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Non-thermal plasma for oxidation of gaseous products originating from thermal treatment of wastes

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Abstract

A plasma reactor generating non-equilibrium plasma in a gliding discharge was applied as one of the modules of a new laboratory device for hazardous waste destruction. The degradation process of wastes containing an organic part was carried out in two stages. The first one consisted of thermal decomposition of wastes in an inert atmosphere (pyrolysis process in argon flow—the gaseous products are formed from the organic part of wastes). In the second stage products of pyrolysis were oxidized in a gliding discharge. This work was focused on study of the parameters influencing the oxidation process of gases originating from pyrolysis and flowing into the plasma reactor. Oxygen was introduced into the plasma reactor simultaneously with the gases. We investigated two factors significantly affecting the oxidation process: (a) the oxygen concentration in the initial mixture of argon and oxygen and (b) the total flow of argon and oxygen gases. The best oxidation efficiency of the processing gases in the plasma was reached when the oxygen content did not exceed 20% and when the total flow of argon and oxygen was low enough not to cause disturbances of functioning of the plasma reactor.

Keywords: Waste decomposition; Used-up oil; Non-equilibrium plasma; Plasma oxidation; Pyrolysis process

1. Introduction

Waste disposal is a very important issue for environmental protection. Thermal technologies such as incineration, gasification, pyrolysis, and thermal or non-thermal plasma used for waste destruction are the most effective ones since they limit the waste volume, reduce the waste toxicity, and produce a waste stream for further treatment [1]. Recently plasma technologies have found many applications in waste disposal due to a fast and cheap thermal waste conversion, and because it is an optimal way to eliminate harmful substances from wastes [2].

The waste streams successfully treated and disposed by thermal plasma technologies include: municipal solid waste, medical waste, incineration ash, polychlorinated biphenyl, hazardous fly ash, low-level radioactive waste, etc. [3,4]. However, thermal (equilibrium) plasma is realized not only with very high gas temperatures (~8000 K), and high densities of energy but also with low selectivities of chemical processes and high energy consumptions. These factors lead to economic disadvantages.

Large possibilities of selective chemical reactions give non-thermal (non-equilibrium) plasma. In this case, instead of heating the entire gas stream, the electric energy is used to produce energetic electrons, which generate active species at a relatively low gas temperature. Non-thermal plasmas enable one to achieve high specific productivity and high energy efficiency for a wide range of chemical processes [5,6]. This kind of plasma may be generated by a variety of electrical discharges such as corona, radio-frequency, microwave, spark, and gliding, mostly under low pressure [7].

We use a non-equilibrium plasma in a new laboratory device to destroy hazardous wastes containing an organic part and to develop a new technology for safe waste degradation process. Our technology is set up in two stages. The first one is the thermal decomposition of wastes in an inert atmosphere (pyrolysis process in argon flow—the gaseous products are formed from the organic part of

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wastes); in the second stage, products of pyrolysis are oxidized in a non-equilibrium plasma. The non-equilibrium plasma is generated by a gliding arc discharge [8] in a plasma reactor to which oxygen is simultaneously introduced.

In this work we investigate two factors in the gliding discharge that significantly affect the oxidation process of gaseous pyrolysis products: (a) the oxygen concentration in the initial mixture of argon and oxygen flowing into the plasma reactor and (b) the total flow of Ar and O_2 gases. The gaseous products were formed during the thermal decomposition of used-up oil in the inert atmosphere. The used-up oil originating from the vacuum pump was applied as the waste.

2. Experimental

The laboratory device in which the used-up oil degradation process was realized consisted of 6 modules: an electric furnace, a plasma reactor, a water cooler, a neutralizer, a carbon adsorber, and a ventilator. The whole device operated under low vacuum [9,10].

Waste oil samples were introduced into the furnace where their thermal decomposition in the argon stream occurred. As a result of oil degradation, mainly hydrocarbons were formed and transported by argon to the plasma reactor to which oxygen was simultaneously introduced. The gliding discharge was initiated between three stainless-steal knife-shaped electrodes and moved along electrodes by the total stream of gases (argon, oxygen, and hydrocarbons) until its breakdown. In the plasma column the oxidation of hydrocarbons into carbon dioxide and carbon oxide took place. The gases leaving the plasma reactor were cooled and purified in the module of neutralizer/adsorber.

In order to determine the oxidation efficiency of gaseous pyrolysis products in the gliding discharge, gas samples were collected at the end of water cooler and analyzed with gas chromatography methods. The Agilent Technologies 6890N apparatus with thermal conductivity detector (TCD) was used to measure the concentrations of CO, CO_2, O_2, and H_2, while the Shimadzu Gas Chromatograph 2014 with flame ionization detector (FID) was applied to determine the concentrations of simple aliphatic hydrocarbons C_2–C_4 remaining in the exhaust gases after oxidation.

Elementary analysis of the oil waste was performed using Perkin-Elmer Elemental Analyzer 240 and Haraeus Elemental Analyzer vario EL III.

3. Results and discussion

3.1. Elementary analysis

Elementary analysis of used-up oil showed that the main components of the sample were carbon (84.85%) and hydrogen (12.17%), whereas chlorine (0.25%) and sulfur (0.21%) were only contaminants. Oxygen was also an oil component, but it was not determined using this method.

3.2. Waste degradation process

3.2.1. Influence of oxygen content on the process of pyrolysis product oxidation

The influence of oxygen content, in the initial mixture of argon and oxygen, on the oxidation process of hydrocarbons formed during the pyrolysis of used-up oil was analyzed for three different O_2 concentrations (9.1%; 19.3% and 29.5%). The concentration of CO_2 and CO in the gases behind the plasma reactor defined the efficiency of hydrocarbon oxidation. The parameters of three processes are collected in Table 1. The total flow rate of Ar and O_2 in all cases did not change and equalled 0.98 $N\,m^3/h$.

As shown in Figs. 1 and 2, thermal conditions in the electric furnace during the oil sample destruction processes were nearly the same (see the temperature courses), thus one could expect that the amount of hydrocarbons formed in this module should be the same in all three experiments.

Table 1
Parameters of experiments determining the influence of oxygen concentration, in the gas introduced to the plasma reactor, on the oxidation process of gaseous products formed during the pyrolysis of used-up oil

Parameter	Unit	Experiment		
		1a	2a	3a
Mass	g	10.1	10.0	10.2
Flow rate of Ar	$N\,m^3/h$	0.69	0.79	0.89
Flow rate of O_2	$N\,m^3/h$	0.29	0.19	0.09
Total flow rate of $Ar+O_2$	$N\,m^3/h$	0.98	0.98	0.98
O_2 concentration	%	29.5	19.3	9.1
Mass reduction	%	96	96	88
Power	kW	1.13 ± 0.05	1.14 ± 0.03	1.11 ± 0.02
Temperature rate in the furnace*	°C/min	5 (24–151 °C) 2 (151–557 °C)	5 (34–165 °C) 2 (165–504 °C)	5 (24–163 °C) 2 (163–410 °C)

*Relevant temperature ranges are specified in parentheses.