Comparative analysis of MSW thermal utilization technologies for environment friendly WtE plant

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Abstract. A comparison of the technologies of thermal utilization of solid chemical waste was carried out, the advantages and disadvantages of the thermal utilization technologies of WtE thermal power plants used in worldwide were given. A method of comparison and selection of the preferred technology of thermal utilization, depending on the specific conditions of the placement of TPPs at MSW, is proposed. Thermal utilization can be classified into three categories (combustion, gasification and pyrolysis), the difference between them lies in the amount of excessive air present in combustion chamber. The gasification technology that can be often in use in WtE can be divided into two main types – slugging gasification and plasma gasification.

1. Introduction
The use of waste as a resource for recycling and energy producing is becoming an increasingly attractive option for commercial structures and local governments around the world. Thermal treatment helps to reduce the disposal of unsorted MSW (municipal solid wastes) at landfills, and also allows to recycle waste that cannot be effectively used to obtain secondary raw materials or recovery by biological treatment (for example, composting) when using waste sorting technologies.
In accordance with [1], the Strategy for the development of industry for the treatment and disposal of industrial and consumption waste for the period up to 2030 has been approved in Russia with using the "3R" principle (waste reduction, reuse, recycling into secondary raw materials). Thus, energy complexes in which the heat obtained during thermal treatment of MSW is used to generate electrical and thermal energy to supply Waste to energy plant or external consumers (hereinafter MSW WtE plant) become a part of MSW disposal management system.
The industrial application of WtE plants in Russia is limited to only a few large industrial units [2]. The lack of experience in the field of engineering and design makes serious difficulties when it comes to choosing the type and equipment for different and specific conditions. At the moment, there are no recommendations or methodic that helps to make right choice of the technology for thermal treatment of MSW and the structure of WtE thermal power plants in general.
The authors develop a methodology for comparing and choosing the preferred structure of WtE plant for different conditions of its location and different morphological composition of MSW, determine the requirements, analysis tasks, list of options and list of comparison criteria for WtE plants.
structures. At the first stage of developing a methodology for comparing WtE plant structure, a review of the most widely used technologies in the global industry for thermal utilization of MSW (including a comparison of plasma gasification of wastes technology) was made, also a list of possible options and criteria for comparing them was made. Technologies with is classically used in the waste treatment field is — incineration, pyrolysis, gasification.

2. Review of MSW thermal treatment technologies
Thermal utilization processes can be divided into three categories (combustion, gasification and pyrolysis), which differ depending on the value of the excess air ratio in the combustion chamber: as shown in Fig. 1, combustion takes place in an environment with excess air, gasification is a process of partial oxidation, requiring excess air is slightly below the stoichiometric level, and pyrolysis occurs in the absence of air supply.

![Figure 1. Difference of air excess factor for different technologies of thermal utilization of MSW](image)

The technologies of MSW thermal treatment of can be divided into the following types: moving grate combustion and fluidized bed combustion (combustion category), as well as gasification and pyrolysis. The gasification technology can be divided into two main areas – slagging gasification and plasma gasification.

2.1 Moving grate MSW combustion technology
There are many types of furnaces with grates, which differ by the type of grate (swinging, rotating, reverse reciprocating, etc.), type of cooling (without cooling, with water or air cooling). The most popular technology for grate combustion of MSW is the reverse reciprocating moving grate technology.

The grate consists of movable cams that are moving the MSW in a layer. The waste enters the boiler through a feeder that located in the upper part of the grate and moves along the grate in the direction of the slag removal system in the lower part of the grate. Primary air is supplied under the grate, cools the cams and then fed to the furnace, secondary air is supplied to the zone of the furnace located above the MSW layer. Thus, mixing the MSW in conjunction with good air access ensures a sufficient degree of burning out of the fuel. The scheme of work and the external view of reverse reciprocating grate furnace are shown in Fig.2.

The technology of MSW incineration with reverse reciprocating grate is supplied by many global suppliers has established costs of equipment. The main suppliers of WtE technology for MSW with a reverse reciprocating grate: Babcock Wilcox Velund, Keppel-Seghers, Lurgi, Martin Engeneering and CNIM.
Advantages of technology:
- Mature, established, many reference plant worldwide;
- No feedstock preparation required, relatively simple, robust technology;
- Numerous reputable experienced technology suppliers;
- Relatively low CAPEX and OPEX compared with some more advanced technology.

Disadvantages of technology:
- Electrical efficiency is limited by the steam temperature;
- Suffers from poor perception, primary due to legacy of older generation of incinerators;
- Generally better suited to large scales (>150,000 tpa);
- Lowest ecological characteristics;
- High level of mechanical unburns, especially when it meets with high moisture MSW.

2.2 Fluidized bed MSW combustion

There are three types of fluidized bed combustion technology: stationary fluidized bed, circulating fluidized bed and revolving fluidized bed (RFB). Revolving fluidized bed is the most interesting technology, because of low breakthrough of the sand material of the layer goes from furnace to the gas cleaning system [3].

There are 2 types of RFB installations- installations operating with single-vortex and double-vortex fluidized bed. When the fuel is burned in a two-vortex fluidized bed, in the lower part of the furnace, in which the main burning of the waste takes place, due to the appropriate air supply, the grid form and the furnace design, pair vortex zones are formed - the so-called RFB. The technology has a fairly simple mechanism with no moving parts inside the furnace. The furnace has a sloping floor and two moving air vortices driving the MSW mixed with sand.

The revolving fluidized bed consists of two vortex zones with an elliptical cross section arranged mirror-like and moving towards each other (the view of the furnace produced by Ebara Corporation is shown in Figure 3). The advantage of the furnace with a RFB is a high level of turbulence and, as a consequence, a high thermal stress and small size of the combustion device, low amount of chemical and mechanical unburnt fractions. More than 80 factories have been built in Japan to combust RDF using a similar technology, there are a few plants in the EU and Russia (WtE plant №4 in Moscow).
Advantages of technology:
- Mature, established, many reference plant worldwide;
- No moving parts inside the furnace;
- Numerous reputable experienced technology suppliers;
- Low level of mechanical unburns, less dependent on fuel moisture;
- Ecological parameters are higher than in moving grate technology (combustion is more stable).

Disadvantages of technology:
- Electrical efficiency is limited by the steam temperature;
- Relatively high CAPEX and OPEX (up to 1.3-1.5 times) in compare with moving grate technology;
- Generally better suited to lager scales (>150 000 tpa);
- Preparing MSW to RDF is necessary;
- Big amount of fly ash disposal.

2.3 Slagging gasification waste treatment technology
Technologically, the gasification process can be classified as an intermediate between pyrolysis and combustion, since it involves partial oxidation of the fuel. Oxidation occurs when there is an excess of air that is not sufficient for the oxidation of the fuel to proceed: the synthesis gas produced in the gasification process is not fully oxidized, and the coke that is produced in the layer is burns completely.

The temperature at which gasification occurs is, about 450–600 °C. The gasification process requires pretreatment of MSW, which includes sorting and shredding with RDF production.

This technology has become widespread in Japan, biggest suppliers are Mitsubishi HI-MSW Gasification & Ash Melting System (see Figure 4) and JFE Engineering.

According to a study of the MSW processing market conducted by the Ministry of Ecology of Japan (published on March 6, 2014), for 10 years from 2003 to 2013, the total daily capacity of WtE plants with gasification, slagging gasification technology increased by 10,000 tonn/day, while the capacity of WtE plant with combustion technology (incineration on the grate) decreased to 21,000 tons [4].

Figure 3. External view of revolving fluidized bed furnace
Figure 4. MSW treatment with Gasification & Ash Melting System technology

**Advantages of technology:**
- Reduction of dioxin generation in fume gases, low emissions;
- Reduction of dioxins in the ash residue;
- Return ash to the reactor to melt it and remove it in form of melted slag;
- Low amount of disposals with 3 and 4 hazardous class;
- There are reputable experienced technology suppliers in Japan;
- High electrical efficiency possible by use of syngas engines or turbine compared to steam turbine;
- Acceptable for WtE factories with different capacity.

**Disadvantages of technology:**
- Expensive with high capital and operational costs;
- Waste feedstock preparation is required to produce RDF;
- Oxygen or additional fuel is required to make high enough temperature;
- High technological process needs high educated operators.

2.4 **Plasma gasification**

Plasma gasification is carried out in an environment with low oxygen content, in this process synthesis gas, molten slag and molten metal are produced, the proportions and composition is depend on the composition of the waste. The recovery of synthesis gas in a heat recovery boiler or gas turbine makes it possible to use the technology in the construction of a WtE plants, using waste as fuel.

Since plasma gasification occurs with low excess air, the total volume of flue gases decreases, which in leads to a reduction in capital costs of the construction of a power plant and a flue gas cleaning unit, making the flue gas cleaning system more efficient and compact [8].

Emissions of pollutants such as nitrogen oxides (NOx) and sulfur dioxide (SOx), H2S (hydrogen sulfide), NH3 (ammonia) are reduced in plasma gasification installations, and decomposition of dioxins and furans occurs at high temperatures of plasma arc.

Despite the high environmental performance of plasma gasification installations, only a few industrial WtE plants were built, because of low level of knowledge of technology, high capital and operating costs.

There are two main configurations of plasma gasification installations: a configuration in which a plasma generator (plasma arc and electrodes) is located in the main waste thermal utilization reactor and a configuration in which a plasma generator (plasma converter) is external and is used for decomposition of carbon-containing fractions in the synthetic gas. The process with an external
plasma converter will be discussed further; the reactor with an internal plasma generator will be discussed on the example of the AlterNRG reactor.

AlterNRG (Canada) proposes the design of a plasma RDF gasification reactor for WtE plants, which is part of a steam power plant, the synthesis gas produced during plasma gasification is burned in a heat recovery boiler to produce superheated steam. A scheme of a plasma reactor manufactured by AlterNRG (Canada) is shown in Fig. 5. The main element of the process is a plasma gasification reactor, which is a vertical shaft furnace.

The plasma gasifier inside is covered with refractory material. The diameter of the reactor is 9.7 meters, height is 19 meters. In this design, the waste does not pass through the plasma torch. Indeed the plasma torches do not impinge directly on the input waste. Instead, the torches are used to provide the high temperatures required by the cupola. We refer to this design concept as Plasma-assisted Gasification. In this concept, the role of the plasma torches is to create a stream of very hot air (the plasma plume) which provides an intense input of heat energy into the reactor, supplemented by heat released by the met coke which is slowly consumed. The plasma torches therefore are energy input devices and the plasma assists the gasification reactions to take place. The electrical energy input to the plasma torches is also used as a control parameter to accommodate and counteract the expected variations in waste CV.

The gasification reactions will convert the organic component of the MSW/tyre feedstock into a syngas which exits at the top of the PGR while the inorganic components are converted into a molten slag that exits at the bottom of the reactor at about 1,650 °C and is sent to the slag handling system where recoverable metals are removed. The PGR operates with very high temperatures in the lower portion of the reactor and both oxygen and steam will be injected into the process. The high temperatures also significantly increase the kinetic rates of the various chemical gasification reactions. In Japan, three thermal power plants were built to process waste using AlterNRG technology. The plants of Yoshii, Utashinai and Mihama-Mikata, the main characteristics of the objects are given in Table 1.

Table 1. WtE plant with AlterNRG technology [8]

| Location                | Daily capacity, ton/day | Annual capacity, ton/year | Built   |
|-------------------------|-------------------------|----------------------------|---------|
| Yoshii, Japan           | 24                      | 7,200                      | 1999    |
| Utashinai, Japan        | 180                     | 49,500                     | 2003    |
| Mihama-Mikata, Japan    | 22                      | 6,600                      | 2003    |

The average number of hours of operation of plasma gasification WtE plant is 7,300 hours per year, which is less than the declared number of hours of operation of WtE plant working on the moving grate-burning technology (8,200 hours per year), but is a good indicator for developing technology.
2.4.1 WtE plant with plasma MSW treatment

The structure of WtE plant for MSW treatment using a plasma gasification system differs from WtE plant with other technologies, and will be described on the example of WtE plant produced by Advanced Plasma Power (United Kingdom). The technological line consists of two chambers plasma incineration unit:

- Primary chamber, fluidized bed gasifier;
- Secondary chamber, plasma converter.

In the process of gasification and plasma conversion, synthesis gas is created, the purity of which is sufficient, for supplying the gas turbine engine.

The process line includes a fluidized bed gasifier, gas from this chamber goes to plasma-arc gas processing chamber. A prepared RDF is fed to the gasifier and the raw syngas is subsequently treated in a plasma conversion stage where the problematic tarry species, contained in the syngas, are effectively cracked and reformed to produce a syngas comprising primarily carbon monoxide and hydrogen. After conventional cleaning of the syngas to remove particulates and acid gas contaminants the syngas may be fed to gas engines or turbines.

Process diagram for plasma WtE factory 100 000tpa is shown on fig. 6.

![Figure 6: WtE plant with plasma converter unit](image)

The MSW is supplied to the resource recovery factory, which extracts secondary material resources and materials containing harmful substances. Sorted waste is shredded to produce RDF.

RDF is fed into the gasifier with steam and oxygen (in the absence of air). This process provides sufficient heat to maintain the fluid bed temperature and produce a “crude syngas”. The syngas contains significant quantities of long chain and aromatic hydrocarbons which would condense as tars and residues if allowed to cool.

The crude syngas is transferred from the gasifier to the plasma converter via a refractory lined duct. In the plasma converter a graphite electrode from which a thermal plasma arc is generated. The syngas is exposed to elevated temperatures and intense ultra-violet light. The effect is to “crack” and reform the tars and chars contained in the syngas into their basic composition of hydrogen (H2), carbon monoxide (CO), carbon dioxide (CO2) and water (H2O).

The ash and dust particles associated with the syngas drop out of the gas stream and are incorporated into a molten slag pool which builds up in the base of the converter. This molten material is continuously removed from the plasma converter via an overflow weir and cooled for use as a vitrified and stable material.
The gas cooling system comprises a heat recovery boiler designed to reduce syngas temperatures from 1,200°C to 160°C and generate saturated steam at 10 bar(g) pressure. The basis of the design is a water tube boiler. The steam generated is used in the process; surplus steam is used for local heating duties or export.

The dry gas cleaning system, operating at 150 to 180°C, removes fine particulate materials from the syngas stream, neutralises acid gases and removes heavy metal vapour. The syngas passes to the ceramic particulate filter via an insulated duct into which the reagents sodium bicarbonate and activated carbon are injected. Particulate matter, including the by-products from the reagent reactions, is trapped on the ceramic filter elements and periodically removed using a nitrogen reverse pulse system.

From the dry gas cleaning phase, the syngas is cooled by direct contact with scrubbing liquor in a condenser scrubber. The unit is used to drop the syngas temperature to circa 30°C. The gases are passed through a second, alkaline, scrubber to remove acid gases - in particular sulphur dioxide and hydrogen sulphide. The hydrogen sulphide is chemically oxidised to produce a stable effluent. The syngas leaving the wet cleaning system is clean syngas ready for use in power generation.

The Power Island is fed by the clean syngas from the gas production system and generates electrical power from direct combustion of the clean syngas in gas engines or turbines.

In the process of plasma gasification of MSW, the utilization rate of thermal energy of the fuel reaches 90%, the efficiency of net power of WtE plant using Advanced Plasma Power technology reaches 25%. WtE plant at the MSW with a capacity of 100,000 tons/year produces up to 20 MWt of electrical energy.

**Advantages of technology:**
- Potential to produce a clean syngas for use in engines or turbine;
- Can produce a high quality slag similar to slagging process;
- Able to add-on plasma units to more established combustion or gasification plants;
- High ecological parameters.

**Disadvantages of technology:**
- High CAPEX and OPEX;
- High parasitic electrical load;
- Achieving high availability may be challenging;
- There is a few industrial WtE unit.

2.5 **Pyrolysis of MSW**

Pyrolysis is a process in which oxygen is excluded from the reactor, which is heated externally to produce the elevated temperature environment that causes the organic solids (waste input) to breakdown via physical and chemical processes into three products; solid char, pyrolysis oil and pyrolysis gas with the proportions of each being governed by the operating temperature within the pyrolysis reactor. As a result of the fact that the combustion of MSW occurs with a lack of oxygen, a smaller amount of nitrogen oxides (NOx) is formed.

The synthesis gas obtained during the pyrolysis process is burned in the boiler furnaces with production of steam and electricity. Pyrolysis reactor is shown on fig.7.
The pyrolysis technology has become widespread in Japan, where Mitsui Engineering & Shipbuilding has built 8 WtE plants based on installations with a capacity of 42 000–135 000 tpa. [5].

Advantages of technology:
- Potential to produce a clean syngas for use in engines or turbine;
- High ecological parameters;
- reduced amounts of flue gas generated during combustion, which reduces the cost of the gas cleaning system.

Disadvantages of technology:
- High CAPEX and OPEX;
- There is a few industrial WtE unit;
- As the result of char producing, calorific value of fuel Is low;
- Risk of explosion in case of contact with air;
- There is no reliable suppliers.

3. Comparison of MSW thermal treatment technologies

For carrying out a comparative analysis, have been selected MSW thermal treatment technologies that have wide industrial application in the Russian and foreign industries. The analysis was carried out according to the criteria proposed by the authors. Comparison of technologies for thermal treatment of MSW is given in Table 2.

| Factor                                      | Moving grate combustion | Fluidized bed combustion | Slagging gasification | Plasma gasification | Pyrolysis |
|---------------------------------------------|-------------------------|--------------------------|-----------------------|--------------------|-----------|
| Content of hazardous in fume gases that goes to gas cleaning system | High                    | Medium                   | Low                   | Low                | Low       |
| WtE plant annual capacity                   | Up to 1000 000 tpa     | Up to 500 000 tpa        | Up to 220 000 tpa     | Up to 100000 tpa   | Up to 135000 tpa |
| Lowest amount of 3rd class hazardous disposals | ~5%                    | ~8%                      | ~3%                   | ~2%                | ~3%       |
| Waste volume reduction                      | 75-85%                  | 73-83%                   | 85-92%                | 87-95%             | 70-80%    |
| Preparing of MSW                            | Not required            | Need to prepare          | RDF is required       | RDF is required    | RDF is required |
| The possibility of localizing the production of main equipment in the Russian Federation | Possible, Except for the furnace, which is a proprietary technology | Possible, Except for the furnace, which is a proprietary technology | negotiations with manufacturers is required |
| Quantity of plants worldwide                | More than 1000          | Less than 200            | Less than 25          | Less than 25      |
| Level of capital costs                      | Low                     | Medium                   | High                  | Higher             | High      |
| Level of operational costs                  | Low                     | Medium                   | Medium                | Higher             | High      |
The reverse reciprocating grate combustion technology is, in accordance with [2], the best available technology. In general, the technologies of grate combustion and fluidized bed combustion are comparable, but the advantage of the grate-burning technology is the lower cost of equipment and the smaller amount of generation of fly ash with hazard class 3.

The operation of the boiler with the RFB at WtE plant № 4 in Moscow is characterized by slagging of the furnace walls at temperatures above 700 °C. At temperatures below 500 °C, incomplete combustion of individual components of the solid waste takes place. In contrast to the grate combustion, combustion in a RFB fluidized bed makes up 1.5–2.5 times more ash [6]. Thus, operating experience of WtE plant № 4 in Moscow showed that for unsorted MSW, the most preferred method of thermal processing is burning in furnaces with reverse reciprocating grate, while RFB fluidized bed combustion technology should be used for burning prepared MSW (RDF).

The disadvantage of reciprocating grate combustion technology on WtE plants that working on unsorted or partially sorted MSW, is low environmental friendliness. Daily and seasonal variations in the composition of unsorted MSW lead to continuous changes in the combustion parameters in the WtE plant boiler, which, causes significant fluctuations in the concentrations of toxic components in the fume gases and as a result, the gas cleaning system operation became not stable [7].

The pyrolysis technology is well developed, but it is rarely used because economic reasons: due to the high content of combustible in solid residues during pyrolysis, the utilization rate of fuel heat is about 1.6 times lower than with grate combustion [8].

The technology of slagging gasification with melting ash residue has number of advantages associated with low yield of waste with hazard class 3 (ash combustion residues after the melting process are discharged as non-toxic slag; when burning RDF, the mass of heavy metals that goes to ash and fume gases is significantly reduced). At the same time, the gasification technology is expensive, and today there are no industrial installations in Russia.

The plasma gasification technology of waste has a great advantage from the high environmental friendliness of the process in comparison with combustion and pyrolysis technologies point of view. The synthesis gas produced as a result of plasma gasification can be effectively used to produce electrical energy in gas turbines WtE plant. The vitrified slag obtained as a result of slag melting can be used in construction because it is not a waste of the 3rd or 4th hazardous class. Plasma installations can be used as part of WtE plant with combustion technology in order to melt the slag and slag vitrification. The main disadvantages of plasma gasification technology are high cost and low level of knowledge. To date, none of the companies has announced the industrial WtE plant at the MSW using plasma gasification.

Assessment of capital costs at this stage is made by relative comparison, obtaining specific indicators of capital costs is the task of the next stages of the study.

**Conclusion**

As follows from the conclusions of Chapter 3, it is not possible to determine the best technology for thermal utilization of MSW without making a research and analysis; each technology has its advantages and disadvantages.

For further research, it is planned to consider the following criteria affecting the performance of WtE plant (the value of each criteria depends on the location factor of WtE plant in each specific case):

- The morphological composition of MSW and the dynamics of its change;
- Extraction of secondary raw materials at WtE;
- Thermal efficiency of WtE plant;
- Emission of harmful substances in flue gases;
- Emission of harmful substances in ash and slag;
- The level of capital costs;
- The level of operating costs.

Thus, to conduct an objective assessment, the technology of thermal utilization of MSW should be selected as part of the overall structure of the WtE plant and determined for specific placement conditions. The priorities to choosing the structure of the energy complex are, first of all,
environmental friendliness of waste incineration (since low environmental performance indicators are normative and socially unacceptable), and secondly, efficiency (since the payback period of the project is a significant factor for potential investors).

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