Energy Saving in a Thermal Remediation System for Oil-Contaminated Soil (Heat Recovery Using a Pre-drying unit and a Heat Exchanger)

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ABSTRACT

Thermal remediation systems for treating oil-contaminated soil offer more reliable remediation capabilities than do washing and bioremediation techniques, but have the drawback of large unit energy consumption, which places a large load on the environment. A generic incinerator that produces high-temperature combustion gases as in thermal soil remediation methods is fitted with a boiler, and electric power is generated by using a steam turbine for heat recovery. In terms of scale and the characteristics of the processed materials, pre-drying of the soil was found to be appropriate for reducing the energy consumption of the soil remediation plant. In this research, we developed a system for reducing energy consumption by two methods that reduce the load of remediation on the environment. These methods are recovering heat from the 800℃ exhaust gas produced in the secondary incinerator in order to perform pre-drying using indirect heating drier units before heating the soil in the kiln, and installing heat exchangers to pre-heat the air for incineration. A bypass duct is installed in the soil pre-drying unit for controlling the heat exchange capacity. Furthermore, to increase efficiency, an exhaust mechanism for soil microparticles is installed and intake using air suction is implemented. Theoretically, this device can produce energy savings of 35% compared with conventional devices and increase the processing capacity to 110% that of devices of the same size that are not fitted with the energy-saving devices. In this study, the effectiveness of this system is verified at an actual soil remediation plant.

Key Words : Oil contaminated soil. Rotary kiln. Soil remediation

1. Introduction

In Japan, soil contamination has expanded in urban areas as a consequence of post-war economic activities that emphasized productivity with insufficient environmental consideration. Typical contaminants include heavy metals, volatile organic compounds (VOCs), and oil-based pollutants. Remediation technologies for contaminated soil include bioremediation, which utilizes the oil-degrading capability of microorganisms; soil washing, which treats oil-contaminated soil through washing and classification; and thermal treatment, in which the soil is heated to separate contaminants from the soil and subsequently treat them by thermal decomposition. Each method has specific characteristics. Bioremediation can reduce remediation costs compared with other methods; however, remediation performance depends on microbial activity for oil decomposition and is therefore strongly influenced by environmental conditions such as ambient temperature, resulting in an uncertain treatment period. In the soil washing method, residual by-products remain after washing and classification and must be treated at external waste disposal facilities or the like. In contrast, the thermal remediation method ensures reliable treatment by forcibly removing oil contaminants from soil through heating and thermal desorption. However, this method requires substantial energy input for heating and consequently imposes a significant environmental load (Hashimoto et al., 2006). In the conventional heating system previously developed by the authors, high fuel consumption has been identified as a major technical issue (Horai et al., 2013). In thermal desorption processes, gases generated by the volatilization of oil contaminants desorbed from the soil are contained in the exhaust gas. This gas is heated to approximately 800°C for complete thermal decomposition. A considerable amount of energy is consumed in this high-temperature process. Therefore, effective heat recovery from the large volume of exhaust gas is essential for achieving energy savings. In general, waste heat can be recovered by installing a waste heat boiler and generating electricity using a steam turbine generator, or by installing a heat exchanger to preheat the combustion air and thereby recover thermal energy. However, in relatively small-scale power generation systems, the power generation efficiency is low compared with the capital investment, resulting in poor economic feasibility. Furthermore, when the thermal energy contained in the exhaust gas is recovered solely through preheating of the burner combustion air, the temperature of the preheated air becomes excessively high. In addition, the temperature differential between the exhaust gas and the preheated air cannot be sufficiently maintained. Thus, an extremely large heat exchange area is required, and the installation cost of the heat recovery equipment becomes significantly high.

In this study, to effectively address the high energy consumption, which is a major challenge of the oil-contaminated soil thermal remediation system based on thermal treatment, a soil pre-drying unit employing an indirect-heating rotary kiln was developed and implemented at an actual plant. The energy-saving performance and overall effectiveness of the improved soil remediation system were experimentally verified and evaluated.

2. Conventional Soil Remediation Technologies

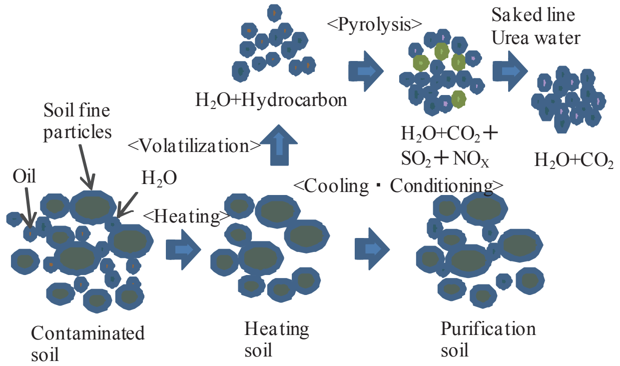

Fig1 Conception diagram of the purification by the heating

Remediation of oil-contaminated soil by thermal treatment is carried out by heating the soil to increase the vapor pressure of the oil contaminants, thereby thermally desorbing them from the soil. The gases volatilized by heating are introduced into a secondary combustion chamber, where the temperature is raised to 750–800°C to decompose the oil vapors into water and carbon dioxide, thereby rendering them harmless. Figure 1 shows a conceptual diagram of the soil remediation process. The treatment methods are classified according to the soil heating temperature. They are categorized into thermal decomposition, in which the soil is heated to 800–1000°C to decompose oil components; thermal desorption, in which the soil is heated to 400–600°C to desorb oil contaminants; and low-temperature heating treatment (thermal drying), in which the soil is heated to 200–300°C to volatilize and separate oil components (Central Environmental Council, Soil and Pesticide Sectional Meeting, 2006). The types of oil that can be remediated are determined by the soil heating temperature. As the heating temperature increases, even heavy oil fractions that are difficult to decompose can be treated. In addition, when treating substances that may generate dioxins by thermal decomposition in the secondary treatment unit, the process gas is retained in the secondary combustion chamber at a temperature of 800°C or higher for at least two seconds. In addition, a cooling tower is installed to rapidly cool the gas through the temperature range in which de novo synthesis of dioxins may occur.

In the thermal treatment method, the soil supplied from a feed hopper is introduced into a heating kiln, where it exchanges heat with the high-temperature exhaust gas generated by a burner and is heated to a designated treatment temperature for processing. The treated soil is conditioned in a cooling unit for the purposes of cooling and dust control. Meanwhile, the exhaust gas generated in the heating kiln contains volatilized oil contaminants and is introduced into a secondary combustion chamber, where it is retained at a temperature of 800°C or higher for at least two seconds to decompose hydrocarbons and dioxins. The gas is cooled in a cooling tower in order to rapidly pass through the temperature range in which de novo synthesis of dioxins may occur. After particulate matter is removed by a bag filter, the treated gas is discharged through a stack.

In the system used in this study, remediation of heavy oil fractions such as tar and pitch is assumed; therefore, the process is classified as thermal desorption, in which the soil is heated to 400–600°C.

Figure 2 shows the heat balance of the remediation

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process. The calculation conditions are as follows: soil processing capacity of 25 t/h; moisture content of 30%; soil heating temperature of 600°C and exhaust gas treatment temperature of 800°C. The equipment efficiency conditions are assumed to be an infiltration air flow rate of 120 Nm^3/min and a heat loss from the equipment of 5%. The heat required for soil heating corresponds to the sensible heat necessary to raise the temperature of dry soil which does not contain moisture from ambient temperature to 600°C. The heat accounts for approximately 17% of the total heat input. The heat required for moisture evaporation shown in the figure corresponds to the energy necessary when the soil is heated to temperatures above 100°C. To heat the soil above 100°C, it is firstly necessary to evaporate the moisture contained in the soil. This heat corresponds to the energy utilized as the latent heat of vaporization of the moisture. This energy accounts for approximately 34% of the total heat input. The objective of thermal treatment is to remove the contaminated oil from the soil. However, evaporation of the soil moisture is necessary in order to treat the oil. It is therefore evident that the amount of moisture contained in the soil has a significant influence on the overall energy consumption. The heat required for exhaust gas heating corresponds to the energy necessary to raise the infiltration ambient air and combustion exhaust gas to the exhaust gas treatment temperature of 800°C. The heat required for steam heating represents the energy necessary to raise the water vapor evaporated from the soil to the same treatment temperature. The sum of these two components constitutes the heat required to elevate the gas to 800°C and thermally decompose the oil vapors into water and carbon dioxide. When heat loss from the equipment is included, these components account for approximately 50% of the total heat input. In the exhaust gas treatment stage, water vapor accounts for approximately 12% of the heat requirement, indicating that the moisture content of the soil also affects the energy demand of exhaust gas treatment.

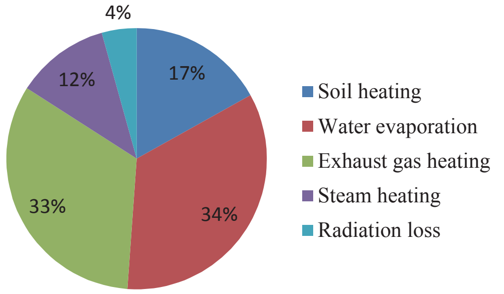

Fig2 Heat balance in the soil purification processing

In conventional soil remediation plants, exhaust gas heated to approximately 800°C is rapidly cooled in a cooling tower to a temperature suitable for treatment by a bag filter. Dioxin re-synthesis occurs within the temperature range of 250–400°C, and the gas must be rapidly quenched as it passes through this critical range. However, the temperature range between 800°C and 400°C provides significant potential for waste heat recovery. Approximately 50% of the total thermal energy is retained in the exhaust gas, and energy savings can be achieved by recovering a portion of this heat.

In order to improve the energy efficiency of the soil thermal remediation system, reducing the moisture content of the soil and recovering heat from high-temperature exhaust gas are effective.

3. Newly Developed Energy-saving Soil Remediation System

In selecting a remediation method, it is necessary to comprehensively consider factors such as the type and extent of oil contamination, the remediation period, and the surrounding environment. For example, in urban areas where land prices are high, it is important to complete remediation within a short period—even if relatively high treatment costs are required—in order to enable effective land utilization. In such cases, thermal remediation becomes advantageous. In on-site treatment projects, the remediation plant is typically installed as a temporary facility for the duration of the work. In general, the investment in the equipment is planned to be recovered within a single project. Therefore, the cost-effectiveness of energy-saving equipment in a single remediation project becomes a key factor in decisions regarding its introduction. Important parameters in evaluating the introduction of energy-saving equipment include soil treatment capacity, remediation period, equipment performance, and fuel costs.

As described above, thermal remediation plants have the advantage of ensuring reliable remediation compared with other treatment methods, since the soil is heated to thermally desorb the oil contaminants. However, this method also has the disadvantage of high energy consumption. Therefore, in the present study, in order to address this issue, a method for recovering waste heat from the exhaust gas heated to 800°C was investigated, and a newly developed energy-saving soil remediation system was established.

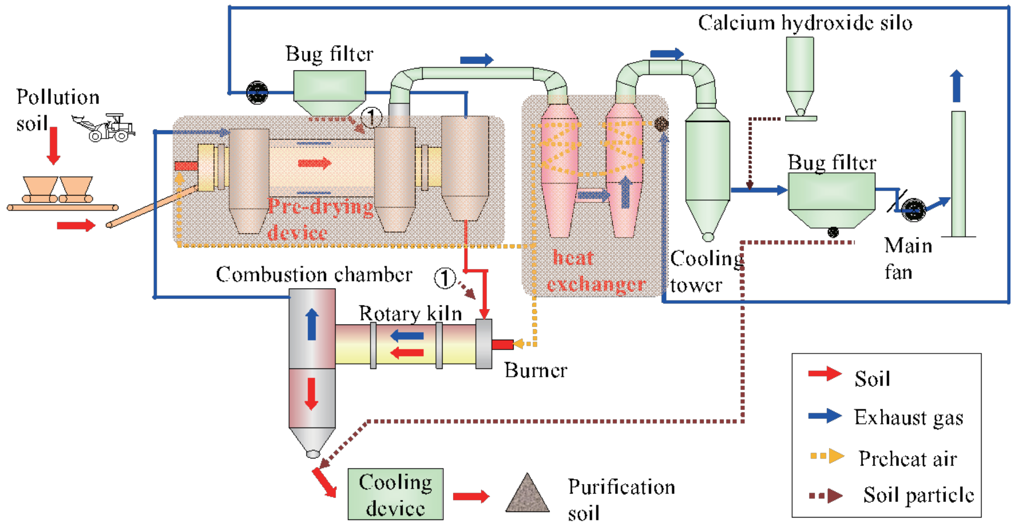

Fig3 Flow of Saving energy model remediation system for oil-contaminated soil

As described above, typical methods of waste heat recovery in heating furnaces and incinerators include generating steam in a boiler and using the steam to drive a steam turbine generator for power production, recovering heat as hot water using a hot-water boiler, and recovering the heat for use as combustion air. However, power generation using a steam boiler requires a certain minimum scale to ensure economic feasibility. The treatment capacity of a soil remediation plant is at most approximately 25 t/h, and the heat input supplied by the burner is about 15 MW. Even if the waste heat were utilized for power generation, the actual power output would be less than 1 MW when system losses are taken into account, making it difficult to recover the equipment investment within a short period. Further, for implementation in an on-site plant, practical constraints such as the limited construction period and available installation space make such a system unrealistic. In addition, even when waste heat is recovered in the form of hot water, its practical utilization is subject to operational constraints, making its application difficult.

The major difference between the soil remediation plant addressed in this study and a conventional incinerator lies in whether the material to be treated possesses intrinsic calorific value. In a soil remediation plant, the treatment target is soil containing oil and moisture and, in principle, does not possess a significant calorific value. Although the oil fraction has calorific value, the oil content in typical contaminated soil is generally less than 10,000 ppm; therefore, from the standpoint of the overall heat balance, its contribution as a heat source is negligible. In contrast, the waste treated in an incinerator typically has a calorific value of approximately 4,000–10,000 kJ/kg and does not require external energy input for treatment. In most cases, with auxiliary combustion, the calorific value of the waste alone is sufficient to maintain the exhaust gas temperature at 800°C; therefore, no heat can be effectively recovered as combustion air preheating. In the soil remediation plant, a large amount of fuel must be combusted to heat the soil and exhaust gas, making it possible to utilize waste heat within the system. However, if heat is recovered solely through the combustion air, the temperature of the preheated combustion air exceeds 500°C. In addition, a sufficiently large temperature difference cannot be maintained between the heat source side and the heat-receiving side, and a large heat exchange area is required for the heat exchanger, resulting in increased equipment costs. In this study, an indirect heating kiln was employed as a pre-drying unit to reduce the moisture content of the soil prior to the soil heating treatment kiln, and a method for recovering waste heat was investigated using the soil heating treatment kiln.

Figure 3 presents the system flow diagram of the newly developed soil remediation system. The process gas heated to 800°C is first utilized in a pre-drying unit to pre-dry the soil. Subsequently, heat is recovered using a heat exchanger to preheat combustion air for the burner. The off-gas generated in the pre-drying unit, which contains water vapor and oil-derived gases, is utilized as the combustion air.

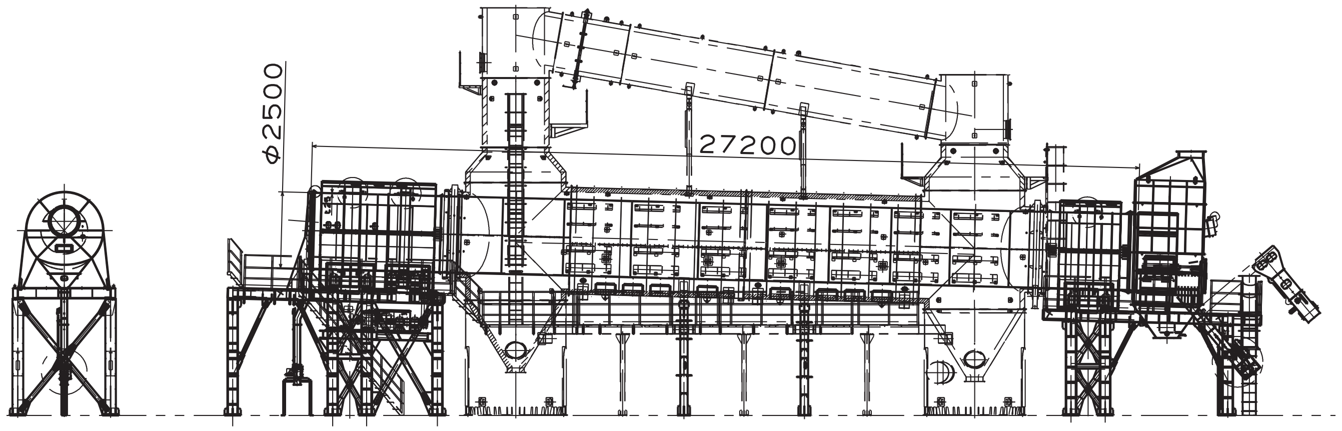

Fig4　Side view of the pre-drying device

3.1 Pre-drying unit

The pre-drying unit evaporates moisture contained in the treated soil by utilizing waste heat at 800°C from the secondary combustion chamber. A side view of the pre-drying unit is shown in **Figure 4**. The unit has a double-cylinder structure including an outer shell and an inner cylinder. High-temperature exhaust gas at 800°C flows through the space between the outer and inner cylinders, while the soil fed into the inner cylinder is indirectly heated and dried through a SUS steel plate. The inner cylinder has dimensions of 2.5 m in diameter and 27 m in length and is constructed of SUS304 stainless steel with a thickness of 25 mm. The cylinder is installed at an inclination and rotates, allowing the material to move downward along the slope. **Figure 5** shows an internal view of the pre-drying unit. Lifters are installed inside the inner cylinder. As the cylinder rotates, the soil is lifted and then dropped from the upper portion of the cylinder, thereby loosening the soil and improving conductive heat transfer through contact with the heat transfer surface of the inner cylinder. This motion also promotes material dispersion and enables convective heat exchange with the gas heated by indirect heating inside the cylinder. The inner cylinder reaches a high temperature due to heat exchange with the external exhaust gas, and therefore, radiative heat transfer is also expected to occur.

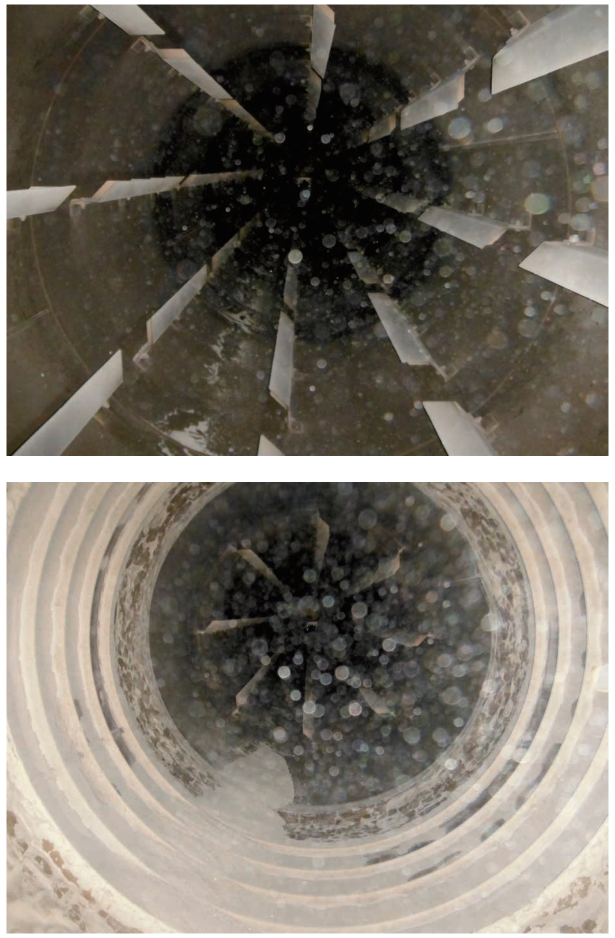

Fig5　inside of the pre-drying device

A mechanical challenge of this system is that, as the inner cylinder is heated by exhaust gas at 800°C, when the temperature of the inner shell rises, its mechanical strength may be significantly reduced, leading to deflection of the inner cylinder. Furthermore, repeated stress caused by rotational motion may induce fatigue, potentially shortening the service life of the equipment. Therefore, to prevent overheating of the inner shell, continuous retention of soil inside the inner cylinder is required during operation. A bypass duct equipped with a damper is installed at the top of the unit to control the flow rate of high-temperature exhaust gas that is used to heat the inner cylinder. When the surface temperature inside the inner cylinder becomes excessively high as measured by a radiation thermometer, the high-temperature exhaust gas is delivered through the bypass duct to reduce the temperature rise of the drying unit shell. If soil is deposited on the inner surface of the cylinder, the heat transfer coefficient in conductive heat transfer is significantly reduced. Under such conditions, the adhered soil deposits function as a thermal insulating layer, causing the inner cylinder shell to reach excessively high temperatures and potentially leading to the problems described above. Once deposits are formed, they may adversely affect the drying capacity and soil conveying performance of the pre-drying unit. In addition, loads exceeding the design values may be imposed on the inner drum support structure. Therefore, it is essential to prevent the formation of internal deposits of soil. Furthermore, the exhaust gas contains a large amount of fine soil particles on the order of 100 μm. Accordingly, these particles accumulate on the inner surface of the outer cylinder when the high-temperature exhaust gas flows through the space between the outer and inner cylinders. To discharge the accumulated fine particles, flights are attached in a spiral configuration to the outer surface of the inner cylinder. The rotational motion of the inner cylinder causes the fine soil particles to be conveyed and discharged into hoppers installed on both sides of the unit.

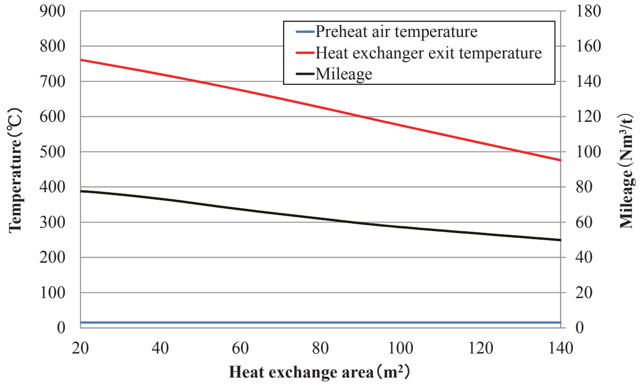

Fig6　Effect of the heat exchange area to give to exhaust gas temperature and the mileage

Figure 6 presents the estimated results of the heat exchange area of the pre-drying unit and its effect on improving fuel efficiency. In this estimation, the conditions used in the above heat balance calculation were applied, and the target overall heat transfer coefficient was assumed to be 46 W/m^2·K. As the heat exchange area increases, the specific fuel consumption decreases. When the heat exchange area reaches 80 m^2, the fuel consumption is improved from 79.1 to 62.0 Nm^3/t. The temperature of the high-temperature exhaust gas leaving the pre-drying unit correlates with the reduction in specific fuel consumption. At a heat exchange area of 80 m^2, the temperature also decreases from 800°C to 625°C. As the heat exchange area increases, more energy is recovered from the high-temperature exhaust gas, resulting in a decrease in its temperature. Consequently, the temperature difference between the high-temperature exhaust gas and the material becomes smaller, which in turn requires a larger heat exchange area. Accordingly, as the amount of heat exchanged increases, the heat transfer performance per unit area decreases. Furthermore, increasing the heat exchange area requires a larger pre-drying unit. Once the unit exceeds a certain size, transportation and installation costs rise significantly. Due to these constraints, there exists an optimal size that provides the greatest cost effectiveness. In addition, a heat exchanger is installed downstream of the pre-drying unit in this soil remediation system, and therefore, it is necessary to determine each heat exchange area by considering the balance between the heat recovery capacity and the equipment cost of both systems.

3.2 Heat Exchanger

In the heat exchanger, the high-temperature exhaust gas, from which part of the energy has already been recovered by the pre-drying unit, exchanges heat with the off-gas generated therefrom. The recovered thermal energy is then utilized for preheating the combustion air for the burner. The exhaust gas temperature first increases to 800°C in the secondary combustion chamber and then reduces to approximately 600°C through heat recovery in the pre-drying unit. The gas is subsequently supplied to the heat exchanger. The off-gas generated in the pre-drying unit contains water vapor and, depending on the type of oil contaminating the soil, may also contain volatile organic compounds (VOCs). Therefore, a thermal decomposition treatment of these components is required. To achieve this, the off-gas is heated through heat exchange and subsequently utilized as combustion air, where it is combusted within the rotary kiln that is used for heating the contaminated soil. However, the oxygen concentration is insufficient when only the off-gas is used as combustion air for the burner. Accordingly, ambient air is drawn in through the material feed inlet of the pre-drying unit, and the unit is operated so that the oxygen concentration of the combustion air is maintained at 15% or higher. Similar to the pre-drying unit, a bypass duct is installed at the top of the heat exchanger to control the outlet temperature not to fall below the dioxin re-synthesis temperature. Specifically, when the energy recovery efficiency of the pre-drying unit or the heat exchanger becomes excessively high and the temperature falls below the dioxin re-synthesis temperature, the exhaust gas is bypassed to reduce the heat recovery rate.

Figure 7 shows a side view of the pre-drying unit. The system adopts a counterflow configuration, in which the exhaust gas on the heat-releasing side and the exhaust gas on the heat-receiving side flow in opposite directions for heat exchange. The two units of the system are connected in series so that the overall height is reduced while maintaining a configuration that secures the exhaust gas flow path. The heat exchanger is of a multi-tubular type. The exhaust gas for heat release flows inside the tubes, while the off-gas combustion air for heat receipt flows outside the tubes. **Figure 8** shows a photograph of the multi-tubular structure inside the heat exchanger. The structure is configured to allow the exhaust gas to pass through the interior of the tubes to prevent deposition of soil particulates, as the exhaust gas contains a significant amount of fine soil particles. In addition, the flow rate on the heat-receiving side is smaller than that on the heat-releasing side. Accordingly, baffles are installed internally to increase the gas velocity and thereby enhance the heat transfer coefficient. This configuration ensures that the heat-receiving gas contacts the outer surfaces of the tubes at a relatively high velocity.

Figure 9 presents the results of a simulation estimating the relationship between the heat exchange area and the improvement in fuel efficiency. The figure suggests that as the heat exchange area increases, the temperature of the preheated air rises, resulting in improved fuel efficiency. In addition, the exhaust gas temperature on the heat-releasing side appears to decrease with increasing heat exchange area due to the increase in heat recovery.

Higher preheating temperatures of the combustion air yield greater energy-saving effects. However, the temperature difference between the heat-releasing and heat-receiving gases decreases as the heat exchange area increases. Consequently, the heat exchange capacity per unit area declines, leading to a diminishing improvement effect. Furthermore, the exhaust gas leaving the heat exchanger needs to be maintained at a temperature of 400°C or higher in order to prevent the re-synthesis of dioxins.

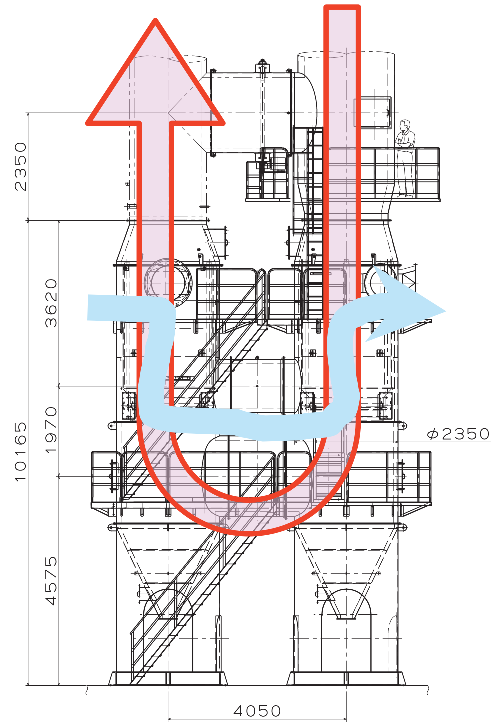

Fig7　Side view of the heat exchanger

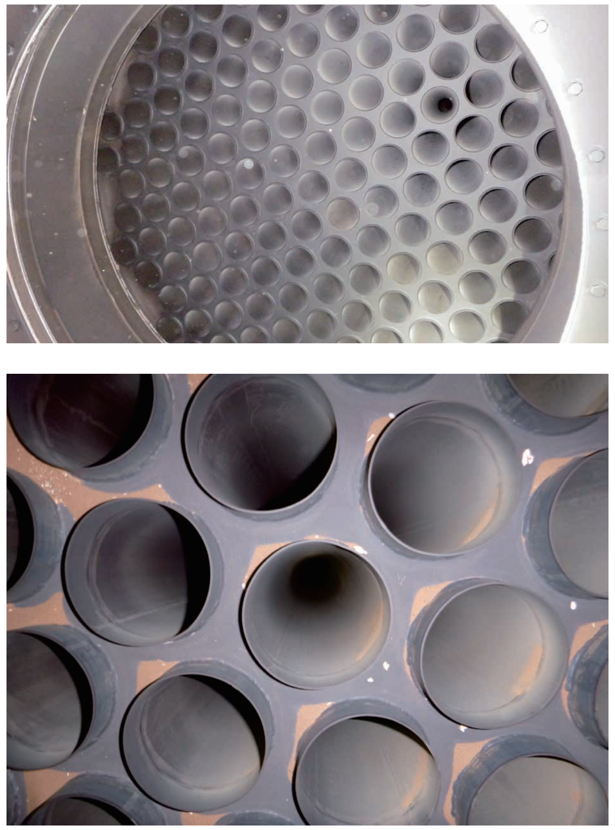

Fig8　inside of the heat exchanger

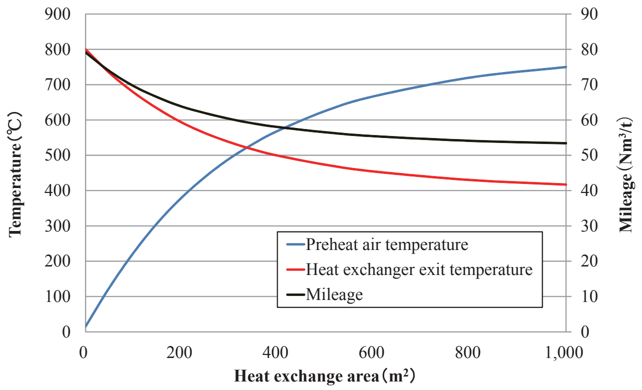

Fig9　Effect of the heat exchange area to give on gas temperature and mileage

4. Verification of Performance in Actual Operation

The proposed system was introduced into an actual soil remediation process, and its energy-saving performance was evaluated. The evaluation was conducted at a soil treatment capacity of approximately 20 t/h and a soil moisture content of approximately 20%. The energy-saving effects of the pre-drying unit and the heat exchanger are summarized below.

4.1 Energy-Saving Effect of the Pre-drying unit

Figure 10 shows the operating data of the pre-drying unit. The exhaust gas treatment temperature in the secondary combustion chamber was 820°C, and after waste heat recovery in the soil pre-drying unit, it decreased to 600°C. This temperature reduction of the exhaust gas corresponds to the amount of heat recovered by the unit. The figure also presents the treatment capacity and the energy-saving effect. The system was operated at a slightly lower throughput than the rated capacity of 25 t/h. However, it was confirmed that an energy-saving effect close to the target value of 19% was achieved. The overall heat transfer coefficient was set at 46 W/m²·K as the design target value, and the results indicate that the expected performance was almost achieved. It should be noted that the overall heat transfer coefficient evaluated here is not based solely on the heat exchange area where the soil contacts the heat transfer surface inside the kiln. Instead, it is calculated using the total surface area of the inner kiln cylinder. This approach is adopted because soil heating within the kiln occurs not only through thermal conduction from the inner cylinder to the soil, but also through thermal radiation from portions of the inner cylinder that are not in direct contact with the high-temperature soil, as well as through convective heat transfer associated with evaporated gases passing through the interior of the cylinder. The overall heat transfer coefficient is therefore a critical parameter in kiln design, as it determines the required heat exchange area. It is strongly influenced by the conditions of the soil and the residence behavior of materials within the kiln.

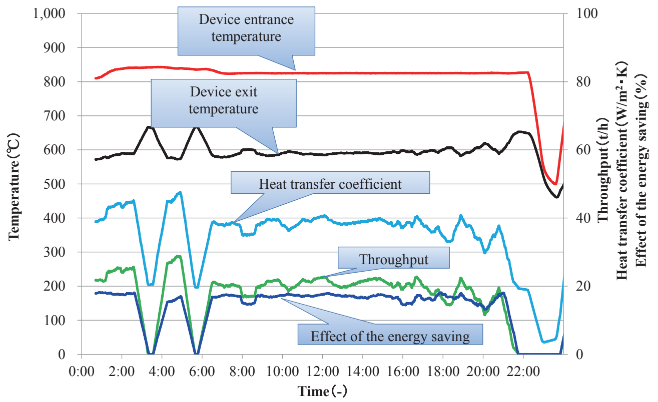

Fig10　Operative data of the pre-drying device

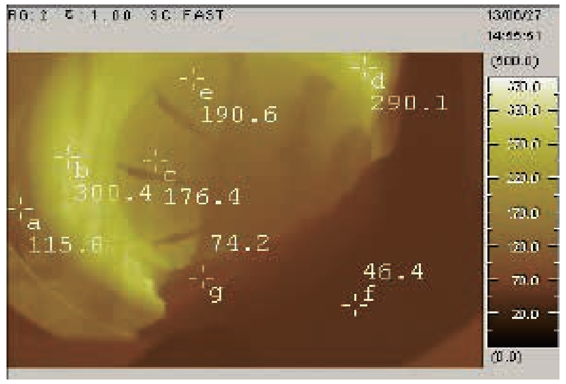

Fig11　Thermography of the pre-drying device

Figure 11 shows a thermal image of the kiln interior taken from the material feed side. The material filling ratio was approximately 20%, and the wall temperature reached about 300°C at its highest points. The rotational speed of the kiln was 2.2 min⁻¹. While variations in wall temperature distribution can be observed along the longitudinal direction, no significant temperature variation is evident in the circumferential direction. At the design stage, it was a concern that significant temperature differences in the circumferential direction could cause the inner cylinder to distort due to differential thermal expansion, thereby adversely affecting the structural integrity of the system. Therefore, calculations were performed in advance to confirm that no substantial circumferential temperature variation would occur. The results were consistent with these predictions. One contributing factor is the 25-mm thickness of the SUS inner cylinder plate, which provides a sufficiently large thermal capacity. In addition, the soil retained inside the unit is lifted by the lifters, and it is presumed that heat conduction is enhanced by the agitation of the soil. Furthermore, it is also considered that convective heat transfer with the evaporated gas is promoted.

4.2 Energy-Saving Effect of the Heat Exchanger

Figure 12 shows the operating data of the heat exchanger. The inlet temperature of the heat exchanger is 590°C, and the temperature decreases to approximately 460°C at the heat exchanger outlet. This temperature change of the exhaust gas corresponds to the amount of heat recovered by the unit. After heat recovery in the heat exchanger, the exhaust gas temperature is maintained at 400°C or higher, indicating that it remains above the temperature range at which de novo synthesis of dioxins may occur.

The figure also presents the treatment capacity and the energy-saving effect. The system was operated below its rated capacity, and the achieved energy-saving effect was approximately 14%, which falls short of the target value of 21%. The design target for the overall heat transfer coefficient was 33 W/m²·K; however, the average measured value was approximately 29 W/m²·K. One possible reason for this discrepancy is the relatively low volumetric flow rate of the preheated air on the heat-receiving side. To compensate for this, baffle plates were installed inside the heat exchanger to increase gas velocity and reduce the thickness of the thermal boundary layer. However, the effect of this approach appears to have been insufficient.

5. Relationship Between Energy Savings and Processing Capacity

In soil remediation plants, the primary factor limiting processing capacity is the exhaust gas treatment capacity. In the secondary combustion chamber, the exhaust gas is required to remain for at least two seconds at 800°C. In the cooling tower, the exhaust gas is required to remain for an additional four seconds for cooling. As the moisture content of the treated soil increases, the burner firing rate required to heat the soil also increases, resulting in a higher exhaust gas flow rate. Furthermore, a greater amount of water vapor evaporates from the soil. Due to these effects, an increase in soil moisture content leads to limitations in the processing capacity of the soil remediation plant. **Figure 13** illustrates the influence of soil moisture content on processing capacity and specific fuel consumption. As shown in the figure, the processing capacity decreases as the soil moisture content increases. In addition, the specific fuel consumption is strongly affected by the processing capacity and decreases as the moisture content decreases, as described above.

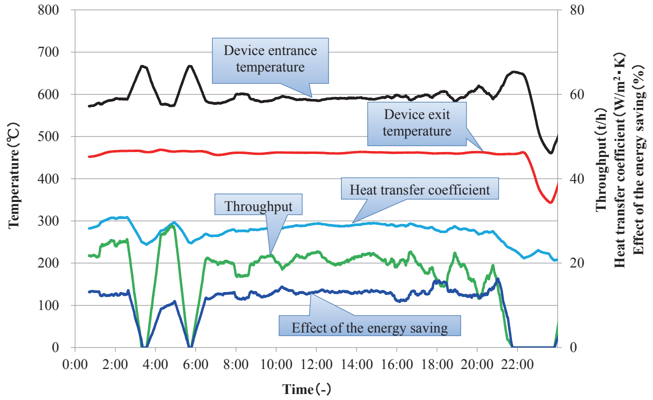

Fig12 Operative data of the heat exchanger

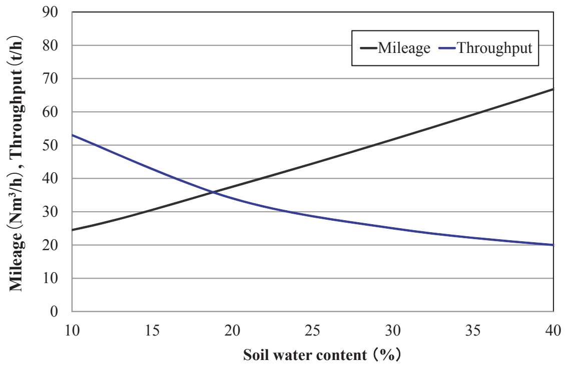

Fig13 Effect of soil water content to give on mileage and throughput

When a pre-drying unit and a heat exchanger are installed as part of an energy-saving system, the fuel consumption of the burner used to heat the soil is reduced. As a result, the volume of exhaust gas decreases. When systems of the same size are compared, the system equipped with energy-saving devices can achieve a higher processing capacity than a system without such devices. By introducing the energy-saving system, not only the environmental load can be reduced, but the overall size of the equipment can also be reduced. Consequently, the total equipment cost can also be lowered.

6. Conclusions

A soil thermal remediation system ensures reliable remediation performance. However, it has the disadvantage of high energy consumption rate and significant environmental load. To improve these characteristics, a method of recovering heat from exhaust gas at 800°C was adopted. The recovered heat is utilized to pre-dry the soil in an indirect heating dryer before it is introduced into the heating process. In addition, a heat exchanger was installed to preheat the combustion air. Through these measures, an energy-saving soil remediation system was developed. The findings obtained from the present study are summarized as follows:

1. The energy balance of a thermal remediation system for oil-contaminated soil was estimated, and the energy consumption of each process was analyzed to identify key areas requiring improved fuel efficiency.
2. Energy-saving measures were investigated, and a full-scale system was developed incorporating soil preheating using a pre-drying unit and heat recovery through combustion air preheating by means of a heat exchanger.
3. An energy-saving soil remediation system was constructed at full scale, and its energy-saving performance was experimentally verified.
4. In the remediation of actual contaminated soil, the overall heat transfer coefficients of both the soil pre-drying unit and the heat exchanger were evaluated and confirmed.

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