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Treatment of Oily Waste Using a Scaled-up Carbonization Kiln

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A carbonization kiln was scaled up by a factor of 100 and used to treat oily waste while utilizing off-gas combustion. Initial oil concentration in waste material ranged from 57,700 to 881,000 mg/kg-dry, and oil removal rates exceeded 99.97% by carbonization at 600 °C with superheated steam. Weight reduction rate of the oily waste was 8.9 to 95.0%, with higher ratios of initial water and organic matter resulting in higher weight reduction rates. Oil recovery rate increased with higher oil load, whereas heating time and fuel consumption per unit oil load decreased. However, excessive oil load relative to the scale of the kiln caused decreased oil recovery rate and increased off-gas generation, resulting in difficult control of off-gas combustion. The scaled-up kiln achieved oil removal performance equal to or superior to smaller experiments. The oil load of the waste material was shown a key parameter for both oil recovery and processing efficiencies related to heating time and fuel. Appropriate oil loads should be identified based on prioritization of such operational factors.

Keywords
Oily waste, Oily sludge, Superheated steam, Carbonization, Oil recovery, Off-gas

1. Introduction

Treatment of oily wastes generated in production and refining processes is one of the major environmental issues facing the petroleum industry in oil producing countries. Oily wastes such as crude oil storage tank sludge and oil-based drilling mud contain various hazardous materials such as oil (petroleum hydrocarbons) and heavy metals. Generation of oily waste is increasing, and combined with the processing cost and capacity limitations of currently available treatment technologies, is resulting in the accumulation of large amounts of untreated oily waste. Consequently, inexpensive and effective treatment methods are now needed.

Various technologies have been investigated for the treatment of oily wastes. Solvent extraction has high oil removal efficiency, and allows oil recovery, but the cost is very high and is considered to be impractical. Biological treatment methods capable of large-scale treatment such as land farming can be implemented at low cost, but the treatment period is lengthy and the space requirement is large. Additionally, some oily wastes such as crude oil storage tank sludge contain resin and asphaltene that is difficult to treat biologically. Thermal decomposition treatment such as carbonization has high oil removal capability and also allows oil recovery, so development continues as a promising technology. For example, addition of various catalysts improves the oil recovery amount and recovered oil quality, resulting in decreased overall treatment cost. However, the properties of oily wastes can vary greatly by location and over time, so thermal decomposition treatment using a catalyst must adapt the optimum conditions, such as catalyst type and addition amount, to the properties of the oily waste to be treated.

This study investigated carbonization treatment (pyrolysis) using superheated steam, without any catalyst, to remove oil from waste. Superheated steam is generated under the operating pressure (steam at 100 °C under normal pressure) and further heated to a temperature higher than the boiling point. This superheated steam heats anoxically, as heat is directly applied without air. Air heating acts only by convection, whereas superheated steam has very high heat energy that can be transferred by condensation and radiation, as well as convection, resulting in superior heat efficiency compared to air heating.

In an earlier study, carbonization treatment using superheated steam removed oil concentrations in waste...
of 59,800 to 217,000 mg/kg-dry at rates of 99.9 % or more. However, the treatment scale was small, i.e., 0.3-0.5 kg/batch. Furthermore, the amount of gas generated from the small amounts of oily waste was minimal, so the off-gas could not be effectively utilized. Application of this technology to industrial oily waste treatment will require investigation of the difference in thermal and reaction conditions between small-scale experiments and industrial-scale treatment.

Therefore, this study evaluates the carbonization treatment of oily wastes under conditions closer to industrial treatment, i.e., the test scale was increased by a factor of 100, and the effects on oil removal and recovery were evaluated. Furthermore, utilization of off-gas generated by the scaled-up process as heating fuel was evaluated to assess the effects on heating time and fuel consumption.

2. Materials and Methods

2.1. Oily Waste

Samples of oily wastes were collected from two oil fields in Oman (Site-C and Site-D). Oily sludge was collected from concrete pits designed for crude oil storage tank sludge (oily sludge pit or OSP). Oil that is separated by gravity over time is recovered by skimming in these pits. Then the heavier oily sludge remaining at the bottom of the pits is mixed with local sand and processed as oil-contaminated sand (OCS). The oily sludge sample from Site-C was collected from the bottom of a pit after oil recovery, whereas the samples from Site-D were collected from the top surface of full pits prior to oil recovery. In particular, OSP D2 appeared to contain relatively more oil than oily sludge collected from the pit bottom at Site-C, as reflected in the high oil concentration (881,000 mg/kg-dry) of OSP D2. OCS was collected from the contaminated soil area. Oil-based mud (OBM) from well drilling operations was collected from its storage pits and areas. Two different samples of OSP and OBM were collected at Site-D. Table 1 shows the properties of each oily waste.

| Type                  | Abbreviation | Oil content [mg/kg-dry] | Water content [%] | Ignition loss [%] | Sulfide [mg/kg-dry] | Sulfur [mg/kg-dry] |
|-----------------------|--------------|-------------------------|-------------------|------------------|---------------------|--------------------|
| **Site-C**            |              |                         |                   |                  |                     |                    |
| Sample 1              | OSP C1       | 283,000                 | 23.2              | 41.7             | 2,210               | 19,500             |
| Sample 2              | OBM C2       | 109,000                 | 9.6               | 12.8             | 88                  | 8,180              |
| Sample 3              | OCS C3       | 103,000                 | 3.6               | 17.2             | <20                 | 15,500             |
| **Site-D**            |              |                         |                   |                  |                     |                    |
| Sample 4              | OSP D1       | 191,000                 | 7.2               | 24.3             | 890                 | 7,100              |
| Sample 5              | OSP D2       | 881,000                 | 12.4              | 94.7             | 780                 | 8,100              |
| Sample 6              | OBM D3       | 121,000                 | 9.8               | 12.6             | -                   | -                  |
| Sample 7              | OBM D4       | 154,000                 | 9.6               | 9.2              | -                   | -                  |
| Sample 8              | OCS D5       | 57,000                  | 1.8               | 10.4             | -                   | -                  |

- : not measured.

Fig. 1 Carbonization with Superheated Steam System

Fig. 2 Oily Waste Loading Method to Prevent Bumping
ber. Air (oxygen) was purged from the chamber with nitrogen gas at 10-20 mL/min. Initial heating was carried out using kerosene for most Site-C sample tests and later diesel for the other tests, as the latter was less costly and more readily available. Superheated steam was prepared by supplying tap water into the carbonization chamber at 3 mL/min. Off-gas generated from heating of the oily wastes was cooled in a condenser, and oil and water were recovered. Ice was charged into the condenser as needed. Remaining off-gas after passing through the condenser was returned to the carbonization kiln and combusted for heating. Operation of the air blower and switching between fuel and off-gas combustion was automated by a control circuit. A dry desulfurization unit was installed in the stack for removal of any sulfur gases present in the flue gas. Thermocouples were installed in the carbonization kiln to control and monitor treatment progress. Heating was stopped when the temperature of the carbonization chamber reached a predetermined temperature. After overnight cooling and confirmation that the temperature of the carbonization kiln was sufficiently lowered, the carbonization trays were removed from the kiln.

### 2.3. Carbonization Treatment

#### 2.3.1. Carbonization Treatment of Simulated Sludge

A preliminary test was carried out using a simulated sludge to determine the optimum treatment temperature for oil removal, confirm off-gas combustion, and for initial analysis of the off-gas and flue gas components. The simulated sludge was prepared from C heavy oil, which was judged to be similar to the oil present in Omani oil sludge, added to sand, so that the sludge oil concentration was roughly 20%, and water content was roughly 7%. Nozzles for gas sampling were installed in the off-gas piping after the condenser, and before and after the flue desulfurization equipment. The preliminary test conditions are shown in Table 2.

#### 2.3.2. Carbonization Treatment of Sample Oily Waste

Carbonization treatment of sample oily waste was carried out under the treatment conditions shown in Table 3. The maximum amount of treated oily waste was 48 kg/batch, which is roughly 100 times larger than previous experiments. Oil concentration, ignition loss, and water content of residue were measured after carbonization treatment to evaluate the oil removal rate and weight reduction rate. The oil recovery rate was evaluated as the ratio of recovered oil quantity to the oil load of the waste. Here, the oil load is defined as the amount of oil in the sample oily waste. In addition, the time and fuel efficiencies per unit of oily waste were calculated from the treatment time and fuel consumption. Here, the treatment time was the heating time until the carbonization chamber reaches a predetermined temperature at which heating was stopped.

### Table 2 Preliminary Test Parameters for Simulated Oil Sludge

| Amount (kg/batch) | Treatment temperature (°C) |
|-------------------|-----------------------------|
| Test 1            | 37                          | 500                         |
| Test 2            | 56                          | 600                         |
| Test 3            | 56                          | 650                         |

### Table 3 Treatment Test Parameters and Measurements for Each Oily Waste Sample

| Sample  | Amount (kg/batch) | Oil load (kg/batch) | Treatment temperature (°C) | Residence | Recovered oil | Off-gas component |
|---------|-------------------|---------------------|----------------------------|-----------|---------------|-------------------|
|         |                   | Oil content         | Water content              | Ignition loss | Amount | Carbon number |
| Treatment 1 | OSP C1  | 8.0                | 1.7                        | 600        | ○ -         | -                 |
| Treatment 2 | OSP C1  | 16.0               | 3.5                        | 600        | ○ -         | -                 |
| Treatment 3 | OSP C1  | 32.0               | 7.0                        | 600        | ○ ○ ○      | ○ ○ ○            |
| Treatment 4 | OSP C1  | 32.0               | 7.0                        | 600        | ○ ○ ○      | ○ ○ ○            |
| Treatment 5 | OSP C1  | 48.0               | 10.4                       | 600        | ○ ○ ○      | ○ ○ ○            |
| Treatment 6 | OBM C2  | 16.0               | 1.6                        | 600        | ○ -         | -                 |
| Treatment 7 | OBM C2  | 16.0               | 1.6                        | 600        | ○ -         | -                 |
| Treatment 8 | OBM C2  | 48.0               | 4.7                        | 600        | ○ ○ ○      | ○ ○ ○            |
| Treatment 9 | OCS C3  | 16.0               | 1.6                        | 600        | ○ -         | -                 |
| Treatment 10 | OCS C3 | 24.0               | 2.4                        | 600        | ○ -         | -                 |
| Treatment 11 | OSP D1  | 8.0                | 1.4                        | 600        | ○ -         | -                 |
| Treatment 12 | OSP D1  | 32.0               | 5.7                        | 600        | ○ ○ ○      | ○ ○ ○            |
| Treatment 13 | OSP D2  | 32.0               | 24.7                       | 600        | ○ ○ ○      | ○ ○ ○            |
| Treatment 14 | OBM D3  | 32.0               | 3.5                        | 600        | ○ ○ ○      | ○ ○ ○            |
| Treatment 15 | OBM D4  | 16.0               | 2.2                        | 600        | ○ -         | -                 |
| Treatment 16 | OBM D4  | 32.0               | 4.5                        | 600        | ○ ○ ○      | ○ ○ ○            |
| Treatment 17 | OCS D5  | 32.0               | 1.8                        | 600        | ○ ○ ○      | ○ ○ ○            |
| Treatment 18 | OCS D5  | 32.0               | 1.8                        | 600        | ○ -         | -                 |

○: measured. - : not measured.
2.4. Analytical Methods

2.4.1. Water Content and Ignition Loss

The water content and ignition loss of the oily waste were measured based on "Considerations for guidance on the general waste treatment business (Ministry of the Environment, Government of Japan)." Briefly, water content was determined by heating at 105 °C for 1 h, and ignition loss was determined by heating at 600 °C for 3 h. Therefore, the water content value may also include any light oil content which evaporated during heating up to and at 105 °C.

2.4.2. Oil Concentration and Carbon Number Composition

Oil concentration was evaluated as total petroleum hydrocarbons (TPH) by infrared (IR) spectrometry based on the guidelines for oil pollution countermeasures. The extraction solvent for the IR method was H-997 (manufactured by Horiba, Ltd.), and a calibration curve was prepared with A heavy oil.

Carbon number composition of oil in waste was evaluated by the gas chromatographic distillation test carried out for oil content with boiling point range of 700 °C or less (C6-C100), conforming to ASTM D 2887 and ASTM D 6352. The results of the carbon number composition analysis were divided into three ranges of C6-C12, C13-C28, and C29-, and their abundance ratios were calculated.

2.4.3. Off-gas and Exhaust Gas Components

Methane (CH₄) and carbon dioxide (CO₂) were measured using a gas monitoring device (ECOPROBE 5: RS DYNAMICS Co. Ltd.). Carbon monoxide (CO), hydrogen sulfide (H₂S), sulfur dioxide (SO₂), hydrogen (H₂), and hydrogen chloride (HCl) were measured using gas detector tubes (GASTEC Corp.). The preliminary test showed H₂ concentration in the off-gas exceeded the measurement range of the detector tube. Therefore, the gas sample was collected in a Teflon-coated glass bottle for H₂ measurement by gas chromatography coupled with a thermal conductivity detector in a lab.

3. Results and Discussion

3.1. Carbonization Treatment of Simulated Sludge

Table 4 shows the preliminary test results for the simulated sludge. Combustion of off-gas occurred from 300 °C. H₂S was detected in the off-gas, but HCl was not detected at any stage. No SO₂ was detected in the flue gas, nor any odor or soot. After heating of the simulated sludge to 500 °C, the upper portion of the residue was powdery, but the lower portion was hard and lumpy. This indicated that removal of the oil content was incomplete. After heating of the simulated sludge to 600 °C and 650 °C, both upper and lower portions of the residue were powdery, suggesting that removal of the oil content was complete. Table 5 shows the oil concentration and water content before and after treatment at 600 °C.

Table 5 Oil Content, Water Content and Ignition Loss before and after Preliminary Carbonization Treatment Test at 600 °C

| Type                  | Oil content [mg/kg-dry] | Water content [%] | Ignition loss [%] |
|-----------------------|-------------------------|-------------------|-------------------|
| Before carbonization  | 99,000                  | 7.0               | 21.7              |
| After carbonization   | not detected            | 0.1               | 3.2               |

3.2. Carbonization Treatment of Oily Waste Samples

3.2.1. Residue after Carbonization Treatment

Carbonization treatment was carried out for the oily waste samples based on the preliminary test results using the simulated sludge. Table 6 shows the amount of residue, water content, ignition loss, and oil concentration after treatment of each oily waste. The water content of all residues was 1.00 % or less, similar to the results of the previous small experiments (0.00-0.06 %). Ignition loss ranged from 1.47 to 42.32 %, with only Treatment 13 (OSP D2) resulting in the large loss of 42.32 %, and the loss was comparable to the results obtained in the previous small experiments (3.40-12.37 %). The ignition loss remaining in the residue was judged to consist of organic matter that became charred during the carbonization treatment. The large loss for Treatment 13 is believed to be due to low inor-
ganic matter content (4.6%) of the processed waste (OSP D2), which was significantly lower than the values for the other oily wastes (44.8-88.0%). The oil concentration was 54 mg/kg-dry or less in all treatment residues, indicating that all oily wastes had been adequately treated. The scale-up process had no significant effect on the oil concentration remaining in the residue compared with the results of the previous small experiments (N.D.-65 mg/kg-dry).

### Table 6 Residue Amount, Oil Content, Water Content and Ignition Loss of Oily Wastes after Carbonization Treatment

| Sample   | Residue [kg] | Oil content [mg/kg-dry] | Water content [%] | Ignition loss [%] |
|----------|--------------|-------------------------|-------------------|------------------|
| Treatment 1 OSP C1 | 5.08 | - | - | - |
| Treatment 2 OSP C1 | 9.48 | - | - | - |
| Treatment 3 OSP C1 | 18.70 | 42 | 0.02 | 3.50 |
| Treatment 4 OSP C1 | 19.90 | 45 | 0.25 | 3.38 |
| Treatment 5 OSP C1 | 18.80 | 11 | <0.01 | 4.10 |
| Treatment 6 OBM C2 | 12.89 | - | - | - |
| Treatment 7 OBM C2 | 13.12 | - | - | - |
| Treatment 8 OBM C2 | 38.70 | 41 | <0.01 | 2.45 |
| Treatment 9 OCS C3 | 13.08 | - | - | - |
| Treatment 10 OCS C3 | - | - | - | - |
| Treatment 11 OSP D1 | 5.76 | - | - | - |
| Treatment 12 OSP D1 | 22.20 | 18 | 1.00 | 2.17 |
| Treatment 13 OSP D2 | 1.60 | 6 | 0.19 | 42.32 |
| Treatment 14 OBM D3 | 25.40 | 33 | <0.01 | 1.85 |
| Treatment 15 OBM D4 | 12.46 | - | - | - |
| Treatment 16 OBM D4 | 24.80 | 54 | <0.01 | 3.70 |
| Treatment 17 OCS D5 | 28.70 | 8 | 0.11 | 1.47 |
| Treatment 18 OCS D5 | 29.15 | - | - | - |

*: not measured.

### Table 7 Weight Reduction Rate and Oil Removal Rate of Carbonization Treatment of Oily Wastes

| Sample   | Weight reduction rate [%] | Oil removal rate [%] |
|----------|--------------------------|---------------------|
| Treatment 1 OSP C1 | 36.5 | - |
| Treatment 2 OSP C1 | 40.8 | - |
| Treatment 3 OSP C1 | 41.6 | 99.99 |
| Treatment 4 OSP C1 | 37.8 | 99.99 |
| Treatment 5 OSP C1 | 60.8 | 100.00 |
| Treatment 6 OBM C2 | 19.5 | - |
| Treatment 7 OBM C2 | 18.0 | - |
| Treatment 8 OBM C2 | 19.4 | 99.97 |
| Treatment 9 OCS C3 | 18.3 | - |
| Treatment 10 OCS C3 | - | - |
| Treatment 11 OSP D1 | 28.0 | - |
| Treatment 12 OSP D1 | 30.6 | 99.99 |
| Treatment 13 OSP D2 | 95.0 | 100.00 |
| Treatment 14 OBM D3 | 20.6 | 99.98 |
| Treatment 15 OBM D4 | 22.1 | - |
| Treatment 16 OBM D4 | 22.5 | 99.97 |
| Treatment 17 OCS D5 | 10.3 | 99.99 |
| Treatment 18 OCS D5 | 8.9 | - |

*: not measured.

### 3.2.2 Weight Reduction Rate and Oil Removal Rate

Table 7 shows the weight reduction rate and the oil removal rate of each oily waste calculated from Tables 1, 3, and 6. The weight reduction rate of oily wastes ranged from 8.9 to 95.0%, depending on the oily waste type. The weight reduction rates for OSP were higher than for other oily wastes, similar to carbonization in the previous small experiments. Figure 3 shows the relationship between the ratio of the sum of water and organic matter and the weight reduction rate of each oily waste. Here, ignition loss of oily waste is considered as organic matter. Weight reduction rate increased with higher ratio of the sum of water and organi-
ic matter, which reflects the treatment principle that most water and organic matter are removed by carbonization treatment, indicating that the scaled-up process remained effective.

The oil removal rate was calculated from the amount of oil in the oily wastes and the amount of oil remaining in the process residues. Oil removal rate was more than 99.97% for all oily wastes, indicating that the scaled-up process remained effective. Therefore, waste material with high oil concentration can be treated effectively, so oily sludge could be directly treated by carbonization, eliminating the need to mix with sand for bioremediation, and thus reducing the overall amount of oily waste requiring treatment.

3.2.3 Oil Recovery

Figure 4 shows the relationship between oil recovery rate and oil load. The oil recovery rates ranged from 0.0 to 95.2%, and increased with higher oil load. However, the oil could not be recovered for Treatment 17 (OCS D5) because the oil load was relatively low at 3.3 kg/batch. In contrast, the oil recovery rates for Treatment 5 (OSP C1) and Treatment 13 (OSP D2) were slightly lower relative to their oil load, possibly resulting from the oil load exceeding equipment capacity. Excessive oil load is believed to generate greater amounts of off-gas that cannot be efficiently processed by the condenser, resulting in lower oil recovery rate. The scaled-up carbonization kiln of this study achieved the highest oil recovery rates with the oil load of waste material in the range of 7.0 to 10.4 kg/batch.

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Figure 5 shows the carbon number range ratios of the oil in the oily waste and the oil recovered during carbonization treatment of the waste. The ratio of lower carbon numbers (C6-C12) of recovered oil was higher than that of oil in the oily waste for all types of oily waste. C6-C12 in oily waste was between 1.9% and 5.8%, whereas C6-C12 in recovered oil was between 20.0% and 35.5%. Carbonization using superheated steam presumably caused thermal decomposition of hydrocarbons with larger carbon numbers to form molecules with lower molecular weights. Temperature control of the cooling water was not implemented for this study, but the components of recovered oil could possibly be influenced by controlling the cooling water temperature, thereby increasing the quality and value of the recovered oil.

3.2.4 Off-gas Components

Thermal decomposition of oily wastes during carbonization generates flammable off-gases such as CH₄, CO, H₂S, and H₂ that are not condensed into the recovered oil. Figure 6 shows the amounts of flammable off-gases generated at different temperatures by Treatment 4 (OSP C1) and Treatment 12 (OSP D1). For all oily wastes, the flammable gas concentration was less than 1% at 100°C, but increased at 300°C or 400°C. This finding was roughly consistent with the operational timing of off-gas combustion observed during the carbonization tests. Previous thermogravimetric analysis of oil sludge from also showed that the mass reduction increases after around 300°C. Hydrogen

![Fig. 4 Relationship between Oil Load and Oil Recovery Rate](image)

![Fig. 5 Carbon Number Range Ratios of Oil before and after Recovery](image)
concentration increased above 300 °C, and CO₂ concentration also increased with temperature, presumably due to dehydrogenation of aromatic groups in the oily waste at higher temperature and to the water gas shift reaction (CO + H₂O → CO₂ + H₂) involving the H₂O in the generated gas and the superheated steam. Any differences in the oily waste may be reflected in the components of the off-gas, but no relationship was found.

In addition to the above, the following trends were confirmed.
- Concentration of CH₄ increased at temperatures of 400 °C and 500 °C.
- Concentration of CH₄ was relatively high in the measured flammable gases.
- H₂S was present in trace amounts, up to 1.2%.
- HCl was below the detectable limit (0 ppm).

Utilization of off-gas and oil recovery are considered to be trade-offs. If the components of the off-gas depend on the oily waste and can be controlled, more effective oil recovery and utilization of off-gas will be possible, and more economical oily waste treatment will be possible.

3.2.5 Heating Time and Fuel Efficiency

Figure 7 shows the relationship between the oily waste amount and the heating time. The treatment time increased with higher amount of the same type of oily waste. However, the heating time per unit oily waste amount decreased with higher amounts of waste. For example, for OSP C1, the treated amount of 8, 16, 32, and 48 kg required heating times of 155, 190, 205 (mean of 2 treatments), and 275 min respectively. The heating times per unit amount were 19.4, 11.9, 6.4 (mean of 2 treatments), and 5.7 min/kg, respectively. Therefore, treatment efficiency in terms of time was improved by increasing the waste amount per treatment batch.

The oily wastes treated in the previous and present scaled-up experiments were different and do not allow for direct comparison, but treatment time per unit oily waste was significantly less in the scaled-up experiments. Specifically, oily waste 300-500 g was treated in about 210 min, or treatment time per unit oily waste of 420-700 min/kg, whereas treatment times per unit oily waste of 4.8-19.4 min/kg were clearly shorter after scale-up.

On the other hand, heating times depended on the type of oily waste treated, specifically the oil load of the waste. Figure 8 shows the relationship between oil load and heating times per unit oil load. Heating time per unit oil load decreased with higher oil load. For example, Treatment 5 (OSP C1) and Treatment 8 (OBM C2) used different oily wastes in the same amount (48 kg/batch), resulting different oil loads. Treatment 5 (OSP C1) with oil load of 10.4 kg/batch required 24.4 min less heating time per unit oil load than Treatment 8.

![Fig. 6 Off-gas Components at Each Treatment Temperature](image)

![Fig. 7 Relationship between Oily Waste Amount and Heating Time](image)
(OBM C2) with oil load of 4.7 kg/batch. Higher oil load was believed to increase the amount of generated off-gas due to thermal decomposition of oily waste, resulting in faster heating of the carbonization chamber due to increased off-gas combustion.

Figure 9 shows the relationship between fuel consumption per unit oily waste and oil load. Similar to the relationships between heating time and oily waste amount and oil load; fuel efficiency improved with greater amounts of the same type of oily waste treated, i.e., less fuel was used per unit oily waste amount. Additionally, the fuel consumption per unit oil load improved with higher oil load in different types of oily waste. For example, Treatment 5 (OSP C1) and Treatment 8 (OBM C2) using 48 kg/batch of oily waste had oil load about 2.2 times greater, but fuel consumption per unit oil load about 1.9 times less for Treatment 5 (OSP C1). Higher oil load generates more off-gas by thermal decomposition, so consumption of fuel can be reduced by utilizing the off-gas for heating.

Figure 9(c) shows the fuel consumption per unit heating time with respect to the oil load for OSP C1 (Treatments 1-5). Similar to Fig. 9(a) and 9(b), fuel consumption per unit heating time tended to decrease with higher oil load. Expression of this relationship by a linear regression equation showed the y-intercept is 10.8. Assuming this value as the fuel consumption per unit heating time with oil load of 0 in OSP C1 oil waste treatment so without off-gas combustion, and the fuel consumption is 8.3 L/h with the oil load is 10.4 kg (Treatment 5); then the fuel consumption reduction rate in this case can be estimated as 23.4 %. Therefore, the scale-up experiments including off-gas combustion confirmed reduction of fuel consumption, with greater effect using higher oil loads.

However, oil load exceeding the capacity of the carbonization kiln proved to be problematic. Treatment 13 (OSP D2) had the largest oil load in this study at 24.7 kg/batch. The amount of off-gas generated during the test was judged to be excessive, as the high combustion of off-gas resulted in combustion temperatures above 1000 °C, as well as oxygen deficient state leading to incomplete combustion of off-gas. Inspection of the inside of the carbonization kiln after the test revealed significant soot deposition in the piping (Fig. 10). For continued safe operation, the affected parts of the carbonization kiln were dismantled and
cleaned. These results suggest that higher oil load generates more off-gas, so fuel consumption may be conserved; but excessive oil load with respect to the capacity of the carbonization kiln causes loss of control of off-gas combustion, and the kiln may be damaged. Identification and operation below the maximum oil load appropriate for the scale of the carbonization kiln is essential. For the present kiln, the maximum oil load for safe processing was considered to be between 10.4 kg/batch and 24.7 kg/batch.

4. Conclusion

Scale-up of the carbonization kiln by a factor of 100, i.e., from about 0.5 kg to a maximum of 48 kg, and carrying out carbonization treatment tests of oily waste with off-gas combustion obtained the following findings.

- Oil concentration in the residue after carbonization treatment was 54 mg/kg-dry or less, and oil removal rate was greater than 99.97 % for all oily wastes.
- Weight reduction rate of oily waste by carbonization treatment was 8.9 to 95.0 %, and was greater with higher proportion of water and organic matter in the oily waste. Consequently, both the amount of treatment residue and overall amount of waste to be treated can be greatly reduced by applying this carbonization treatment to OSP directly after drying, rather than after mixing with sand to make OCS for biotreatment.
- Oil recovery rate of the carbonization treatment increased with higher oil loads, up to a certain oil load after which the rate decreased. Highest oil recovery rates were achieved with oil loads ranging from 7.0 to 10.4 kg/batch, for this carbonization kiln.
- Carbon number composition in the recovered oil confirmed that hydrocarbons with large carbon numbers were converted to hydrocarbons with lower molecular weight by thermal decomposition using superheated steam.
- Temperature of 300 °C or higher in the carbonization chamber increased the flammable gas concentration in the off-gas, and off-gas combustion was confirmed. Differences in oily waste types are presumed to affect the components of off-gas, but no relationship was found.
- Higher amount of oily waste reduced the heating time and the fuel consumption per unit amount of oily waste. Additionally, heating time and fuel consumption per unit oil load, and the fuel consumption per unit heating time, were all decreased with higher oil load. These decreases in heating time and fuel consumption are attributed to the higher amounts of off-gas generated and used for combustion and heating.
- However, excessive oil load for the scale of the carbonization kiln generates too much off-gas, and combustion becomes difficult to control, possibly leading to damage of the kiln.

The present study indicates that the carbonization kiln can be scaled up, with similar or better results. Oil load appropriate to the scale of the carbonization furnace is a key parameter, and the optimum operating conditions for lowest cost operation should be determined from the relationships between oil load, oil recovery, processing time, fuel consumption, and components of off-gas.

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要 旨
スケールアップした炭化炉を用いた油性廃棄物の処理

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本報では、炭化炉の処理規模をこれまでの約100倍にスケールアップし、油性廃棄物の炭化処理を実施した。油性廃棄物中の油分濃度は、57,700～881,000 mg/kg-dry と高濃度を示すものもあったが、600 ℃での過熱水蒸気を用いた炭化処理によって99.97％以上の油分除去率を示した。また、油性廃棄物の減量率は8.9～95.0 ％の範囲であり、油性廃棄物の水分および有機物の割合が大きいほど高い減量率を示した。油性廃棄物による油負荷量が増加するにつれて回収率は増加し、単位油負荷量あたりの処理時間と消費燃料が低下する傾向を示した。一方、油負荷量が過剰になると油回収率は低下し、オフガスの発生量が増加することでオフガス燃焼の制御が困難になることが示された。以上より、スケールアップ後の炭化炉において、スケールアップ前と同等以上の油分除去処理が可能であることを示した。油性廃棄物を油負荷量が重要なパラメーターであり、油回収量の増加を目的とした場合や処理効率(処理時間や燃費)を目的とした場合など、目的に合った油負荷量を見つける必要がある。