Heat recovery of waste gases in thermal-oxidative waste disposal systems using gas turbine techniques

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Abstract. The issues of utilization of heat recovery of high-temperature waste gases of thermal-oxidative solid and liquid waste disposal systems using cogeneration gas turbine techniques with reverse order of processes are considered. The article presents technological scheme, calculation method, design characteristics and analysis of energy and environmental efficiency of thermal-oxidative solid and liquid waste disposal systems based on rotating, layer and chamber furnaces using gas turbine techniques with reverse order of processes. The results of the analysis indicate the possibility of additional generation of electric and thermal energy, which will significantly reduce fuel consumption in the replaced thermal power plants and the corresponding negative environmental impacts. The coefficient of heat utilization in the thermal oxidation neutralization system can reach 0.72 – 0.79, the coefficient of efficiency of the system (CEWEP) 1.17 – 1.57. The obtained calculated data can be used in selecting the best available techniques for energy waste disposal using thermal-oxidative neutralization and gas turbine techniques with reverse order of processes.

1. Introduction
In the course of human life, a large amount of production and consumption waste is generated that cannot be processed, which is mainly disposed of at special landfills or in thermal waste disposal systems (TWDS).

Burial at the landfill and its subsequent maintenance is an expensive undertaking and takes land occupied by the landfill out of land use for 15 to 20 years.

One of the preferred options for the disposal of such wastes is their thermo-oxidative neutralization with heat recovery (Waste-to-energy, WtE), which reduces their volume for disposal or subsequent disposal by about 10 times, it is useful to use the heat of thermal oxidation for heat supply and electrical energy. Thermal-oxidative waste disposal systems (TOWDS) are characterized by a short processing time of waste, including hazardous and / or extremely hazardous, the ability to control the composition and purification of exhaust gases.

So, in Japan more than 70% of BWW are burned with electric energy, in 55% in Sweden, in France waste incinerators in the suburbs of Paris provide more than 80% of the city’s energy consumption [1].

In the process of thermo-oxidative neutralization of waste, high-temperature flue gases are formed at a temperature of 900 - 1200°C, which may contain fly ash [2, 3]. To reduce the costs of neutralization, the heat of the exhaust flue gases is usually used in gas-water heaters to produce hot water or in steam boilers-utilizers for producing water vapor, which can be used for heat and power supply, their drawback is a rather large metal consumption [4–6].
Recently, energy microturbine techniques and plants for various purposes, in particular for autonomous energy-technological complexes, are developing [7–12].

Their advantage is a more energy-efficient conversion of high-temperature heat of gases into mechanical or electrical energy, the ability to work at low energy loads, low operating costs, high reliability.

The present work is devoted to the study of the possibility of using gas turbine techniques for the utilization of the heat of exhaust gases from thermal oxidative waste disposal systems (TOWDS) in order to increase their energy and environmental efficiency required when choosing them as the best available technique (BAT).

2. Problem Statement

There are a large number of works devoted to the research and development of gas turbine techniques for thermal utilization of solid household and industrial waste [13–15]. Of particular interest is the use of gas turbine techniques with a “reverse” sequence of processes that allow to utilize the heat of exhaust high-temperature gases of TOWDS by directly using them as a working fluid of a cogeneration gas turbine unit [16, 17, 18].

The absence of sound gas-turbine techniques for the direct utilization of heat of the high-temperature exhaust gases of TOWDS as a working fluid of a gas turbine allows us to formulate the task of the study - the development and calculation-theoretical analysis of the energy and environmental efficiency of the technological scheme of TOWDS using cogeneration gas-turbine technology with an “inverse” sequence of processes for utilizing the heat of the outgoing high-temperature flue gases needed to further substantiate the choice of BAT.

Figure 1 shows the technological scheme of TOWDS with the utilization of the heat of the exhaust gases when using cogeneration gas-turbine technology with a “reverse” sequence of processes [17, 18].

The scheme includes a gas turbine (GT), in which the high-temperature flue gases (FG) coming from TONS expand from atmospheric pressure to the vacuum generated by the gas compressor (GC). The work performed in this case is used to drive a gas compressor (GC) and an electric generator (EG). Flue gases (FG) worked out in a gas turbine (GT) enter a gas-water heater (GWH) and a gas cooler (GC), in which, due to the heating of cold water, they are cooled to a temperature of 27–30 °C and sent to a gas compressor (GC), in where the flue gas pressure (FGP) rises to atmospheric.

If necessary, for example, during the thermal oxidation of solid waste, the scheme provides for the preliminary cleaning of flue gases in front of the gas turbine of solid ash particles using ceramic filters (F), as well as the subsequent gas cleaning system (CS), after which the cleaned flue gases with a smoke exhaust (SE) ) are removed through the chimney (C) into the environment. As filters, it is possible to use ceramic filters developed at SRIOGAZ with pulse regeneration, equipped with Madisson Filtor Gerafil ceramic elements, capable of operating at temperatures up to 900 °C with the simultaneous removal of dioxins and nitrogen oxides, as well as filter units with ceramic filter elements of ZAO “STI BAKOR” [19–23].

If the temperature of the flue gas exceeds the permissible temperature for the ceramic filter (F) and gas turbine (GT), they are replaced by atmospheric air (Air).
3. Results and discussion

To assess the energy efficiency of using cogeneration gas-turbine techniques with a “reverse” sequence of processes, calculations of gas-turbine techniques technological schemes for thermal-oxidative neutralization of solid waste using rotary kilns (coefficient of excess air $\alpha = 2$) and layered furnaces (coefficient of excess air $\alpha = 1.6$), as well as liquid non-combustible waste using chamber furnaces (coefficient of excess air $\alpha = 1.1$).

When performing the calculations, the following were adopted: the temperature of the exhaust flue gases from the thermal-oxidative neutralization system $t''_{TOWDS} = 1200^\circ$C, diesel fuel is the additional fuel to maintain the required temperature of the neutralization process, the heat loss in the reaction volume of TOWDS is 5%, the temperature of the flue gases in front of the gas turbine (GT) - 800 °C, 850 °C and 900 °C, in front of the compressor - 21 (except option 7, where it is taken equal to 40 °C) the degree of increase in gas pressure in the gas compressor (GC) - 3; pressure loss coefficient - 0.95; isentropic efficiency of the turbine - 0.82; compressor - 0.8, mechanical efficiency - 0.92; electric generator - 0.95. Also, mixing into the flue gases of atmospheric air was taken into account, which was necessary to reduce their temperature to an acceptable temperature for a gas turbine.

The productivity of TOWDS for waste was adopted at 1000 kg/h, the elementary chemical composition of the working mass of solid waste was similar to municipal household waste (MHW). The coefficient of excess air in TOWDS $\alpha = 2$.

The calculations were carried out according to known methods [24–26]. The calculation results are shown in Table 1.

Table 1. The main calculated characteristics of thermal oxidative treatment systems using cogeneration gas turbines with a “reverse” sequence of processes.

| Name of indicator                        | Unit of measurement | Options for operating modes |
|------------------------------------------|---------------------|-----------------------------|
| Waste performance                        | kg/h                | 1  | 2  | 3  | 4  | 5  | 6  | 7  |
| The coefficient of excess air in TOWDS   | $\alpha$            | 1.6 | 2  | 2  | 1.6 | 2  | 1.6 | 1.1 |
| Flue gas temperature before GT           | °C                  | 800 | 800 | 900 | 900 | 850 | 850 | 850 |
The consumption of additional fuel to maintain the required temperature of the process of thermal-oxidative waste disposal, kg/s:

\[
B = \frac{V_G \cdot c_G \cdot t_{TOWDS} + q_{VAP} - q_{W}^{p} \cdot (1 - q_{LOSS}) - \alpha_{ot} \cdot V_{ot}^{p} \cdot c_{Air} \cdot t_{Air}}{Q_{AF}^{CAL}}
\]

\(V_G\) – the volume of flue gases generated during thermal-oxidative waste disposal of 1 kg of waste, m³/kg;
\(q_{VAP}\) – the heat of vaporization of the waste components, kJ/kg;
\(c_G, c_{Air}\) – specific volumetric heat capacity, respectively, of flue gases and air, kJ/(m³°C);
\(t_{TOWDS}\) – the temperature of flue gases in the process of thermal-oxidative waste disposal, °C;
\(Q_{W}^{p}\) – lower net calorific value of combustible components 1 kg of waste, kJ/kg;
\(q_{LOSS}\) – heat loss of the process of thermal-oxidative waste disposal;
\(\alpha_{ot}\) – coefficient of excess air of the process of thermal-oxidative waste disposal;
\(V_{ot}^{p}\) – theoretical amount of air for thermal oxidation of 1 kg of waste, m³/kg;
\(t_{Air}\) – air temperature, °C;
\(Q_{AF}^{CAL}\) – specific net calorific value of 1 kg of additional fuel, kJ/kg;
\(G_{W}\) – waste productivity, kg/s;

\(N_E = W_E \cdot G_G \cdot G_{W}\)

\(W_E\) – specific electrical work of 1 kg of flue gases in gas turbines, kJ/kg;
\(G_G\) – the mass of flue gases at the gas turbine unit, referred to 1 kg of waste, kg/kgₜ.

Thermal power of gas turbines, kW:

\(Q_{TE} = Q_{GWH-GO} \cdot G_G \cdot G_{W}\)
Available thermal power, kW:

\[ Q_{\text{Avail}} = G_W \cdot Q_{\text{HW}}^p + B \cdot Q_{\text{HAF}}^p \]

Heat utilization coefficient:

\[ \eta_U = \frac{N_E + Q_{\text{TE}}}{Q_{\text{Avail}}} \]

Savings equivalent fuel in a replaceable boiler room, kg/h:

\[ \Delta B_{\text{KY}} = \frac{Q_{\text{TE}} \cdot 3600}{Q_{\text{EF}} \cdot \eta_{\text{KY}}} \]

\[ Q_{\text{EF}} \] – specific heat of combustion of equivalent fuel, kJ/kg;
\[ \eta_{\text{KY}} \] – Efficiency of the replaced boiler house (accepted \( \eta_{\text{KY}} = 0.9 \))

Savings in fuel equivalent in a replaceable power plant, kg/h:

\[ \Delta B_{\text{EPP}} = \frac{N_E \cdot 3600}{Q_{\text{EF}} \cdot \eta_{\text{EPP}}} \]

\[ \eta_{\text{EPP}} \] – Efficiency of the replaced power plant (accepted \( \eta_{\text{KY}} = 0.37 \)).

When evaluating the energy efficiency of the Waste-to-energy technology of TOWDS by the Confederation of European Waste Processing Plants (CEWEP), the primary energy savings (heat of combustion of the fuel), as well as the efficiency of TOWDS, determined by the ratio between the energy received during the thermal oxidation of waste and energy, are taken into account consumed by the process itself (calorific value of additional fuel) [9, 10, 11].

Primary energy utilization coefficient:

\[ K_U = \frac{N_E + N_E}{\eta_{\text{EPP}} \cdot \eta_{\text{KY}}} \]

System efficiency coefficient:

\[ K_E = \frac{N_E + Q_{\text{TE}}}{B \cdot Q_{\text{H}}} \]

The results presented in Table 1 show that when the performance of the thermal oxidative treatment system for recyclable waste is 1000 kg/h and the temperature of the exhaust flue gas is 1200 °C, the use of cogeneration gas turbine technology with a “reverse” sequence of processes when changing the coefficient of excess air in the process of neutralizing solid waste from 1.6 to 2 allows you to get additional electric 316 - 516 kW and thermal 2519 - 3409 kW of power, save 343 - 465 kg/h of standard fuel in a replaceable boiler and condensation power plant.

The heat utilization coefficient in the system reaches 0.73 - 0.78, the primary energy is 0.92 - 1, and the system efficiency is 1.17 - 1.57. When the system operates, 8000 h/year, annual equivalent fuel savings in replaced heat power plants will amount to 2744 - 3720 t/year.

Under the given initial conditions: the productivity of the recyclable waste, the temperature of the exhaust flue gases, the change in the temperature of the flue gases in front of the gas turbine from 800 °C to 900 °C in the conditions of cogeneration gas-turbine technology with a “reverse” sequence of processes has little effect on the energy efficiency of the system. This is due to a change in the composition and consumption of flue gases through a gas turbine unit, associated with the supply of additional air for dilution of flue gases in front of a gas turbine. The consumption of flue gases through a gas turbine installation varies from 3.33 to 5.22 kg/s.

With thermal-oxidative disposal of liquid non-combustible waste, an excess air coefficient of \( \alpha = 1.1 \), a flue gas temperature in front of a gas turbine of 850 °C and an additional fuel consumption of 323
kg/h, respectively, an additional electric one can be obtained - 151.7 kW and thermal - 2094.8 kW of power, to save 380.7 kg/h or 1213.6 t/year in replaceable heat power plants for standard fuel. The heat utilization coefficient in the system is 0.626, and taking into account the latent heat of vaporization of waste water vapor - 0.79, respectively, the primary energy utilization factor is 0.815 and 0.99, and the system efficiency is 0.59 and 0.77. The consumption of flue gases through a gas turbine installation is 2.84 kg/s.

4. Conclusion
The analysis of the results showed the possibility of efficient utilization of the heat of the exhaust gases from the thermal oxidative waste disposal systems using cogeneration gas-turbine techniques with a “reverse” sequence of processes for additional production of electric and thermal energy.

To ensure energy-efficient operation of such a system, it is necessary to integrate it into the consumer’s energy-saving system, in which the demand for energy corresponds to the energy supplied.

Knowing the costs of flue gases through a gas turbine installation, you can choose a typical gas turbine installation, on the basis of which to develop and implement a recycling system.

For example, at a flue gas flow rate of about 5 kg/s, the DO49R gas turbine engine, which is part of the thermal power plant of a thermal power station - 2.5, can be recommended as a basic unit [17].

To implement the considered technology, it will be necessary to develop a filter for cleaning high-temperature flue gases based on ceramic elements, a gas-water heater and a gas cooler, which correspond to the characteristics and parameters of flue gases and a gas turbine installation.

The calculated data obtained in the work can be used to identify the best available techniques for energy waste utilization using thermal-oxidative waste disposal and gas-turbine techniques with a “reverse” sequence of processes.

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