Long-Duration Thermal Decomposition of Waste based upon existing coke and plasma technology

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Abstract. The current global problem of accumulation of municipal solid waste (MSW) and a possible way to solve it is considered. To date, there are different ways to treat MSW: recycling (processing), incineration and disposal. Each of them has its advantages and disadvantages. Waste disposal is the least environmentally safe method, but now it is the main one in Russia because of its availability. This article proposes a scheme for recycling MSW, which is based on already existing coke, energy and plasma technologies. Within the scheme, thermal destruction of waste is carried out in a coke battery, and the subsequent melting of the residue is carried out using plasma technologies (in an electric arc furnace or in an open bucket with heating from the plasmatron). The plasma module, in which the melting takes place, can be implemented both with the circuit in question and attached to an existing incinerator. The result of melting is a low-grade stone that does not need to be buried. Gases released from MSW in the process of thermal destruction, after deep cleaning, are used to generate electricity. The source of thermal energy required for the operation of the proposed scheme for recycling solid waste is thermal power plants using natural gas as fuel. The interaction between the flue gases passing through the coke oven battery and leaving the TPP with coke oven gases is excluded due to the design features of the coke oven battery. This allows you to dramatically reduce the amount of gas to be deep cleaning, which significantly reduces the cost of cleaning equipment. The use of coke-oven batteries of modern design minimizes environmental pollution. The article assesses the energy consumption for the implementation of the proposed scheme for a plant processing 100 thousand tons of solid waste per year. The source of thermal energy for which is the standard unit of thermal power plants with a capacity of 500 MW. It is shown that working in conjunction with a waste recycling plant changes the heat balance of TPPs by no more than 10%.

1. Introduction
Today, with the rapid growth of production capacity, there is a rapid increase in the volume of MSW throughout the world, which negatively affects the general state of the environment and creates a threat to human health. For example, about 500 kg of waste per year is accounted for one citizen of Russia [1]. Those, every year Russians produce about 70 million tons of household garbage. For the United States, this number is about 230 million tons per year [2]. The problem is that MSW not only occupy vast territories, but also emit harmful compounds during decomposition (which can last dozens or even hundreds of years).
Table 1. Decomposition of MSW.

| Accumulation of decomposition product | Non-degradable solid sediment MSW (often toxic mass) |
|---------------------------------------|------------------------------------------------------|
| Filtrate formation                    | Liquid with harmful substances. It is formed as a result of precipitation on MSW or due to the release of moisture by waste |
| Landfill gas emission                 | Mostly methane (40-75%) and carbon dioxide (25-45%) |
| Reproduction of pathogenic microorganisms | Various pathogenic bacteria constitute the sanitary hazard of MSW |

The concept of MSW, in addition to waste produced by the population, also includes waste produced by trade enterprises and various types of institutions. Depending on the level of development of the country, as well as a number of other reasons, the composition of MSW is different and heterogeneous. In Fig. 1 given the composition characteristic of Russia [2].

It can be seen from Fig. 1 that waste contains valuable materials (paper, glass, etc.) that can be effectively used. Therefore, solutions to the problem of accumulation of MSW are able to partially recoup the cost of their implementation by obtaining a certain resource from waste.

2. Existing methods for waste management

Modern methods of combating garbage are in the disposal, recycling (processing) or incineration of solid waste. And usually, in the countries all three ways are implemented simultaneously. However, the share of using each of them within a single country is different.

Each method of waste management has its own advantages and disadvantages. It should be noted that the disposal of waste is the least environmentally safe method, although now in Russia it is the main (more than 90%, Fig. 2) because of its low cost. In addition, this method is ineffective because it does not allow to obtain a valuable resource from waste, as opposed to recycling or incineration.

Worldwide, incineration of MSW is used to a greater extent than waste-material production/recycling. Now it is the most popular way of waste management, although the priority is increasingly shifting towards recycling.

2.1. MSW incineration.

The process of incineration of MSW is aimed at obtaining heat energy released during waste burning (waste-to-energy).
Heat energy is a valuable resource, therefore this way of waste management is attractive for most countries. The leader in the use of incineration waste is Japan (about 73%, Fig. 3). Hitachi Zosen Corp. is considered the main waste management company in this country. 

Waste incineration is implemented in special furnaces in incineration plants. There are more than 2500 incineration plants in the world, generating a total of approximately 130 TWh of electricity [4].

MSW as a product of human life is a renewable source of energy. In addition, waste is concentrated near populated areas, which reduces the cost of transporting this “fuel” to the incineration plant. The considered method of waste management is the most expensive of the existing ones. The high price is due to the cost of environmental protection equipment. The cost of environmental protection equipment reaches half the cost of the entire implementation of the method. The burning of MSW occurs with the formation of strong carcinogenic compounds - dioxins and furans, which, without proper equipment, can lead to negative consequences. Despite this, many incineration plants around the world save on such equipment and as a result significantly worsen the ecological situation in the world.

Recycling of MSW is supposed to be carried out in stages (Table 2). For this purpose, the named technologies are implemented consistently.

3. The proposed scheme for recycling MSW
This article proposes a solution to the problem of accumulation of MSW, based on thermal processing of waste. The considered scheme includes two technologies:

- Long-Duration thermal decomposition of material (pyrolysis).
- Melting with the use of plasma technology.
At the first stage of recycling, sorted incombustible waste undergoes pyrolysis, i.e. their thermal decomposition occurs at a temperature of about 1000 °C for ~ 24 hours. The process is carried out in a special sealed (without oxygen) chamber called the coke oven chamber. Therefore, this process is also called coking. As a result of this process, the waste is converted into slag. In addition, “coke” gases (~30% of the initial amount of the substance) are released as the material decomposes. In the proposed recycling scheme, it is assumed that the “coke” gases after deep cleaning will be used to generate electricity at the mini-TPP 10 MW.

The second stage of MSW recycling is the melting of slag (solid fraction remaining after the coking process). Melting is proposed to be carried out in an electric arc furnace, or using a plasmatron at temperatures up to ~ 2400 °C. The result will be a low-grade stone, resembling obsidian, which does not need to be buried and can later be used in construction.

| Table 2. Stages of recycling the MSW of the proposed scheme. |
|-----------------|---------------|----------------|--------------------|
| Stage | Technology | Raw material | Product | Product application |
| I | Thermal decomposition (coking) | Incombustible MSW (100 thousand tons/year) | Slag (70%) | - |
| | | | Coke oven gas (30%) | Electricity generation |
| II | Melting with the use of plasma technology | Slag | Low-grade stone | Construction |

The expected number of recyclable non-combustible MSW is 100 thousand tons/year. The source of thermal energy required for the operation of the proposed scheme is a thermal power plant with a 500 MW power unit using natural gas as a fuel.

3.1. Coking
The coking process consists in the oxygen-free thermal decomposition of raw materials, with the aim of obtaining coke and volatile chemical products (coke oven gases).

This process is implemented in a special chamber, the heat supply to which is carried out through a wall of refractory bricks. This avoids the oxidation of raw materials.

There are 4 stages of coking, which are determined by the temperature conditions of heating the material [5]. All stages can simultaneously coexist in the coke oven chamber; therefore, the transformation of the starting material into coke occurs in layers (Fig. 5). The process is carried out...
from the outer wall of the chamber to the center. The raw materials located near the wall are heated first, then quickly baked and converted into coke. Middle layers change much later. Only after 8 hours the softening of the material reaches the middle. At the end of the coking period (usually 14 ÷ 24 hours), a coke cake is formed - a sintered massif broken by vertical and horizontal cracks. Due to the fact that the process is directed from two sides of the walls to the center, approximately along the vertical centerline, the coke cake breaks into two parts (Fig. 5).

- The first stage (T=100÷245 °C) is the removal of moisture.
- The second stage (T=170÷435 °C) - the continuation of heating.
- The third stage (T=380÷585 °C) - transition of the material into a plastic state, with maximum fluidity. This temperature is characterized by the release of the greatest amount of tar and gas.
- The fourth stage (T=485÷850 °C) is the transition of the material from plastic to solid state, with the formation of a semi-coke first, and then coke.

3.1.1. Coke oven battery. A group of coke ovens operating in a single technological mode, having a common foundation, devices for supplying heating gas and discharging products of combustion and coking is called a coke oven battery [5]. This construction allows to process a large amount of material. In the proposed scheme for recycling MSW, a coke-oven battery of German production is considered, since they are now leading in this area. One of the most popular companies involved in the development and production of such batteries is ThyssenKrupp Industrial Solutions (Germany) [5].

A coke oven consists of a coking chamber and a heating system. The chambers usually have an average width of 0.42 ÷ 0.59 m, a length of 13 ÷ 16 m and a height of 4.5 ÷ 7.8 m. Moreover, the chamber width is cone-shaped for the convenience of pushing out the coke cake. In the upper part of the chamber there are hatches for loading the material being coked. Here are the hatches for removal of volatile products of coking.

The coke oven heating system includes gas distribution zones, regenerators and heating piers. Heat recovery increases battery efficiency. Regenerators utilize the heat of flue gases from the heating pier to heat air and heating gas. In modern coke ovens, regenerators are located under the walls and coking chambers.

The most environmentally hazardous zones of a coke oven battery are a coke oven, namely, its valve (door), channels for supplying or discharging heating gas, as well as channels for discharging coke gas. Creating a better door seal to prevent emissions is implemented according to the iron-on-iron principle, which consists of tightly fitting clean metal surfaces to each other. In Germany, FLEXIT flaps are used. The main features of these doors are malleable cast-iron flexible housing and elastic membrane made of stainless steel. The high elasticity of the membrane helps to compensate for the bending of sealing surfaces that occurs at high and wide doors. This ensures maximum gas tightness.

In addition, the EnviBAT system regulates the pressure in each furnace chamber. To prevent emissions during material loading, the chambers and the gas collector are under vacuum. These and other systems minimize the environmental hazard of the coke oven battery.

4. Plasma module
The final stage of the proposed scheme for the management of MSW is the melting of the solid residue formed at the end of the coking process. As a rule, incineration of MSW in incineration plants is not a waste-free solution, since the ash and slag waste that remains after the combustion is simply buried in the territory of the plant or at the landfill. For this, valuable land plots are allocated, suitable, for example, for agriculture. In addition, disposal results in environmental pollution (atmosphere and groundwater).
Different ideas on the use of ash and slag waste in the production of building materials are proposed in Russia and other countries. They are mainly based on high-temperature (~2000 °C) processing of such wastes using various heat supply schemes: gas or electric melting furnaces. For example, melting in a liquid bath is considered in [6].

The disadvantage of gas furnaces (in which heat is produced by burning gas) is the need for expensive high-performance dust-gas cleaning machines, since a lot of harmful waste gas is produced. Therefore, when slag is melted in an autonomous unit, preference is given to electric furnaces, in which the amount of gases requiring purification is much smaller, which simplifies and reduces the cost of recycling.

In the proposed scheme for recycling MSW, slag melting is assumed using an electric arc furnace or a plasmatron. Plasma module is universal. In addition to the proposed scheme for recycling MSW, it can be attached to an existing incineration plants.

4.1. Electric arc furnace

The furnace body is a cylinder shape with a spherical bottom, where the processed material is located. The design has holders in which graphite rods are installed (usually 3 pieces). Using furnace transformers, the supply of voltage to the electrodes leads to the formation of an electric arc between them, due to which the desired temperature is reached, ensuring the melting of the material. Depending on the relative position of the arc and the material is distinguished [7]:

- Direct-arc arc furnaces (electric arc burns between the electrodes and the material being heated);
- Indirect arc furnaces (electric arc burns between the electrodes located above the material being heated). Heat transfer is carried out by radiation and convection.

4.2. Plasmatron

The plasmatron under consideration belongs to the class of electric arc. Its design is similar to a conventional electric arc furnace. The plasma system includes a plasma generator (plasmatron) with electrodes made of refractory material that generate an electric arc. For receiving the arc category it is used both direct, and alternating current. An inert gas is blown through the arc, as a result of which it is ionized and transformed into a low-temperature plasma (~3000 °C) [8].

4.3. Estimation of the cost of melting 1 ton of slag

The composition of the slag formed as a result of the coking of MSW depends on the initial composition of the waste. Due to the fact that the composition of MSW is heterogenous and depends on the place of formation, it is necessary to conduct experiments to determine the properties of the incombustible fraction of MSW. As a result, the properties of boiler slag (the result of burning coal, coke, etc.) will be taken as a first approximation.

At the exit from the coke oven, the slag temperature is ~900 °C, which simplifies the task of its melting. The estimated upper temperature is ~2400 °C. Then the amount of thermal energy $Q_{melt}$ needed to melt 1 ton of slag:

$$Q_{melt} = m(h_{melt} + C_p \Delta T) = 1625 \text{ MJ},$$

where $m$ is the mass of slag (kg), $h_{melt} = 500$ (kJ / kg) is the heat of fusion, $C_p = 0.75$ (kJ / kg · K) is the specific heat capacity.

Required electric power $q$ per 1 ton:

$$q = \frac{Q_{melt} \cdot 3.6 \cdot 10^6}{5} = 0.556 \text{ kWh} \text{ ton}^{-1}$$

Price for 1 kWh = 5 RUB. The cost of melting 1 ton of boiler slag will be:

$$Z = q \cdot 5 = 2257 \text{ RUB} \text{ ton}^{-1}.$$
5. Estimation of energy consumption for the implementation of the proposed scheme for recycling MSW

The source of thermal energy required for recycling waste is a thermal power plant with a 500 MW power unit. Thermal power station $Q_{st} \approx 1250$ MW.

Since the waste is processed in the coke oven chamber in stages, the heat $Q_{SLW}$, which must be brought to the chamber walls for the thermal decomposition of the material in them, is calculated as follows:

$$Q_{SLW} = Q_{dry} + Q_{destr} + Q_{coke},$$

(4)

where $Q_{dry}$ - heat required to remove moisture; $Q_{destr}$ - heat required for thermal destruction of waste; $Q_{coke}$ - the amount of heat required to complete the process of coking.

The expected number of processed MSW is 100 thousand tons/year, or about 3.2 kg/s. Humidity $X$ waste at the entrance to the coke oven battery is 30%, then

$$Q_{dry} = M \cdot X \cdot h_{lg} = 2.304 \text{ MW},$$

(5)

where $M$ - mass flow rate of MSW (kg/s); $X$ - humidity of MSW; $h_{lg}$ - specific heat of water vaporization (J/kg).

Due to insufficient information on the physical properties of MSW, it is assumed here that $h_{destr} = 500$ kJ/kg is the heat of destruction of the waste, $C_p = 1 \text{ kJ/(kg·K)}$ is the specific heat capacity.

The amount of heat required for thermal destruction $Q_{destr}$:

$$Q_{destr} = M \cdot (1 - X) \cdot h_{destr} = 1.120 \text{ MW}.$$

(6)

For evaluation, it is assumed that the processing of material in the coke oven chamber is from 0 °C to 1000 °C. The third component of the formula (4) is:

$$Q_{coke} = M \cdot C_p \cdot \Delta T = 3.2 \text{ MW}.$$

(7)

Thus, the amount of heat required for the implementation of the entire coking process is $Q_{SLW} \approx 6.624$ MW.

To estimate the energy demand of a plasma module, formula (1) is used. However, instead of mass $m$ (kg), mass slag consumption is used there, which is 30% of the initial consumption $M$ (kg/s) of MSW. Then, the heat output required for slag melting is $Q_{melt} \approx 3.9$ MW.

The total amount of heat required for the implementation of the process of coking and melting $Q_{\Sigma} = 10.524$ MW.

Total, work in conjunction with the proposed scheme for recycling MSW changes the heat balance of TPPs by less than 10%.

6. Conclusion

The international problem of the accumulation of municipal solid waste has remained relevant for most modern countries for a very long time. Having a detrimental effect on our environment, waste, in the absence of proper handling, is indeed a great threat to the whole planet.

In Russia, the level of recycling of solid waste is only ~ 5%, and the main method of waste management is disposal. More than 90% of garbage is sent to open landfills and unauthorized landfills, which are not properly equipped with environmental protection. As a result, pollution of the atmosphere, surface layers of the soil, groundwater and soil occurs. In addition, when placed at landfills, tons (~ 15 million tons/year) of valuable types of raw materials and materials, such as paper, glass, metals, paper, etc., disappear.

This article proposes a scheme for recycling MSW based on well-studied coke and plasma technologies, which leads to significant savings in its implementation. The scheme allows for the complete recycling of MSW: obtaining a valuable resource (low-grade building stone) from the non-combustible fraction of waste without residue. Potentially high economic and environmental indicators make this scheme a promising solution to the problem of MSW.
7. References

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