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THE INVESTIGATIONS ON HEAT TRANSFER AND PARTICULATE CONCENTRATION IN PLASMOCHEMICAL REACTORS

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Abstract. During the inactivation of various organic wastes by conventional thermal methods (distillation, desorption), the process temperature is lower than 1300-1500^0 C. However, this is not sufficient for proper decomposition of waste materials. For the complete decomposition of such materials, the reaction temperature should be raised to 1800^0 C. This article aims to determine the temperature and velocity profile distributions of the high-temperature gas flow inside the plasma reactor. According to the study, the plasma-chemical method for decomposition of sewage sludge is quite effective. The efficiency of the gas-phase sludge decomposition depends on the plasma flow parameters (temperature, velocity, etc.).

Keywords: plasma, temperature, reactor.

Introduction

From many currently worldwide existing neutralization methods of hazardous materials and waste the most widely used are the thermal ones, from which the most efficient (with the efficiency of 99 per cent) is the plasma method, which is considered to be future technology for processing harmful materials (Preis at al, 2013; Nowicki, Ledakowicz, 2014; Jindarom et al. 2007). So far such experimental equipment, which operates on the basis of plasma decomposition method, is designed only by a limited number of hazardous waste neutralization companies. It is not applied in Lithuania (Striugas et al, 2012; Zhang et al, 2013; Tang et al, 2013). The plasma arc technology for the neutralization of waste and hazardous materials is employed in the United States, France, Switzerland and Russia. However, in the global scientific and technical literature, there is almost no scientific data on plasma decomposition methods for the waste that is hard to decompose, which could be widely applied in practice due to their unique capabilities. The necessary condition for this method of the neutralization of the organic waste derived from sewage sludge is for the contaminants to stay in the reaction zone for at least two seconds. The temperature inside the plasma reactor during the process reaches up to 1800 K. The plasma source is used to control the temperature (Valinčius et al, 2004; Kong et al, 2013; Salma et al, 2014). However, the temperature does not distribute evenly in the whole volume of the plasma reactor. Such temperature distribution conditions are determined by the gas flow (gas-phase pollutants and plasma forming gas) mixture. Consequently, the efficient neutralization of the sludge waste depends on the plasma temperature distribution within the reactor. Also, the ionization degree of the gas mixture is not even in the reactor volume. The highest degree of ionization plasma is only obtained near the plasma generator output, while the larger part of the reactor volume consists of heated non-ionized gas (Kreek et al, 2014). While examining the neutralization process of pollutants, it is very important to measure the temperature profiles across the plasma reactor volume. The non-contact temperature measurement method, such as optical spectroscopy method, is not suitable because it can measure only the average value of the plasma temperature inside the reactor. To obtain the temperature profiles of the specific plasma reactor volume points, it is necessary to use contact temperature measurement methods. One of contact measurement methods is using thermocouples (e.g. Platinum-rhodium thermocouple), but it can only measure temperatures reaching up to 1700 K. A sufficiently reliable for measurements of higher temperatures method is the colorimetric probe method. The colorimetric probe is pushed into the gas stream and cooled with high-pressure water flow, making it suitable for measurements of very high temperature. The gas flow temperature and speed are calculated from the heat balance while measuring with the colorimetric probe.

As it is shown by recent studies, the particulates are generated in the plasma reactor during the neutralization of sewage sludge pollutants using the plasma method. These particles predominantly consist of carbon (80 per cent). The particle concentration distribution in the plasma reactor volume depends on the gas temperature and the velocity distribution profiles. To determine the particle concentration at various points of the plasma reactor volume, a special cooled catcher should be used.

This article aims to determine the distribution of temperature and velocity profiles of the high-temperature gas flow inside the plasma reactor. Also, to determine particle concentration distribution in the plasma reactor volume using a special cooled catcher.

Methodology

Plasma-chemical reactor system consists of a plasma generator connected to the plasma reactor chamber. The plasma reactor chamber consists of four separate sections. Each section is cooled separately by a water flow of 5 atmospheres of pressure (Fig. 1). Plasma-forming gas is air with a flow rate of 5 g/s. The primary reactor plasma temperature is approximately 2100 K, and it gradually decreases in the length of the reactor. The gaseous phase contaminants obtained after the gasification of the sewage sludge are injected into the reactor chamber through a separate inlet. The feed rate of the gas phase pollutants into the reactor chamber is about 25 g/s. To measure the temperature and velocity profiles, the colorimetric water-cooled probe was used (Fig. 2).

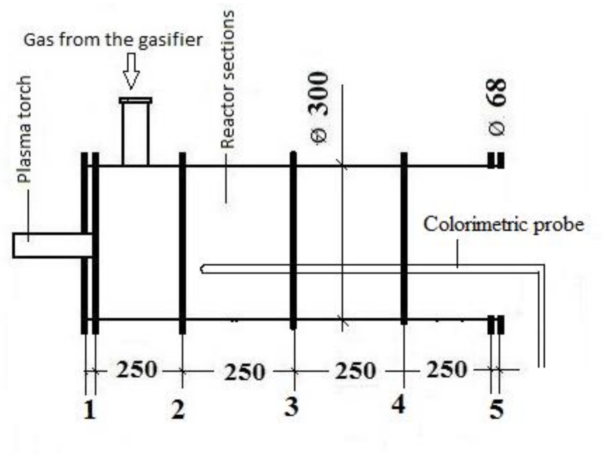

Fig. 1. The scheme for plasma reactor with a measuring colorimetric probe

The colorimetric probe measurement technique is based on the heat balance with and without the suction of gas through the central tube of the probe. The quantity of heat drained by the cooling water during the suction of gas consists of the quantity of the heat transmitted from the external surface of probe Q1 and the quantity of the heat obtained from the sucked gas through the central pipe Q2. If suction is absent, the heat is obtained from the external surface of the probe and equals to Q3 (Fig. 2)

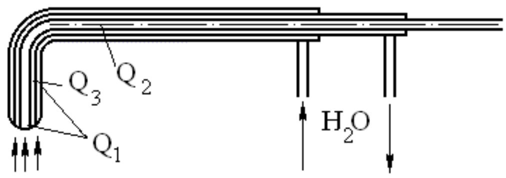

Fig. 2. Schematic view of Colorimetric probe

Then the heat balance equation is:

$$(Q+Q_2)-Q_3 = G_{H_2O}c_p(\Delta T_2-\Delta T_1) \qquad (1).$$

If the gas is not sucked, then Q1 = Q3, and the amount of heat Q2 will be equal to the gas enthalpy change:

$$Q_2 = Gd\cdot\Delta T = Gd(I_1 - I_2) \qquad (2).$$

Having used (2 and 3), we have

$$I_1 = I_2 + \frac{G_{H_2O}}{Gd}c_p(\Delta T_2-\Delta T_1) \qquad (3).$$

This proves that it is not difficult to determine the enthalpy of the gas at the cross-section of the probe inlet. Given the significance of enthalpy and plasma forming gas properties depend on the temperature, it is easy to determine the instantaneous temperature and velocity values. For accurate speed measurement with a calorimetric probe, additionally, it is necessary to know the static pressure at measuring points, as the full pressure is measured by a probe. The flow rate according to the values from the probe is calculated by

$$W = K\sqrt{\frac{2(p_p - p_{st})}{\rho}} \qquad (4).$$

Since the particulates predominantly consist of carbon, the percentage of the concentration of the particulates was obtained by measuring the carbon content at different volume points of the plasma reactor.

For catching the particulates, the colorimetric probe was also used because during the measurement, its external wall was covered with a certain quantity of carbon. The carbon content depends on the place where the probe is located in the reactor volume. Meanwhile, the percentage concentration of carbon was investigated using EDS technique. This methodology allows the identification of the percentage of individual chemical elements.

Results and discussions

The temperature profile in both lengthwise and crosswise flow paths was measured using a water-cooled colorimetric probe (Fig. 3). As it is obvious from the results, the maximum hot gas temperature is at the outlet of the plasma generator and varies in the range between 1400 - 2700 K depending on the central hot gas flow axis. It has been observed that the gas flow temperature is the highest at the central axis of the reactor (as indicated in Figure 3, curve 0) where the ionization degree is the greatest. Meanwhile, the temperature at the periphery of the gas flow is the lowest. At further distances from the plasma generator exit, at about 12 cm from it, the temperature going across the flow axis becomes approximately equal. There are two gas sources in the plasma reactor. The first is the plasma forming gas – the air. This gas is the hottest as it is ionized by the plasma torch. The waste gas is produced from the sewage sludge after gasification in the gasifier (Striugas et al, 2012). The secondary gas is considerably colder (600 K) as compared to the air plasma jet. The primary and secondary gas flows mix in the reactor chamber. The mixing leads to the air plasma temperature decrease.

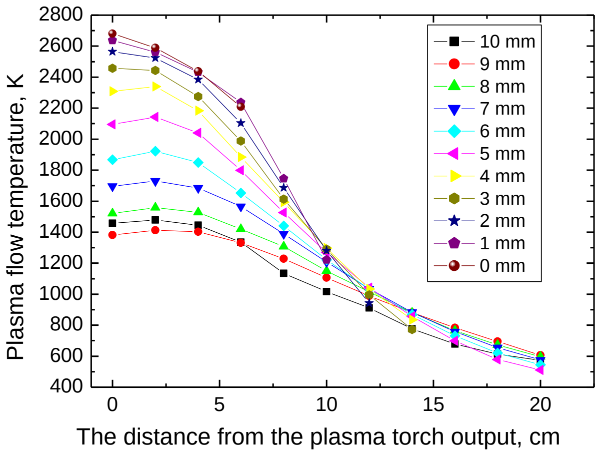

Fig. 3. Hot gas temperature dependence on the distance

The length of the plasma-chemical reactor is 1 m, so the temperature and velocity profiles were measured at the distance of 20 cm from the outlet of the plasma torch since at the greater distances the gas flow temperature drops very rapidly, and the speed reaches just up to 1 to 5 m/s. As shown in Figure 4, the gas flow velocity patterns are similar to the temperature ones. The maximum flow rate is at the central axis of the plasma generator outlet and equals from about 450 to 470 m/s. Meanwhile, at the periphery of the flow at the outlet of the plasma torch, the velocity is about 270 m/s. The reason is that the hot gas flow velocity depends on the temperature. The higher is the flow temperature, the greater is the velocity. Meanwhile, as the research suggests, the gas flow velocity becomes uniform at 9 cm distance from the plasma torch outlet. At a distance of 20 cm or more from the outlet of the plasma generator, the gas flow velocity is just a few meters per second. This feature is important for plasma reactors, whereas, to most effectively neutralize the pollutants, they should be kept in the reaction zone as long as possible. For this reason, the gas velocity is required as low as possible and the temperature, on the contrary, as high as possible.

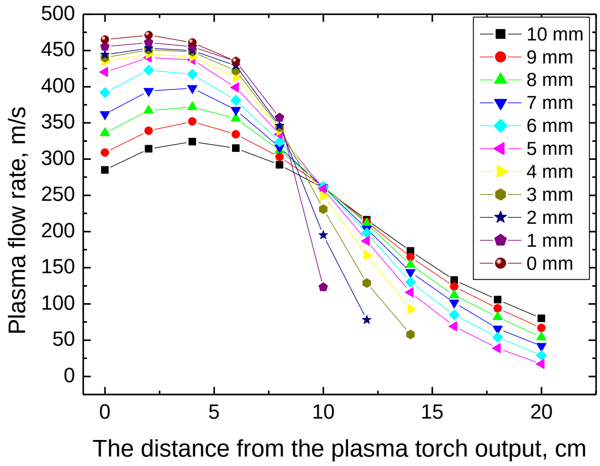

Fig. 4. The plasma flow velocity dependence on the distance

The concentration of particulates also depends on the plasma jet temperature and the velocity in the plasma-chemical reactor. The concentration of particulates was also measured at 20 cm distance from the plasma torch outlet (Fig. 5). The relative concentration of particulates was investigated along the central axis of the plasma reactor (Valinčius et al, 2004). The same colorimetric probe was used as a particulate catcher. EDS studies show that 80 per cent of the particulate matter is composed of carbon. The research shows that the greatest concentration of particulates is at the plasma torch outlet and comprises around 1 per cent of all of the gas mixture mass.

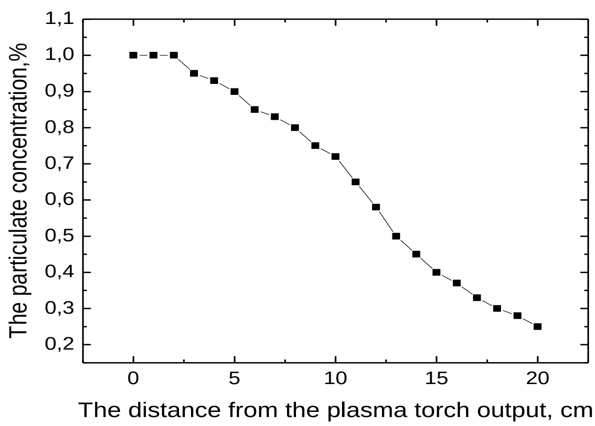

Fig. 5. The dependence of particulate concentration on the distance

Meanwhile, at a distance of 20 cm from the plasma torch outlet, the concentration of particulates is about 0.2 per cent. The reduction of particulate concentration is caused by the fact that some of the carbon turns into volatile gases (carbon dioxide is formed).

Conclusions

According to the study, the plasma-chemical method for the decomposition of sewage sludge is quite effective. The efficiency of the gas-phase sludge decomposition depends on the plasma flow parameters (temperature, velocity, etc.). While digesting the waste, it is necessary to achieve the plasma temperature as high as possible and the velocity as low as possible in the plasma reactor. The measurements with the colorimetric probe indicate that the highest plasma temperature is achieved at the central axis of the plasma torch outlet and reaches up to 2500 K and more. Meanwhile, at the periphery, the temperature of the plasma decreases to 1400 K. The primary plasma forming gas is strongly cooled by the secondary gas, which is obtained during the gasification of the sewage sludge. The velocity variation pattern is similar to the temperature ones. The maximum flow velocity is obtained at the exit of the plasma torch and is about 470 m/s. At the periphery, it is reduced to 300 m/s. At the distance of 20 cm and greater from the plasma torch outlet, the gas velocity rapidly decreases and varies at 1-5 m/s. The concentration of particulates is also at its largest at the plasma generator outlet. Meanwhile, at a distance of 20 cm or more from the plasma generator output, the concentration decreases by approximately 5 times. The study shows that to increase the efficiency of neutralization of pollutants in the plasma-chemical reactor, it is necessary to increase the temperature of the plasma flow or to reduce the gas velocity.

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ŠILUMOS MAINŲ IR KIETŲJŲ DALELIŲ KONCENTRACIJOS PLAZMOCHEMINIUOSE REAKTORIUOSE TYRIMAS

Anotacija

Siekiant neutralizuoti organinės kilmės atliekas, naudojami įvairūs terminiai procesai, pvz., distiliavimas ar desorbcija. Šių procesų temperatūra siekia 1300-1500^0 C, tačiau tai nėra pakankamas rodiklis visiškam organinės kilmės atliekų skilimui. Todėl, siekiant šią problemą išspręsti ir užtikrinti visišką dalelių suskaidymą, reikalinga aukštesnė nei 1800^0 C temperatūra. Šio tyrimo tikslas - ištirti plazmos reaktoriuje esančios plazmos srauto temperatūros pasiskirstymą bei dujų srauto greitį. Gauti rezultatai rodo, jog taikant plazmocheminį atliekų skaidymo metodą, siekiant suskaidyti nuotekų dumblą, proceso efektyvumas yra ženkliai didesnis. Pagrindiniai rodikliai, nuo kurių priklausė nuotekų dumblo skaidymo proceso efektyvumas, buvo plazmos srauto parametrai – temperatūra ir greitis.

Reikšminiai žodžiai: plazma, temperatūra, reaktorius.

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