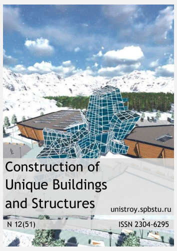
Строительство уникальных зданий и сооружений. ISSN 2304-6295. 12 (51). 2016. 84-92



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Gasification and plasma gasification as type of the thermal waste utilization

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ARTICLE INFO	Article history	Keywords
review **doi 10.18720/CUBS.51.7**	Received: 20.09.2016	plasma gasification, waste utilization, modern technology, syngas, gasifiers, gasification, constructions, buildings, energy efficiency, civil engineering

ABSTRACT

This paper presents an overview of thermal waste utilization. Basic aspects of each process have been discussed, focusing on incineration, pyrolysis and gasification. Moreover, there is a brief comparative analysis of some characteristics (temperature, product, primary products and so on) of stated above processes and advantages and disadvantages of the whole processes. Pros and cons were chosen due to environmental, economic and energy criteria. Gasification process was discussed in deeper way. Pros of the gasification were shown in the comparison of other thermal methods of waste disposal.

The main idea of the paper is to provide information related to the gasification and one of the types – plasma gasification - and to prove the necessity of using such method in waste disposal. Plasma gasification has less air emission and slag toxicity than other thermal technologies for waste disposal.

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1. Introduction

Currently the problem of waste disposal is one of the most pressing issues for the global society. Each year more than 29 billion tons of waste is produced in the world. Most of it is taken to the landfill, where it continues to contaminate the environment with harmful substances from their composition. According to the European Environment Agency, in 2012, municipal waste generation per capita was highest in Switzerland (694 kg / capita), Denmark (668 kg / capita) and Cyprus (663 kg / capita), and lowest in Romania (271 kg / capita) and Albania (262 kg / capita) [1]. These data reflect differences in economic well-being of countries. More rich and affluent countries produce more municipal waste per capita.

Most share of the waste about 25-30% is organic: low-quality lignite, petroleum residues and other combustible waste types. Utilization of these types of waste is one of the most environmentally harmful, inefficient and uneconomical process. This kind of waste is an epidemic threat disrupting aesthetic appearance of the city and surrounding areas [2].

Statistics from the European Environment Agency shows the need of a more effective method for recycling. In the world practice utilization and disposal of waste thermal, chemical, biological and physic-chemical methods, and combinations thereof are used. The article presents most noteworthy in our opinion approaches for practical technology.

This article describes thermal methods of waste disposal. The most used types of thermal methods are combustion, gasification, pyrolysis, heating in air, vacuum, etc. Thermal methods typically include such steps as preparing sludge for processing; high-temperature processing; multi-stage gas cleaning; heat recovery; organic by side (gas oil) and mineral products (oxides, cement, mineral salts).

In emphasis of the article is on plasma gasification. This method has become most prevalent in the last 20 years. The advantages of this method are the high efficiency and productivity of the process, as well as a large variation in the resulting products.

2. Thermal methods of waste disposal

Thermal methods of waste disposal include pyrolysis, combustion and gasification. Each method is discussed below in more detail. Pros and cons of methods were related to the

High-temperature combustion (incineration)

This technology is mainly used in Europe for the incineration of hazardous waste in rotary kilns; however, the process can be applied for other types of furnaces [3]. Incineration temperature in the furnace is brought up to 1500 ° C, which gives advantages in comparison with the same process taking place at 800-900 ° C [4].

Figure 1 provides an overview of the process of waste incineration. Waste through the hopper 1 and hopper 2 is fed into the rotary kiln furnace 4. A is activated by ignition device 3. The combustion products from the furnace set with a slope of 2-5 degrees come into the after burning gasifier 7, where they are neutralized at the temperature above 800 ° C in the flame of the burner 8. Through exhauster 10 they are then transported through the cooling apparatus 9 (waste heat boiler, water heater and so on) and discarded through a funnel 11 into the atmosphere. The resulting ash (4-6%from the overall waste weight) from the collector 5 through conveyor 10 is transferred into the warehouse 12. The ash can be used as filler in the manufacture of building materials.

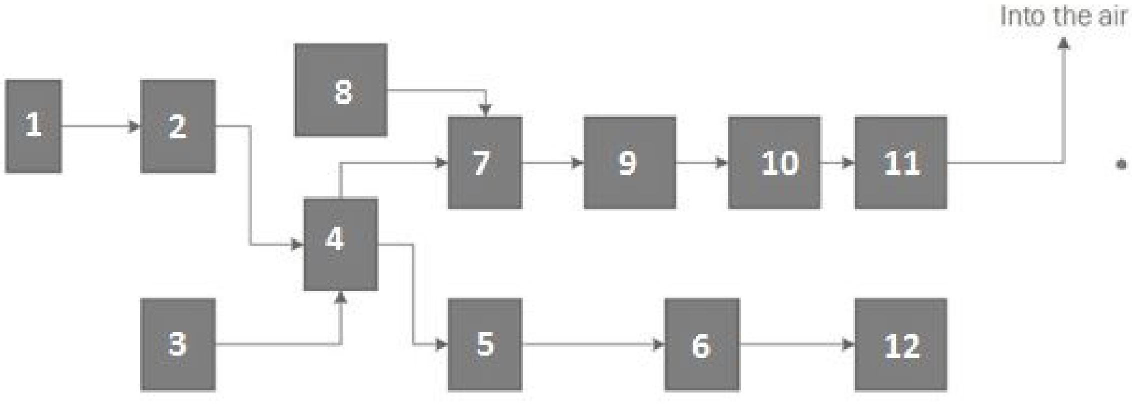

Figure 1. Scheme of incineration process

Efficiency of incineration comes up to 40 % that is one of the lowest efficiencies in the thermal processes. Nevertheless, it is widespread method of waste disposal used in Japan (about 70% of all waste is disposed in this way) due to the high density of buildings and population, as well as the lack of space for storage of solid municipal and industrial waste.

High temperature combustion offers several advantages over other waste utilization processes: (1) reducing the amount of unpleasant odours during utilization, (2) decreasing the amount of harmful bacteria, emissions, (3) the resulting mass does not attract rodents and birds, (4) there is a possibility when burned to produce energy (heat and electricity).

From the other side, it still has disadvantages that make incineration not environmental friendly and high costly process for waste utilization. They are (1) significant environmental disadvantages (for example, large amount of secondary waste, which cannot be used), (2) relatively low temperatures that do not allow to fully decompose complex organic compounds and (3) large volume of flue gas, which increases cleaning costs.

Pyrolysis

Pyrolysis is thermal treatment of organic and inorganic compounds with a limited amount of oxygen. Widely used at present on a commercial scale is tubular furnaces pyrolysis. The design of the pyrolysis equipment is determined by the nature of the raw materials that is used. In general, it includes two main sections: "hot", where pyrolysis feedstock and recycle are carried out, and "cold" - responsible for the separation and purification of the resulting products [5]. The effectiveness of this method of disposal is 80-90%, which is the highest of all methods of thermal utilization. Figure 2 is a schematic diagram of the process pyrolysis waste disposal.

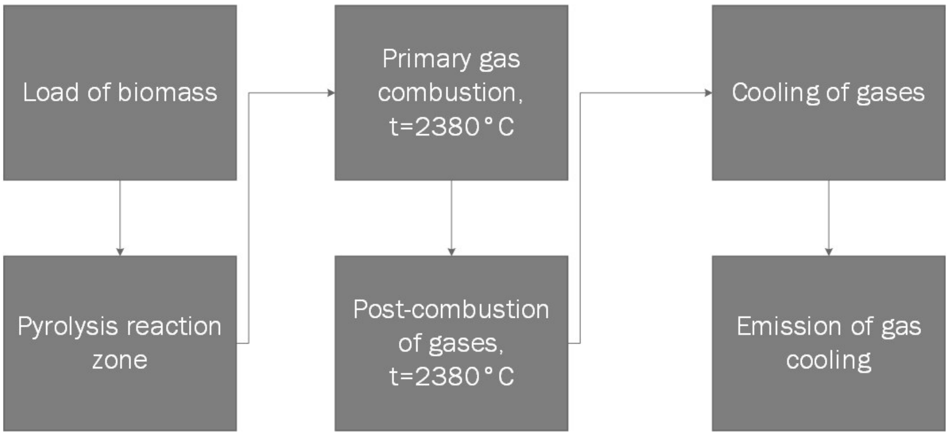

Figure 2. Scheme of pyrolysis process

The advantages of such method are (1) combustion temperature of over 900 ° C hazardous substances are decomposed without getting into the environment, (2) production of pyrolysis oil, that could be used in the plastics industry, (3) isolation of the pyrolysis gas which is produced in sufficient quantity to provide energy production, (4) no waste sorting is required (high-temperature pyrolysis). On the other hand, it presents some disadvantages, such as the formation of harmful chemicals, high costs of equipment and large energy consumption. For this reason, pyrolysis is not so popular in industrial scale as incineration.

Gasification

Gasification is a high temperature thermo chemical process of organic mass interaction with gasification agent, resulting in the production of a mixture of gases (“syngas" or "synthesis gas") [6]. Gasification waste disposal technology was taken from metallurgical industry where gasification in various types of reactors (chamber, cyclone, etc.) at temperatures from 600 ° C to 1100 is widely used for obtaining flammable gases from drilling high-ash coal [7].

Gasification methods' classification can be based on various principles. By fuel state can be distinguished fixed bed or gradually lowered bed gasification, “fluidized bed" method and pulverized fuel flow gasification.

Coal gasification is an endothermic process. By the method of supplying heat can be distinguished autothermal processes in which heat, required for the gasification is obtained by burning portion of fuel injected in the presence of oxygen-containing gasificating agent, and allo- thermal method, in which the required heat is supplied externally by a solid or gaseous coolant.

The process is carried out in the working gasifier of the reactor, which is a single volume that can be functionally divided into three zones:

1. Below lance level zone is the place, where reaction of metal-slag interaction takes place, both at the boundary metal bath - slag bath, and on the border of settling metal drops. When the content of iron oxides in the slag is less than 3%, mainly these are reactions of distribution between metal and slag sulfur, manganese, silicon and other impurities. At higher concentrations of iron oxides in the slag decarburization of metal droplets and of metal at the hearth becomes possible. This reaction is accompanied by emission of CO, which leads to improved mixing, increase of the flow of iron oxides to the metal bath and acceleration of decarburization.
2. Zone of intensely stirred slag. Lances are installed in the longitudinal walls of the reactor in this area, through which melt is blown by oxygen containing blast. In this area, all the basic physical and chemical transformations take place: heating coal particles, removal of moisture and volatile components, gasification of carbonized coal particles, flux dissolution, reduction of iron oxides from coal slag particles with carbon. Slag movement speed in this area is significant and is about 1 m / s.
3. The zone above the molten slag. In fact, this part of the reactor gasifier is a bottom of the boiler, however, functionally belongs to the gasifier. In this zone, there is a significant amount of slag splashing. Slag splashing form on the walls continuously drained slag film. There are lance in the walls for partial post-combustion of gases released from the slag bath. These lances are designed to maintain and regulate the temperature of the slag bath and are used when needed.

One of the main products of gasification technology is syngas. Synthetic gas can be utilized for the production of electricity, heat energy and other purposes. The quality of the synthesis gas depends on the type of the feed, temperature, residence time, etc. [8]. Syngas composition includes the following gases: CO, H2, CH4, and CO2. As the temperature increases grows the amount of carbon monoxide, increasing pressure grows the amount of hydrogen and methane.

The main advantage of gasification (at least from the environmental point of view) is a low level of negative effects on the environment. This is primarily due to rather long process (longer than 3 seconds) - at first gaseous products stay in the zone of oxidation (combustion) at temperatures of 1000 -1200 0C and then in a reducing (anoxic) syngas formation zone. Under such conditions most dangerous substances - dioxins, furans, PCBs, benzopyrenes and other polycyclic aromatic hydrocarbons are thermally decomposed and reductively dechlorined.

Another advantage of gasification, if compared with direct combustion, is much smaller volume of gas to be purified. Furthermore, as a result of complete gas fuel combustion there is significantly less (in times and in some situations an order of magnitude less) number of environmentally damaging chemical compounds (like in the flue gas and the ash residue).

Finally, gasification compared to direct combustion shows less incomplete combustion of fuel as almost 100% conversion of carbon during its transition from a solid to a gaseous state takes place and syngas / bottom ash has practically no soot / unreacted carbon.

As a result of the overview of thermal waste utilization processes, we provide a brief comparative description of thermal disposal methods: high-temperature incineration, pyrolysis and gasification in the Table 1.

Table 1. Main characteristics of thermal disposal methods

Characteristics	Incineration	Pyrolysis	Gasification
Efficiency,%	35-37	80-90	39-42
Primary product	heat	unsaturated hydrocarbons	Syngas
Temperature	Up to 1500 ºC	800 - 900 °C (medium temperature and high temperature)	600 – 1100 ºC
Process	complete oxidation	without the participation of oxygen	partial oxidation
Type of waste	besides individual inorganic types	any kind of waste	any kind of waste
Maximum humidity of raw material,%	70-75	45	10-60

3. Main reactor configuration

A gasifier reactor is one of the main components of the production of syngas. The reason is production syngas production should be as steady as it would be possible. There are plenty of variations of gasifiers, which are described in the scientific papers and research [9-11]. The main different reactor configurations are: Downdraft Fixed Bed, Updraft Fixed Bed, Bubbling Fluidized Bed, Circulating Fluidized Bed, Entrained Flow, Rotary Kiln, Moving Grate [12]. All information was analyzed and below there is brief description of each configuration.

In the fluidized bed gasifier, air is blown through a bed of solid particles at a sufficient velocity to keep them in a state of suspension. The bed is constantly heated and the feedstock is introduced when sufficient high temperature is reached. The fuel particles are introduced at the bottom of the reactor immediately blended with the bed material and almost instantaneously heated up to the bed temperature. As a result of this treatment the fuel is pyrolysed very fast, resulting in a component mix with a relatively large amount of gaseous materials.

In the updraft gasifiers, gas is drawn out of the gasifier from the top of the fuel bed while the gasification reactions take place near the bottom. As the producer gas passes through the fuel bed, it picks-up volatile matter (tars) and moisture from the fuel. Therefore, the gas from the updraft gasifier contains condensable volatiles. The design and operation of the gasifiers is such that the gas comes out at 200-400 C temperature. At this temperature, most of the volatile hydrocarbons are in vapor form, which add to the energy content of the gas.

Downdraft gasifiers are fuel specific. Downdraft wood gasifiers can operate on wood like biomass materials and biomass briquettes with a minimum bulk density of 250 kg/m3 and ash content of less than 5%. In downdraft gasifiers, gas is drawn from the bottom of the reactor while the hottest reaction zone is in the middle. The volatile matter in the fuel gets cracked within the reactor and therefore the output gas is almost tar-free. However, the gas, as it comes out of the reactor, contains small amounts of ash and soot. Fig. 3 shows each type of the gasifier, presented in this section of paper.

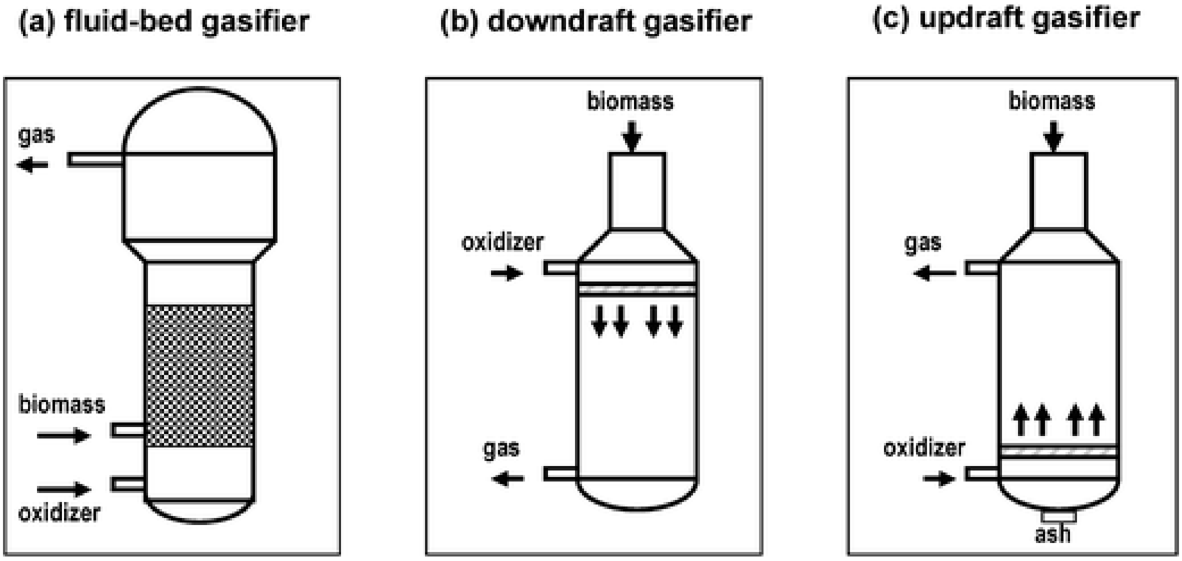

Figure 3. Diagrams of the reactor's types: (a) fluid-bed gasifier, (b) downdraft gasifier, (c) updraft gasifier. Source: R.M. Navarro et al [13]

Based on this review, it cannot be concluded on the best effective configuration from the different experimental results which are strongly linked to the reactor used and the elementary composition of the waste treated [12].

4. Plasma gasification process decryption

At the most basic level, the plasma is thermal energy with a very high temperature. Under natural conditions the plasma is formed by lightning strike when the air is heated around the flash of lightning, turning into plasma with a temperature of approximately 20,000 OS. Since the properties of plasma differ from the three normal States of matter – solid, liquid and gaseous, sometimes it is called the fourth state of matter.

In the process of plasma gasification, the plasma is generated using plasma torches. Inside the gun creates an electrical arc through which air passes to form the plasma. The plasma temperature of about 5000 OS is constrained and directed into the gasifier.

The plasma gasifier is a gasifier from which it displaces oxygen, heated to high temperatures by using plasma. The environment inside of the chamber is devoid of oxygen processed in the gasifier source material is not flammable. Instead, the heat decomposes the source material into hydrogen and simple compounds such as carbon dioxide and water. Organic components are converted into synthetic gas. Inorganic components such as glass, metal and concrete, are melted inside the reactor and arise from its lower part as a non-toxic vitrified molten slag.

Plasma technology as an alternative to any combustion processes is the decomposition of complex molecules into simple compounds by extremely high temperatures with the absence of free oxygen [14].

The process of plasma gasification (high-temperature pyrolysis or gasification of waste) is considered to be very promising and cost-effective, as they process different types of waste (except nuclear) into energy and valuable products for re-use [15].

5. Conclusion

Gasification could be a proposal as an alternative solution for waste utilization with energy production. Plasma gasification offers better environmental performance through lower emissions, reduced volume of waste, the vitrified slag, which could be either landfilled or serve as filler material, such as in road construction [16]. Taking into account all aspects, it could be premature to indicate the gasification as the thermal processing strategy of the future or even as a strong competitor for combustion systems [17]. The success of an advanced thermal technology is determined by its technical reliability, environmental sustainability and economic convenience [17]. Moreover, gasification has all rights to become one of the sources to produce energy on an industrial scale.

Plasma gasification has significant advantages over the other thermal waste utilization. Firstly, it is high percentages of efficiency. The average efficiency is around 42 %. But depending on the type reactor and type of waste it can be around 72 %. It explains that gasification technology advance constantly. Secondly, emissions of CO2 during the process are the lowest in comparison with other thermal methods. Thirdly, it is high quality of the products: syngas and solid rest. Syngas can be used when it is needed (immediately, reserve for the future used, transported to a remoter user and so on). Solid rest is neutral and it can be used as a building material. Through review and comparison we could observe that plasma gasification is more effective, more productive and cheaper, especially than pyrolysis.

The paper shows plasma gasification process in general form: how produced syngas, main reactor configuration, characteristics of the process in comparison with pyrolysis and incineration and so on.

References

[1]. European Environment Agency. Cross-country comparison. Waste – municipal solid waste generation and management [Electronic resource]: AdobeAcrobatReader. URL: http://www.eea.europa.eu/downloads/40507f44ece9499baee2d3c674660998/1430936928/waste.pdf (date of application: 13.09.2016).

[2]. Abramkin N.I., Zakharova R.A., Stepanov R.A. Osnovnye sposoby utilizacii I obezvrezhivvaniya tverdyh othodov I perspectivy ispolzovaniya geotehnologicheskih metodov [Basic ways of recycling and disposal of solid waste and the prospects of using geotechnical methods]. Earth sciences. 2010. No 2. Pp. 164-169. (rus)

[3]. European Commission: Integrated Pollution Prevention and Control. Reference Document on the Best Available Techniques for Waste Incineration. 2006. August.

[4]. Vasiliev I.V., Kapustenko P.A., Perevertaylenko A.Y., Ilyunin O.O., Buhkalo S.I., P.arsenyeva O.A. Problemy I perspectivy nekotoryh sovremennyh tehnologii termicheskoi konversii tverdyh bytovyh othodov [Problems and prospects of some modern technologies of thermal conversion of municipal solid waste]. Integrated technologies of industry. 2013. No 2. Pp. 91-95. (rus)

[5]. Maksimov V.Y. “Poputnaia problema”: ispolzovanie I utilizaciya neftyanogo gaza na predpriyatiyah neftegazovogo kompleksa ["The passing problem": the use and utilization of associated gas at oil and gas enterprises]. Industrial and environmental safety. 2007. No 11. Pp. 28-30. (rus)

[6]. Safin R.G., Timerbayev N.F., Hisameeva A.R., Ahmetova D.A. Gazificacziia vlazhnyx drevesnyh othodov [Gasification of wet wood waste]. Bulletin of Kazan Technological University. 2012. No 17. Pp. 195-199. (rus)

[7]. Bahonina E.I., Covremennye tehnologii pererabotki I utilizacii yglevodorodosoderzhaschih othodob, Soobschenie 1. Termicheskie metody utilizacii I obezvrezhivaniia uglevodorodosoderzhaschih othodov [Modern technologies for processing and recycling of hydrocarbon waste. Message 1. Thermal methods of recycling and disposal of hydrocarbon waste]. Bash. Chem. Mag. 2015. No 1. Pp. 20-29. (rus)

[8]. Kuznetsov V.A. et al. Vliyanie vozdushnoi plasmy v processe gasifikacii tverduh othovov na soderzhanie kondensiruyuschihsia organicheskih veschestv v sintez-gaze lEffect of air plasma in the process of gasification of solid

waste on the content of condensable organic compounds in the synthesis gas]. Successes of Applied Physics. 2013. No 4. Pp. 455-458. (rus)

[9]. Hayashi J. et al., Low-temperature gasification of biomass and lignite: Consideration of key thermochemical phenomena, rearrangement of reactions, and reactor configuration. Energy & Fuels. 2013. No 1. Pp. 4-21.

[10]. Ruiz J.A. et al., Biomass gasification for electricity generation: review of current technology barriers. Renewable and Sustainable Energy Reviews. 2013. No 18. Pp. 174-183.

[11]. Bridgwater A.V. Renewable fuels and chemicals by thermal processing of biomass. Chem. Eng. J. 2003. No 91. Pp. 87–102.

[12]. Fabry F. et al., Waste gasification by thermal plasma: a review. Waste and Biomass Valorization. 2013. No 3. Pp. 421-439.

[13]. Navarro R.M. et al., Hydrogen production from renewable sources: biomass and photocatalytic opportunities. Energy & Environmental Science. 2009. No 1. Pp. 35-54.

[14]. Kobdin V.N., Nechiporuk N.V., Vambol V.V. Sistema upravleniia ekologicheskoi bezopasnostyu pri utilizacii tverdyh bytovyh I proizvodstvennyh othodov [The control system of ecological safety in the disposal of solid municipal and industrial waste]. Ecological Safety. 2014. No 2. Pp. 25-30. (rus)

[15]. Website of the company “Eco-plasma”. Plazmennaia gasifikaciia [Plasma gasification].[Electronic resource]:GoogleChromium. URL: http://www.eco-plasma.ru/technology/plazmennaya-gazifikaciya/ (date of application: 15.09.2016)

[16]. Gray L. Plasma Gasification as a Viable Waste-to-Energy Treatment of Municipal Solid Waste. Solid and Hazardous Waste Prevention and Control Engineering. 2014.

[17]. Arena U., Process and technological aspects of municipal solid waste gasification. A review. Waste management. 2012. No 4. Pp. 625-639.

Газификация и плазменная газификация в качестве типа тепловой переработки отходов

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ИНФОРМАЦИЯ О СТАТЬЕ	История	Ключевые слова
обзорная статья **doi: 10.18720/CUBS.51.7**	Подана в редакцию: 20.09.2016	плазменная газификация, утилизация отходов, современные технологии, синтетический газ, газификатор, газификация, энергоэффективность

АННОТАЦИЯ

В данной статье представлен обзор использования термической утилизации отходов. Основные аспекты каждого процесса были описаны, особое внимание уделено сжиганию, пиролизу и газификации. Кроме того, в статье содержится краткий сравнительный анализ некоторых характеристик (температуры, первичных продуктов и т.д.) изложенных выше процессов, а также их преимущества и недостатки, исходя из экологических, экономических и энергетических критериев. Процесс газификации обсуждался на более глубоком уровне. Достоинства газификации были показаны в сравнении с другими термическими методами утилизации отходов.

Основная идея работы заключается в предоставлении информации, связанной с газификацией и одного из типов - газификацией плазмы, и доказательстве необходимости использования такого метода в утилизации отходов. Плазменная газификация имеет меньше выбросов в атмосферу и токсичных шлаков по сравнению с другими тепловыми технологиями для утилизации отходов.

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Сергеев В.В., Владимиров Я.А., Калинина К.С., Кожукарь Е.В. Газификация и плазменная газификация в качестве типа тепловой переработки отходов /
Sergeev V.V., Vladimirov Y.A., Kalinina K.S., Kozhukar E.V., Gasification and plasma gasification as type of the thermal waste utilization ©

Литература

[1]. European Environment Agency. Cross-country comparison. Waste – municipal solid waste generation and management [Электронный ресурс]: AdobeAcrobatReader. URL: http://www.eea.europa.eu/downloads/40507f44ece9499baee2d3c674660998/1430936928/waste.pdf (дата обращения: 13.09.2016).

[2]. Абрамкин Н.И., Захарова Р.А., Степанов Р.А., Основные способы утилизации и обезвреживания твердых отходов и перспективы использования геотехнологических методов. Earth sciences. 2010. № 2. С. 164-169.

[3]. European Commission: Integrated Pollution Prevention and Control. Reference Document on the Best Available Techniques for Waste Incineration. 2006. August.

[4]. Васильев И.В., Капустенко П.А., Перевертайленко А.Ю., Ильин О.О., Бухкало С.И., Парсеньева О.А., Проблемы и перспективы некоторых современных технологий технической коньерции твердых бытовых отходов. Integrated technologies of industry. 2013. № 2. С. 91-95.

[5]. Максимов В.Ю. «Попутная проблема»: использование и утилизация нефтяного газа на предприятиях нефтегазового комплекса. Industrial and environmental safety. 2007. № 11. С. 28-30.

[6]. Сафин Р.Г., Тимербаев Н.Ф., Хисамеева А.Р., Ахметова Д.А., Газификация влажных древесных отходов. Bulletin of Kazan Technological University. 2012. № 17. С. 195-199.

[7]. Бахонина Е.И., Современные технологии переработки и утилизации углеводородосодержащих отходов. Сообщение 1. Термические методы утилизации и обезвреживания углеводородосодержащих отходов. Bash. Chem. Mag. 2015. № 1. С. 20-29.

[8]. Кузнецов В.А. и др. Влияние воздушной плазмы в процессе газификации твердых отходов на содержание конденсирующихся органических веществ в синтез-газе. Successes of Applied Physics. 2013. № 4. С. 455-458.

[9]. Hayashi J. et al., Low-temperature gasification of biomass and lignite: Consideration of key thermochemical phenomena, rearrangement of reactions, and reactor configuration. Energy & Fuels. 2013. No 1. Pp. 4-21.

[10]. Ruiz J.A. et al., Biomass gasification for electricity generation: review of current technology barriers. Renewable and Sustainable Energy Reviews. 2013. No 18. Pp. 174-183.

[11]. Bridgwater A.V. Renewable fuels and chemicals by thermal processing of biomass. Chem. Eng. J. 2003. No 91. Pp. 87–102.

[12]. Fabry F. et al., Waste gasification by thermal plasma: a review. Waste and Biomass Valorization. 2013. No 3. Pp. 421-439.

[13]. Navarro R.M. et al., Hydrogen production from renewable sources: biomass and photocatalytic opportunities. Energy & Environmental Science. 2009. No 1. Pp. 35-54.

[14]. Кобдин В.Н., Нечипорук Н.В., Вамбол В.В. Системы управления экологической безопасностью при утилизации твердых бытовых отходов и производственных отходов. Ecological Safety. 2014. № 2. С. 25-30.

[15]. Плазменная газификация. [Электронный ресурс]: GoogleChromium. URL: http://www.eco-plasma.ru/technology/plazmennaya-gazifikaciya/ (дата обращения: 15.09.2016)

[16]. Gray L. Plasma Gasification as a Viable Waste-to-Energy Treatment of Municipal Solid Waste. Solid and Hazardous Waste Prevention and Control Engineering. 2014.

[17]. Arena U., Process and technological aspects of municipal solid waste gasification. A review. Waste management. 2012. No 4. Pp. 625-639.

Сергеев В.В., Владимиров Я.А., Калинина К.С., Кожукарь Е.В. Газификация и плазменная газификация в качестве типа тепловой переработки отходов // Строительство уникальных зданий и сооружений. 2016. №12 (51). С. 84-92.

Sergeev V.V., Vladimirov Y.A., Kalinina K.S., Kozhukar E.V., Gasification and plasma gasification as type of the thermal waste utilization. Construction of Unique Buildings and Structures, 2016, 12 (51), Pp. 84-92.