combustflame.2013.12.013

[7] Maika G, Kazunori K, Shigetoshi Y 2018 A simple and fast numerical method for solving flame/smoldering evolution equations [J]. *SIAM Letters* **10** 49-52 10.14495/jsiaml.10.49

[8] Marco AZ, Torero JL, Gerhard JI 2017 Determination of the interfacial heat transfer coefficient between forced air and sand at Reynold’s numbers relevant to smouldering combustion [J]. *International Journal of Heat and Mass Transfer* **114** 90-104 10.1016/j.ijheatmasstransfer.2017.06.020

[9] Khan FI, Husain T, Hejazi R 2004 An overview and analysis of site remediation technologies [J]. *Journal of environmental management* **71**(2) 95-122 10.1016/j.jenvman.2004.02.003

[10] Switzer C, Pironi P, Gerhard JI, et al 2009 Self-Sustaining Smoldering Combustion: A Novel Remediation Process for Non-Aqueous-Phase Liquids in Porous Media [J]. *Environmental Science & Technology* **43**(15) 5871-5877. 10.1021/es803483s