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Study on incineration technology of oil gas generated during the recovery process of oil spill

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ABSTRACT

The objective of this study is to design, set up and operate an incinerator system capable of providing clean exhaust and safety control for burning oil gas generated during the recovery process of oil spill in Taiwan. In this study, we successfully develop a vertical-type incinerator, which consists of five oil gas burners with entrained primary air, a pilot burner, and an auxiliary burner. The incinerator system is equipped with necessary control units in order to achieve safe, easy, fast, and efficient operation. Flame appearance, flue gas temperature and CO emission of the incinerator system for burning oil gas are reported and discussed. Under the long-term operation, it is found that the new designed incinerator is satisfactory for burning oil gas with low supply pressure at various compositions and supply rates during the recovery process of oil spill. It is noteworthy that the results obtained herein are of great significance to provide a good guidance for those who need to design, set up and operate an incinerator system providing clean exhaust and safety control for burning oil gas generated during the recovery process of oil spill in a polluted site with a large area.

1. Introduction

Overflows and leakages from aboveground storage tanks, production processes and transport pipelines carrying crude oil and petroleum products occur frequently [1]. Many more oil and chemical spills occur on land than on water [2]. The spilled hydrocarbons pose environmental threats by contaminating the surrounding soil and underlying groundwater. Not only spilled hydrocarbons pollute the surrounding soil and underlying groundwater but volatile organic compounds (VOCs) also poison environment. Crude oil and petroleum products contain a number of hydrocarbon compounds, some of which are known to be hazardous. It was emphasized that ambient VOCs attribute to 35–55% of the outdoor air cancer risk in the United States [3]. From an environmental point of view, it is necessary to limit the emissions of VOCs because they affect the change of climate, the growth and decay of plants, and the health of human beings and all animals [4].

The air sparging (AS) and soil vapor extraction (SVE) are two growing remediation technologies for removal of volatile organic compounds from sediments and groundwater. AS involves injecting atmospheric air into the aquifer to induce mass transfer of volatile organic chemicals to the vapor phase and mass transfer of oxygen to the aqueous phase. SVE strips volatile organic chemicals bound to soil particles and induce atmospheric-soil vapor exchange in the unsaturated zone [5]. Bioslurping has evolved from a primarily experimental technology to a preferred method for remediating sites contaminated with free-phase product. By combining vacuum-assisted free-product recovery with bioventing and soil vapor extraction, bioslurper systems simultaneously recover free-product and remediate the vadose, capillary, and saturated zones [6]. Bioslurping offers improvement on more traditional free-product recovery technologies, which tends to rely on hydraulic gradients and cones of depression to promote free-product movement. Bioslurping was employed herein to recover leakage oil in the polluted site located in southern Taiwan.

There are many technologies to control emissions of VOCs with many advantages and limitation. They can be divided easily into two ways, destruction based and recovery based. The most common methods are thermal oxidation, catalytic oxidation and active carbon based adsorption. Thermal oxidation system is also known as fume incinerators. Thermal oxidation is very popular since available with thermal energy recovery option to reduce operating costs [7,8]. Thermal oxidation systems burn VOCs at temperatures of 700–1000 °C. Actual operating temperature is a function of system type and the desired destruction and removal efficiency (DRE). Compounds are usually present at low inlet concentrations. They are difficult to burn due to the requirements of greater heat input and retention time in the combustion. Two limitations are considered when using thermal oxidation to remove VOCs. One is that

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inlet concentrations in excess of 25% of the lower explosive limit (LEL) are generally avoided by oxidizer manufactures because of potential explosion hazards [9,10]. The other is a secondary pollutant occurs, that is, an operating temperature near 1400 °C can produce elevated levels of nitrogen oxides [4,11].

Catalytic oxidation systems are similar to thermal oxidation. The main difference is that the catalytic system operates at a lower temperature about 350–500 °C and thus requires lower combustion energy. The catalytic system is well suited to low concentration operations or those operate in a cyclic manner. High concentration VOCs can also be treated with catalytic technology. However, it is not advisable for concentrations in excess of 25% of LEL, which need high costs of catalytic replacement. Another disadvantage is catalytic material can be sensitive to poisoning by non-VOC materials such as sulphur, chloride and silicon.

Carbon adsorption is a very common method of emission of VOCs control [12]. VOCs are removed from the inlet stream by physical adsorption onto the surface of the carbon. Carbon adsorption system is flexible and inexpensive to operate. It is the useful method to remove VOCs for high capacity; non-selective adsorption of gases at ambient temperature. Moisture is one of the crucial parameters to dictate the efficiency and effectiveness of adsorption system. The activated carbon that has adsorbed moisture will lose this moisture by displacement in its preference for organic vapors. For several reasons, the activate carbon system is suitable for most VOCs with molecular weights between 40 and 150 and boiling points from 40 °C to 260 °C.

In general, the thermal oxidation system can be designed to handle a capacity of 1000–500,000 cfm (cubic feet per minute) and VOC concentration range from 100 to 2000 ppm [13]. The catalytic oxidation system can operate at the same range of VOCs concentration, but the capacity is small [4]. For the carbon adsorption, the system is sized according to the maximum flow and concentrations [12]. In our site, the concentration of VOCs can reach 50% (as shown in Table 1), which is greater than the general value of the industry product. Therefore, we cannot use the common method introduced above to remove the emissions of VOCs.

Partially premixed flames have been widely used in practical combustion devices since they have several advantages compared to either non-premixed flame or fully premixed flames. There has been much attention paid to the effects of partial premixing on pollutant emissions and flame stability using jet flames. For instance, the partially premixed flames were found to be less polluting and more stable when proper premixed conditions were maintained [14]. Cheng et al. [15] investigated the effects of partial premixing on pollutant emissions in methane jet flames. They found that with increasing partial premixing, the visible flame height decreased, the overall flame color changed from yellow to blue, and CO emissions decreased. Mishra [16] performed emission studies of impinging partially premixed flames and found that the CO level increased with increase in equivalence ratio for same separation distance. Ko and Lin [17] investigated the effects of gas composition variation on burner performance. The results showed that using a natural gas with higher heating value instead of a natural gas with lower heating value led to an increase in CO emission (caused by incomplete combustion). As abovementioned, quite a few studies with emphasis on partially premixed flames have recently appeared. However, those studies mainly focused on single jet flames burning common fuels (e.g. methane, LPG, and CNG); there is still a lack of studies on the characteristics of partially premixed flames established in multiple-jet burners for burning oil gas generated during the recovery process of oil spill.

In view of this, the objective of this study is to design, set up and operate an incinerator system providing clean exhaust and safety control for burning oil gas generated during the recovery process of oil spill. The method adopted to remove the oil gas is one type of the thermal oxidation. The typical partially aerated burner [18,19] incorporated with auxiliary combustion and entrainment of primary air is employed in this study. On leaving the injector, the gas entrains primary air by a momentum-shearing process between the emerging gas and ambient air [17]. By this way, we can get a partially premixed flame and achieve the reduction of CO emissions.

2. Problem description

The spill site studied herein is located in southern Taiwan. The area of concern for spilled product recovery is approximately 1200 m^2. The capacity of spill oil is about 350 m^3. We examine the recovered oil and find out its composition, which contains 65% gasoline and 35% diesel. The chemical compounds include paraffins, olefins, aromatics, and other trace compounds. According to the ASTM specification, gasoline consists of C4–C10 hydrocarbons

Table 1
Typical compositions of the oil gas from four different pumping wells, where VOCs denotes the total combustible gas and TPH designates total petroleum hydrocarbons.

	Methane	Benzene	Toluene	Ethyl-benzene	Xylene	TPH (as C_4H_{10})	TPH (as C_5H_{12})	TPH (as C_6H_{14})
Well #1								
ppmv	117	8869	9538	646	1318	349,274	281,360	235,557
%	0.012	0.887	0.954	0.065	0.132	34.93	28.14	23.56
VOCs (%)						36.98	30.18	25.60
$N_2 + O_2$ (%)						63.02	69.82	74.40
Well #2								
ppmv	48	3894	5172	27	1006	146,222	117,790	98,615
%	0.005	0.389	0.517	0.003	0.1	14.62	11.78	9.86
VOCs (%)						15.64	12.80	10.87
$N_2 + O_2$ (%)						84.36	87.20	89.12
Well #3								
ppmv	269	12,338	13,385	46	1909	506,629	408,118	341,680
%	0.027	1.234	1.339	0.005	0.191	50.66	40.81	34.168
VOCs (%)						53.46	43.60	36.96
$N_2 + O_2$ (%)						16.54	56.40	63.04
Well #4								
ppmv	252	12,238	14,615	51	2183	482,950	389,043	325,710
%	0.025	1.224	1.462	0.005	0.218	48.30	38.90	32.57
VOCs (%)						51.23	41.84	35.50
$N_2 + O_2$ (%)						48.77	58.16	64.50

[20] and diesel mainly consists of C10–C23 hydrocarbons [21]. Gasoline is more volatile and contains a larger amount of benzene, toluene, ethylbenzene, and xylene than diesel. Table 1 illustrates the compositions of the oil gas from four different pumping wells where TPH designates total petroleum hydrocarbons. From Table 1, we can find that the combustible gas concentration (VOCs) is nearly in the range from 15% to 53% (when TPH is regarded as C_4H_{10}). The percentage of oxygen can reach 18%, which is in excess of the lower explosive limit (LEL).

The significant aims in burner design for a combustion system are to ensure that (1) the correct mixture of gas and air is steady supplied, (2) ignition is controlled and reliable, (3) the resultant flame is of required shape and structure and is stable, and (4) the appliance is inherently safe [17]. However, it is difficult to achieve these goals mentioned above for burning oil gas, because both gas compositions and supply rates of the oil gas are varied [22] in the recovery process of oil spill. Furthermore, at the end of the recovery process, the oil gas may contain various oxygen concentrations at low pressure. This therefore may result in incomplete combustion (i.e., a great increase of CO emissions and/or smoke emissions) [23], flame liftoff [24], flame flashback [24], and even explosion [25]. It is a challenge to design a safety and reliable oil gas incinerator system satisfactory for burning oil gas at various compositions and supply rates during the recovery process of oil spill.

To give a clear insight into the oil gas characteristic we undertake a preliminary test on the spill site before the design and set up of experimental apparatus. The thermal oxidation incorporated with auxiliary combustion and entrained primary air on this site is investigated by using a jet burner, which is a copper tube of 25.4 mm inside diameter with several holes prior to the burner exit to entrain primary air. According to the preliminary results, we obtain two important concepts. One is that the oil gas concentration decreases with increasing operating time. Therefore, the pumping wells need to open stage by stage to prevent the occurrence of yellow flame or extra flame height at the initial operating period. The other is that for the all operating conditions of the thermal oxidation system, the gas supply pressure must be well controlled to get a stable combustion. In other words, if we intend to operate the incinerator successfully and safely, another important key factor is the oil gas supply pressure, which must be well controlled.

In this study, we develop a new incinerator to burn oil gas, which is one method of thermal oxidation. Because of the characteristics of oil gas including low supply pressure, various compositions and supply rates, we employ the typical partially aerated burner incorporated with auxiliary combustion and entrainment of primary air to burn the issuing oil gas. In order to rapidly burn oil gas at various compositions and supply rates, five oil gas burners with entrained primary air are installed underneath the incinerator. We can adjust the number of oil gas burner to be fit for various compositions and supply rates. From an environmental protection point of view, we need to test and analyze the operating data from the incinerator to prevent secondary pollutant problems. In addition, in order to achieve safe, easy, fast, and efficient operation, the incinerator system is needed to be equipped with necessary control units and to be provided with the standard operating process (SOP).

3. Design and set up of an incinerator system

Since a proper design of gas burner capable of burning oil gas at various compositions and supply rates is of great significance, we now tackle the difficulties described above to develop a vertical-type incinerator (as shown in Fig. 1), which consists of five oil gas burners incorporated with entrained primary air, a pilot burner, and an auxiliary burner. The combustion chamber is a cylinder of 540 mm diameter and 2800 mm height. We install ceramic fiber of 50 mm thickness inside the combustion chamber to prevent over-heat under long-term operation. The incinerator is an open system that can supply primary and secondary air to combust oil gas and prevent explosion. In order to rapidly burn oil gas at various compositions and supply rates, five oil gas burners with entrained primary air are installed underneath the incinerator. We can adjust the number of oil gas burner to be fit for various compositions and supply rates.

The pilot burner with a capacity of 8000 kcal/h is installed underneath the incinerator, close to oil gas burners, to provide a permanent LPG premixed flame for stable ignition of oil gas. It can provide an adequate heat source for burning oil gas. The auxiliary burner with a capacity of 10,000 kcal/h, generating an auxiliary LPG premixed flame, incorporated with two layers of wire-meshed screen are installed downstream of the incinerator to ensure complete combustion of oil gas before the exhaust. Four peepholes are installed that are useful and convenient to observe the combustion condition. Additionally, the incinerator system is equipped with necessary control units in order to achieve safe, easy, fast, and efficient operation. For instance, for the safety point of view, the auxiliary burner is incorporated with an UV sensor to detect abnormal ignition or extinction.

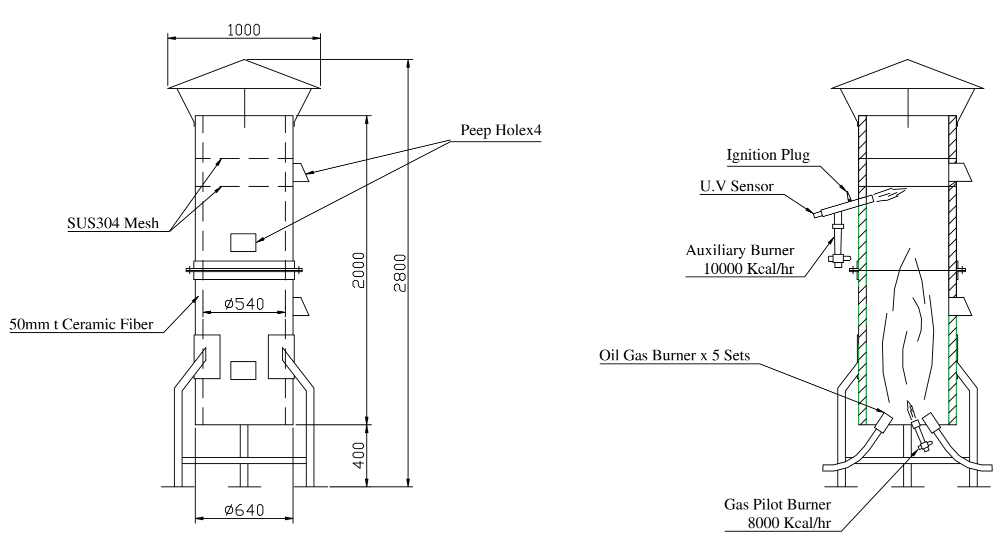

Fig. 1. Schematic of the oil incinerator.

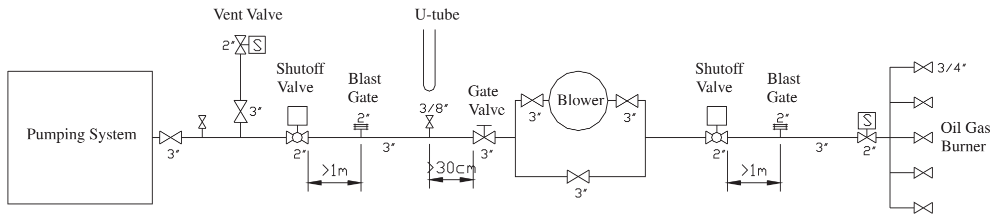

Fig. 2. Schematic of the oil gas supply and safety control system.

A schematic of the oil gas supply and safety control system is shown in Fig. 2. The spilled oil is first recovered from the pumping wells, and then oil and water within it are separated. The oil gas is produced in the recovery process of oil spill, and it is introduced into the oil gas burners. Since the oil gas contains oxygen concentration in excess of LEL, control system must be taken to insure the safety. Two sets of flame-proof switch (Blast gate) and shut-off valve are installed behind the vent valve and before the oil gas burner of the oil gas supply pipe to prevent the flame flashback. Additionally, a flame-arrester made of 1.2 m long wire-meshed screens is installed between the flame-proof switch and the main valve. We also install a vent to discharge the oil gas if the oil gas flow is terminated abruptly because of the starts of flame-proof switch and shut-off valve. When the incinerator is operating, the oil gas supply pressure is an important operating parameter. Therefore, an explosion-protected blower is installed in the by-pass pipe loop to provide pressure high enough and suitable for the burner. The gas oil supply pressure can be monitored by the U-tube manometer.

In this study, the flame appearance, CO emission and temperature of the flue gas are significantly influenced by the following parameters: (1) oil gas composition, (2) the number of pumping well, (3) the number of oil gas burner, (4) oil gas supply pressure, and (5) oil gas supply rate. The presence of higher oil gas concentration increases the amount of theoretical air required for stoichiometric combustion and thus the risk of incomplete combustion. We focus particularly on the CO emission resulted from incomplete combustion in this study. The concentrations of the combustion product components are measured continuously using the commercially available gas pollutant analyzer (MAX-5, Teledyne Analytical Instruments). Meanwhile, a standard K-type thermocouple is used to measure the temperature of flue gas. The position of measurement is on the center of the top cross-section of incinerator but underneath the hood.

We first discuss the uncertainties associated with the measurements before discussing the experimental results. It is noted that the uncertainty of the measurement is usually a small value compared to the scatter of the data that is the result of the changes in operation conditions. Both the error due to sensor installation and the error quoted for the sensor can contribute to uncertainty of the measurement. However, all sensors have been well installed for proper operation of the analyzer. Therefore, the error due to sensor installation is much smaller compared to the error quoted for the sensor. In the measurement of flue gas temperature, about 95% of the recorded temperatures fall within ±10 °C of the mean temperature. The error is caused by the thermocouple reading. The accuracy of the K-type thermocouple provided by Omega Engineering Inc. is ±1.1 °C or 0.4%. By assuming those errors are independent of each other, the overall error is $\pm[(10)^2 + (1.1)^2]^{0.5} = \pm 10.06$ °C, calculated by using the root-sum-square method [26]. The measuring ranges of the emission analyzer are 0–20.9% for O_2 (with measuring accuracy of about ±0.2% from the measured value and resolution of 0.1%) and 0–4000 ppm for CO (with measuring accuracy of about ±5 ppm from the measured value and resolution of 1 ppm).

4. Results and discussion

In this study, we adopt 10 pumping wells (see Table 2) to test and analyze the operating characteristics from the incinerator. Table 2 shows the features of various pumping wells, including water level, oil level and oil thickness. As can be seen, except #2, #3 and #9 wells having thin oil thickness less than 10 cm, the pumping wells adopted herein have oil thickness greater than 100 cm. Especially, #1, #5 and #7 wells have oil thickness greater than 200 cm.

Fig. 3 displays the flame structure at different operating conditions. If the number of pumping well is less than or equal to six, three oil gas burners are employed. The oil gas concentration is too low to ignite, thus only the two pilot flames are observed. If the number of pumping well is seven and three oil gas burners are still utilized, the yellow flame with high flame height occurs.

Table 2
The features of various pumping wells.

Operating sequence	Well no.	Water level (cm)	Oil level (cm)	Oil thickness (cm)
1	#1	616	390	226
2	#2	420	385	35
3	#3	440	409	31
4	#4	525	409	116
5	#5	588	380	208
6	#6	515	355	160
7	#7	555	324	231
8	#8	540	352	188
9	#9	414	407	8
10	#10	497	387	110

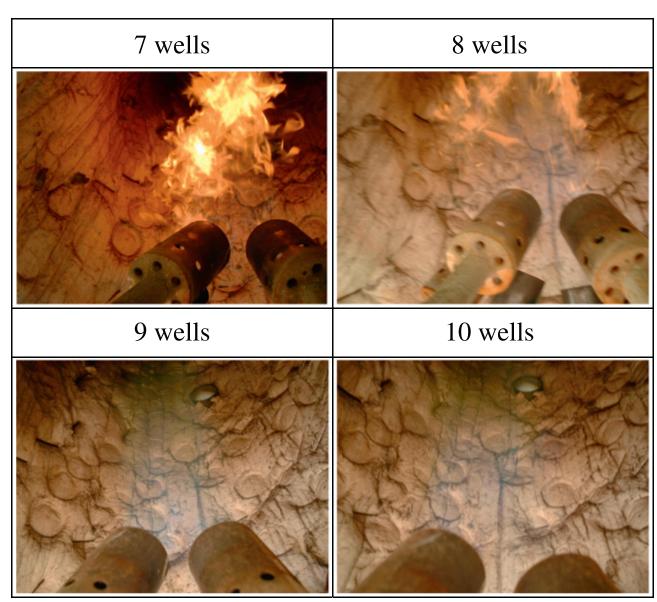

Fig. 3. The flame structures at different operating conditions.

Yellow flame indicates that the primary air is not sufficient. This is because the newly added #7 pumping well possesses the maximum oil thickness (231 cm) corresponding to the high oil gas concentration. This phenomenon is similar to what was found by Ko and Lin [17], i.e., the greater the thermal input is, the more incomplete combustion will result. Now we add one oil gas burner to burn oil gas, that is, we use four oil gas burners. After about 2 min, it is found that the flame color changes from yellow to blue and flame height decreases due to the gradual decrease of oil gas concentration. This characteristic has also been observed by Cheng et al. [15].

When the number of pumping well is eight, we also use four oil gas burners. A yellow flame appears since the oil gas concentration increases again. Similarly, the flame color changes from yellow to blue after 1 min. This is also caused by the gradual decrease of oil gas concentration. As one pumping well is added again, five oil gas burners are employed to burn oil gas produced by the nine pumping wells. It is found that the flame color is still blue and is nearly the same as before. The reason is that the oil gas concentration of newly added pumping well is not high enough to produce a yellow flame. When the number of pumping well is increased to 10, five oil gas burners are also employed to burn the oil gas. The flame height slightly increases but the flame color is still blue.

Fig. 4 shows the variations of CO and O_2 concentrations and temperature of flue gas with time when the numbers of pumping well and oil gas burner are, respectively, six and three. Since the concentration of oil gas is too low to ignite at this condition, only the upper and lower pilot flames exist. Therefore, the temperature and O_2 concentration only slightly increases with time. This result agrees with the observation of flame appearance shown in Fig. 3. However, the CO concentration decreases greatly with time since the oil gas concentration decreases gradually. This characteristic is similar to that with increasing primary aeration, the CO emission decreases (reported by Hou et al. [23]).

Fig. 5 shows the variations of CO and O_2 concentrations and temperature of flue gas as a function of time as the numbers of pumping well and oil gas burner are, respectively, seven and four. The flue gas temperature first rises rapidly and then decreases after it reaches the maximum temperature. The maximum temperature occurs when the flame has the maximum flame height corresponding to the highest oil gas concentration. Under the condition that the maximum temperature occurs, the flame color is yellow, resulted from the high oil gas concentration. However, the variation of CO concentration with time has the opposite trend. That is, with increasing time, the CO concentration first decreases gradually, then rises abruptly to a peak after the temperature reaches maximum value, and finally decreases gradually. The O_2 concentration follows the same trend as the CO characteristic curve. The reduction of O_2 concentration is owing to the increase of oxygen consumption for burning with increasingly high oil gas concentration. The increase of O_2 concentration is due to the gradual decrease of oil gas concentration, leading to the decrease of O_2 consumption for burning with oil gas. Furthermore, as described above, the flame color changes from yellow to blue and flame height decreases due to the gradual decrease of oil gas concentration, which also agrees well with the observations in Cheng et al.'s study [15].

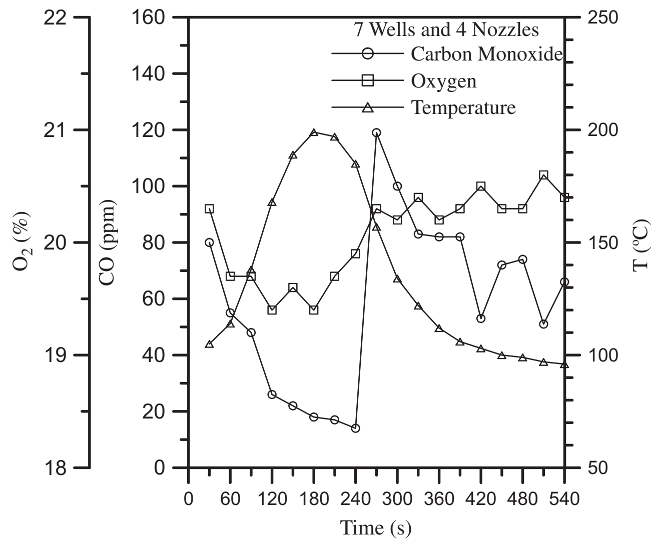

Fig. 5. The variations of CO and O_2 concentrations and temperature of flue gas with time as the numbers of pumping well and oil gas burner are seven and four, respectively.

Fig. 6 shows the CO and O_2 concentrations and temperature of flue gas as a function of time when the number of pumping well

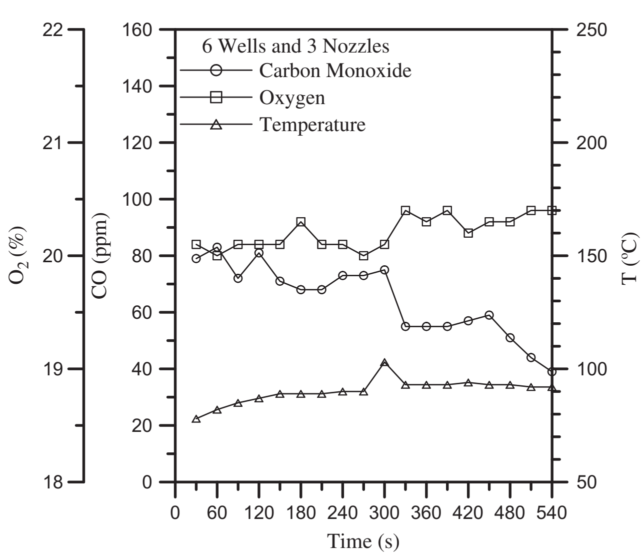

Fig. 4. The variations of CO and O_2 concentrations and temperature of flue gas with time as the numbers of pumping well and oil gas burner are six and three, respectively.

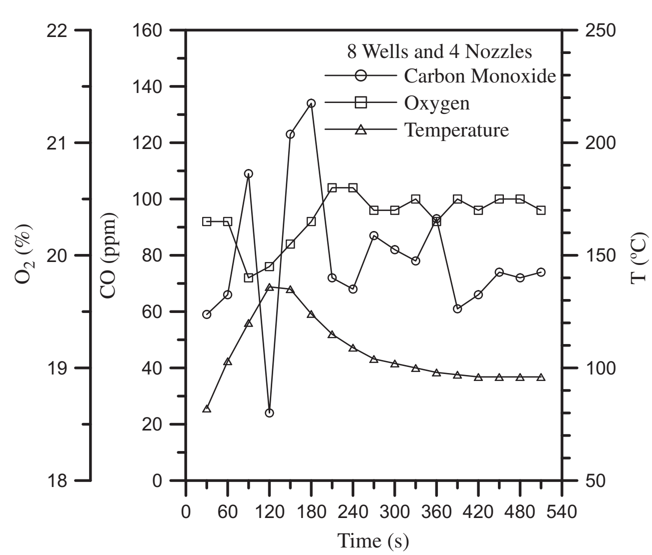

Fig. 6. The variations of CO and O_2 concentrations and temperature of flue gas with time as the numbers of pumping well and oil gas burner are eight and four, respectively.

is equal to eight and the number of oil gas burner is equal to four. The variations of CO and O_2 concentrations and temperature of flue gas with time are similar to those shown in Fig. 5. Fig. 7 illustrates the CO and O_2 concentrations and temperature of flue gas as a function of time as the number of pumping well is equal to nine and the number of oil gas burner is equal to five. As can be seen, the variations of O_2 concentration and temperature of flue gas are almost unaffected by operating time. Also, the characteristic curve of CO concentration versus time is only slightly changed. These results agrees well with the observations of flame appearance shown in Fig. 3 that the flame color is still blue and is nearly the same as before (eight pumping wells and four gas burners). This is because the oil gas concentration of the newly added pumping well is low.

Fig. 8 shows the variations of CO and O_2 concentrations and temperature of flue gas with time as the number of pumping well is 10 and the number of oil gas burner is five. Under this operating condition, the flame color is blue and the CO concentration is lower than 20 ppm after 2 min. This indicates that the oil gas concentration from #10 pumping well is low and the combustion is complete. The flue gas temperature rises as the flame height increases. Based on the results of Figs. 4–8, we can find that the new designed oil gas burner system is satisfactory for burning oil gas at various compositions and supply rates during the recovery process of oil spill.

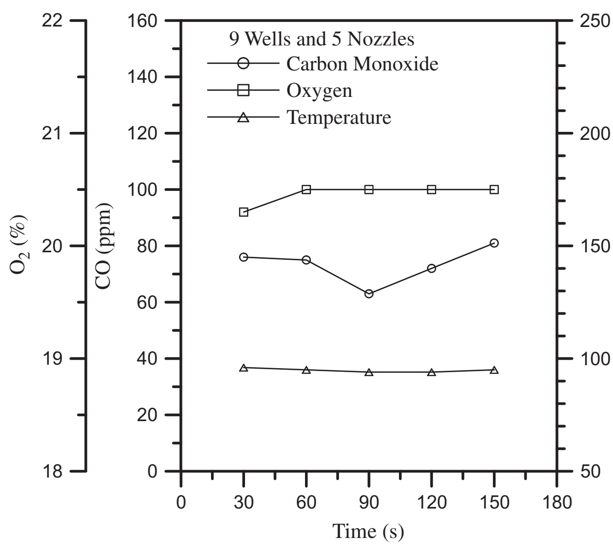

Fig. 7. The variations of CO and O_2 concentrations and temperature of flue gas with time as the numbers of pumping well and oil gas burner are nine and five, respectively.

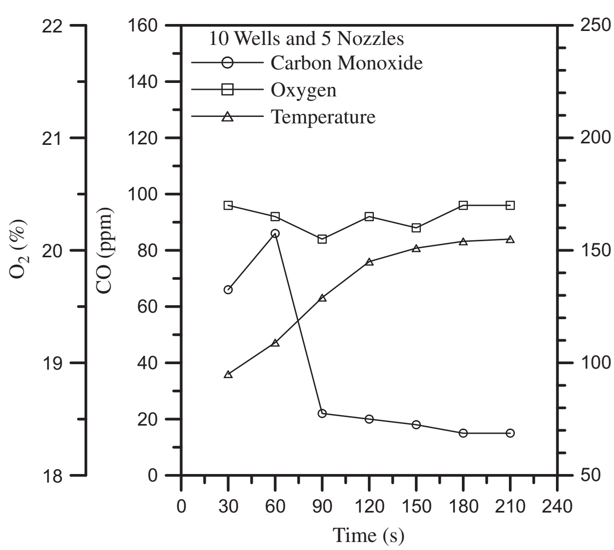

Fig. 8. The variations of CO and O_2 concentrations and temperature of flue gas with time as the numbers of pumping well and oil gas burner are ten and five, respectively.

5. Concluding remarks

Burning oil gas has many difficulties because both gas compositions and supply rates of the oil gas are varied in the recovery process of oil spill. Furthermore, at the end of the recovery process, the oil gas may contain various oxygen concentrations at low pressure. This therefore may result in incomplete combustion (i.e., a great increase of CO emissions and/or smoke emissions), flame liftoff, flame flashback, and even explosion. Without doubt, it is a challenge to design a safety and reliable oil gas incinerator system satisfactory for burning oil gas at various compositions and supply rates during the recovery process of oil spill.

In this study, we successfully develop a vertical-type incinerator, which consists of five oil gas burners with entrained primary air, a pilot burner, and an auxiliary burner. The incinerator system is equipped with necessary control units in order to achieve safe, easy, fast, and efficient operation. For instance, for the safety point of view, the auxiliary burner is incorporated with an UV sensor to detect abnormal ignition or extinction. Since the oil gas contains oxygen concentration in excess of the lower explosive limit (LEL), control system must be taken to insure the safety. Two sets of flame-proof switch (Blast gate) and shut-off valve are installed behind the vent valve and before the oil gas burner of the oil gas supply pipe to prevent the flame flashback. In addition, a flame-arrester made of 1.2 m long wire-meshed screens is installed between the flame-proof switch and the main valve. We also install a vent to discharge the oil gas if the oil gas flow is terminated abruptly because of the starts of flame-proof switch and shut-off valve.

Because of the characteristics of oil gas, including low supply pressure, various compositions and supply rates, we use the permanent pilot supplied by LPG to burn the issuing oil gas. Under long-term operation, we find that the new incinerator system is satisfactory for burning oil gas at various compositions and supply rates during the recovery process of oil spill, and that it can provide clean exhaust and safety control. It is worthy to note that the results obtained in the present study are of great significance to provide a good guidance for those who need to set up and operate an incinerator system providing clean exhaust and safety control for burning oil gas generated during the recovery process of oil spill.

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