Journal of Electrostatics 75 (2015) 99–103

Contents lists available at ScienceDirect

Journal of Electrostatics

journal homepage: www.elsevier.com/locate/elstat

The investigation of neutralization process of gas-phase sewage sludge using thermal plasma method

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ARTICLE INFO

Article history:
Received 19 December 2014
Received in revised form
3 March 2015
Accepted 8 March 2015
Available online 25 March 2015

keywords:
Plasma
Waste
Temperature

ABSTRACT

The purpose of this research is to investigate the influence of plasma flow on the composition of gaseous phase organic waste. The experimental method and simulation program "Chemical Workbench" were used for this research. The gas phase waste was neutralized using air plasma in the temperature range of 1200–1700 K. The reactor simulation results showed that the amount of atomic oxygen and nitrogen decreases by 0.5%, meanwhile the amount of carbon monoxide increases by 0.5 percent, as the plasma forming gas is air. The investigation of percentage concentration results showed that as the temperature reaches 1700 K, the H_2 decreases by 4%, CO increases by 7%, CH_4 decreases by 0.4%, CO increases by 0.5%, N_2 decreases by 5%. The experimental measurement results of percentage concentration correlates sufficiently with simulation results for listed gas.

Introduction

The organic waste mostly consists of organic household garbage, medical waste, unused inorganic fertilizers, sludge waste, etc. [1,2]. Traditional methods for neutralization of such waste is not sufficient since the process temperature doesn't exceed 1300 K. Variety of waste materials consisting of Cl, F, P, Hg combinations, due to insufficient temperature, form new toxic materials, such as dioxins, furans, and other hazardous substances.

It's well known that total amount of municipal organic waste exceed 200 million tons over a year. During the past 50 years the amount of waste per person per day has increased from 1.2 to 2 kg. The quantity of dumpsites in the United States and European Union over the past 10 years decreased while average landfill size has increased [3]. Millions of tons of sewage sludge are annually produced primarily in Japan (70 million tons), China (30 million tons) and the USA (6 million tons) [4]. One of the ways to reduce the amount of organic waste is combustion while receiving the thermal energy. The temperatures of conventional thermal methods (low temperature oxidation, distillation, desorption) for inactivation of a various organic wastes is lower than 1300–1500 K. Therefore, not all of the materials brakes down properly, and, in some cases, can form new toxic materials which is much more toxic product than the initial raw material. However, waste incineration generates a secondary toxic waste, which needs to be eliminated using additional technologies and extra energy [5,6]. In order to completely break down the material, the reaction temperature must be raised up to 1600 K and the materials should be held in the combustion zone for 1–2 s. Such conditions are achieved only in plasma reactor where injected various gas (air, water vapour, hydrogen) flows are heated by plasma generator up to 3000 K. Plasma treatment technology is ideal for hard-fissionable secondary waste neutralization. In addition, the plasma is a unique environment for the specific chemical reactions that are not available in conventional flue gas environments takes place [7,8].

The thermal plasma technology began to develop actively in the fourth decade and was used in the metallurgical and aerospace industry, materials synthesis, etc. where the high temperatures were necessary. Over the past thirty years, plasma technology has gained wide application at the waste containment [9]. The main scientific goal is to create the most efficient decomposition technique using plasma technology with low-power plasma generators, which consumes the least additional energy as possible. By reducing the power consumption, the plasma technology can be used in conjunction with a variety of combustion technologies. These technologies has been investigated and gained a great development. The obtained syngas by splitting hazardous waste using plasma pyrolysis can be used as a fuel [10–12].

The modelling process is usually used in the initial stage of the research. The modelling allows the evaluation of the initial

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http://dx.doi.org/10.1016/j.elstat.2015.03.003
0304-3886/

conditions of the experiment and predicts the results of the experiment. So, the objective of the study is to evaluate the influence of plasma-chemical reactor temperature on the chemical composition of organic waste. This study also aims to evaluate the influence of the average plasma temperature on the percentage concentration of various organic compounds in the reactor. The theoretical model used in the study enables to evaluate the starting conditions of the experiment and the results. The results of this model are compared with the experimental results.

Experiment

The plasma system consists of a power supply system, cooling system, gas injection system and measurement system. The electric arc in the torch can be realized using argon, hydrogen, helium, oxygen and air gases. The heat flux is transferred from the ionized and dissociated gas to the waste material.

Plasma chemical reactor consists of four separated sections (Fig. 1).

All sections are cooled with the 5 atm of pressure water flow

The plasma generator (Fig. 2) consists of hot button type cathode with hafnium emitter, step-formed anode made of high purity copper, intermediate anode for arc ignition and insulating rings for injection of plasma forming gas. It is connected to the first section of the reactor to maintain the proper temperature. The plasma temperature is measured with Type B (platinum/rhodium alloy) thermocouples though the cavities made in the connections of each section of the reactor and is about 1200–1700 K. Such temperature is necessary for the successful degradation of organic waste. The sludge was mixed with wood pellets. So, the processed material consisted of 40% of sludge and 60% of wood. Such ratio between the wood pellets and the sludge quantities were selected for a full gasification of sludge in gasifier. At smaller quantities of wood pellets the full gasification of sludge was not achieved. The solid sludge chemical composition is as follows: C – 12%, H_2 – 5.11 %, N_2 – 5.83 %, S – 1.53% O_2 – 17.5 % and Cl – 0.14%. This sludge of such composition is produced by wastewater treatment plants. The organic waste is gasified before entering the reactor. Gasification takes place in a specific combustion chamber with reduced oxygen content. The flow rate of the gasified waste entering the plasma reactor was 25 g/s.

Air is the plasma forming gas, which enters the plasma generator. Air flow rate within the plasma torch was 7 g/s. The plasma generator parameters: electric current – 150 A, the voltage varied in the range of 280–300 V, efficiency – 0.8. The average velocity of plasma entering the reactor was about 370 m/s. The detailed studies of the plasma torch power, thermal and dynamic characteristics are presented in the literature [13].

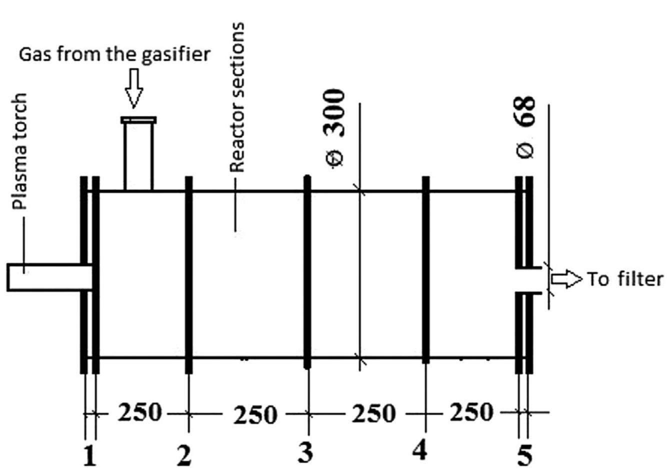

Fig. 1. Schematic diagram of plasma chemical reactor: 1, 2, 3, 4, 5 - thermocouples and sampling.

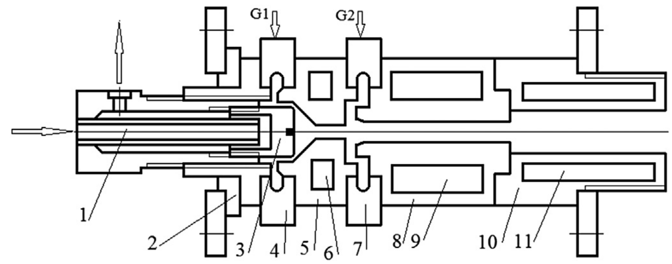

Fig. 2. The schematic view of plasma torch: 1, 6, 9, 11 - cooling water; 2, 4, 5 - the insulating rings; 3 - cathode; 5 - intermediate section; 8, 10 - anode; G1 and G2 - air supply.

The analysis of gaseous samples was performed using Agilent 7890A gas chromatograph with dual channel thermoconductivity detectors (TCDs) and a valve system. The front channel was used for separating O_2, N_2, CO_2, CH_4, CO and light hydrocarbons on dual valve system using Porapak, 60/80 Molsieve and Haysep packed columns. Gas chromatographic conditions were the following: sample loop size 0.25 mL, front channel flow 30 mL/min, back channel flow 10 mL/min, both TCD temperatures 200 °C, valve box temp 120 °C, oven program 40 °C (13 min) > 160 °C (8 min) at 20 °C/min [12]. The chemical composition of gases was used to model the kinetics applying the Chemical Workbench program. Chemical Workbench Reactor Models provide templates for solving reacting-flow problems, including combustion, catalysis, surface processing and plasmas.

The model parameters were evaluated by the length and diameter of the reactor, the gas flow rate, input gas temperature, chemical composition and plasma torch capacity. The plasma-chemical processes occurring in the plasma reactor were modelled using the Chemical Workbench software package. PT-type thermodynamic (TER) reactor was used for modelling. The TER is designed for calculation of the chemical equilibrium of a multi-component heterogeneous system. The model of this type of reactor can be applied for the experimental reactor research used in this work. It was considered that the system was thermodynamically independent and closed during the modelling process (assuming that there is the thermodynamic equilibrium between chemical reactions over the reactor volume). The existence of the gas phase is taken as an obligatory in this model.

Results

The organic waste was processed using plasma flow produced in the plasma generator (PG) using air as plasma forming gas. The PG was directly connected to the reactor chamber. The chemical reactions which are only possible at high temperatures takes place in the reactor. The flow temperature in the reactor has to reach about 1600 K to realize those reactions. The concentration of generated ions and molecules in the air plasma was evaluated using the Chemical Workbench program. Although air consists mainly of nitrogen, oxygen and argon, however, the chemical reactions involve only nitrogen and oxygen, so the model does not take argon gas into consideration. For modelling the temperature of the plasma was selected in the range from 1000 to 2000 K, as the organic waste neutralization reactions for all hardly decomposable materials (remaining as products of gasification) takes place at such temperatures.