Using plasma gasification to reduce plastic waste: thermodynamic analysis and experiment

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Plastic production has sharply increased over the last 70 years. In 1950, the world produced just two million tons. It now produces over 450 million tons (Ritchie et al., 2023). Plastic has added much value to our lives: it's a cheap, versatile, and sterile material used in various applications, including construction, home appliances, medical instruments, and food packaging. However, when plastic waste is mismanaged – not recycled, incinerated, or kept in sealed landfills – it becomes an environmental pollutant. One to two million tons of plastic enter our oceans every year, affecting wildlife and ecosystems. While we might think that much of the world's plastic waste is recycled, only 9% is. About forty percent of the World's plastic still goes straight to landfill – meaning it is not recycled, incinerated, or kept in sealed landfills – putting it at risk of being leaked into rivers, lakes, etc. A promising method for processing plastic waste is plasma gasification. Plasma gasification is the transformation of waste under the influence of high temperature into synthesis gas (CO + H_2). Plasma gasification offers benefits, including waste volume reduction and hazardous waste disposal. Energy recovery from waste is a source of renewable energy and a significant aspect of plasma gasification. Plasma gasification also produces some pollutants, but their amounts are significantly lower and can be further reduced by using advanced technologies and pollution control measures.

This paper presents the results of thermodynamic analysis and experimental studies of the plasma gasification of PET (polyethylene terephthalate), which confirm the prospects for the implementation of plasma gasification of PET with the production of high-calorie fuel gas. PET is a thermoplastic that belongs to the polyester family. PET is used mainly for the producing of containers of various types and purposes (primarily bottles). PET belongs to the group of aliphatic-aromatic polyesters, which are used to produce fibers, food films and plastics, which are one of the most important areas in the polymer industry and related industries. PET consists of repeating ($C_{10}H_8O_4$) units. PET has the following physical properties: density – 1.38-1.4 g/cm³, softening point – 518 K, melting point – 533 K, glass transition temperature – 343 K, decomposition temperature – 623 K.

To carry out the thermodynamic analysis of plasma gasification of PET, the universal program for calculating multicomponent heterogeneous systems TERRA was used (Gorokhovski et al., 2005). It has its own database of thermodynamic properties of 3,000 individual substances in the temperature range of 300–6,000 K. It was created for high-temperature processes computations and based on the principle of maximizing entropy for isolated thermodynamic systems in equilibrium. Calculations of PET plasma gasification were performed in the temperature range of 300–3,000 K at a pressure of 0.1 MPa for the following thermodynamic system, mass fractions: 1 PET + 2.2 air. The purpose of the calculations was to determine the composition of the gas phase of the gasification products, the degree of carbon gasification, and the specific energy consumption for the process. The calculations showed that the degree of gasification increases with increasing temperature, reaching 100% already at a temperature of 1,200 K. At this temperature, carbon completely passes into the gas phase with the formation of CO. With increasing temperature, the concentration of synthesis gas increases to a maximum value of 53.9 vol.% (CO – 38.6, H_2 – 15.3) at T = 1,200 K, practically not changing with a further increase in temperature. At this temperature, the concentration of oxidizers (CO_2 + H_2O) does not exceed 0.8 vol.%. The concentration of nitrogen (N_2) at 1,200 K is 45.2 vol.%. Specific energy consumption for the PET processing process increases with temperature over the entire studied range. At a temperature of 1,200 K, which ensures complete gasification of PET carbon and the maximum yield of combustible gas, the specific energy consumption is 0.8 kWh/kg.

PET gasification experiments were conducted on the installation (Fig. 1), comprised of a DC plasma torch with rated power of 70 kW and a plasma reactor with rated capacity of 50 kg/h (Messerle et al., 2020). Besides the reactor and plasma torch, the experimental setup includes systems for supplying plasma gas and cooling water, a power supply for the plasma torch, and a purification system for the exhaust gases. Samples of gaseous waste gasification products from the experimental setup are collected for analysis. The condensed products of the gasification process accumulated at the bottom of the reactor and were taken for analysis after it was turned off. In the plasma gasification of PET, plasma-forming air was used as a gasifying agent with a flow rate of 19.4 kg/h (15.83 m3/h). Plasma torch power ranged from 68.6 to 74.9 kW. Preliminary heating of the reactor in each of the four experiments was carried out for 0.25 h to a temperature of 1473 K, measured by a pyrometer through the hatch for feeding briquettes into the reactor. According to calculations, at this temperature

the maximum yield of combustible gases is observed during PET gasification. After heating the reactor, 11 PET briquettes with a total weight of 2.75 kg were successively loaded into the reactor through pipe 3 (Fig.1). During PET gasification, combustible gases were continuously removed from the reactor through systems 7–11. The temperature in the reactor varied in the experiments from 1.525 to 1.704 K. The exhaust gas temperature at section 7 outlet varied between 529 and 615 K.

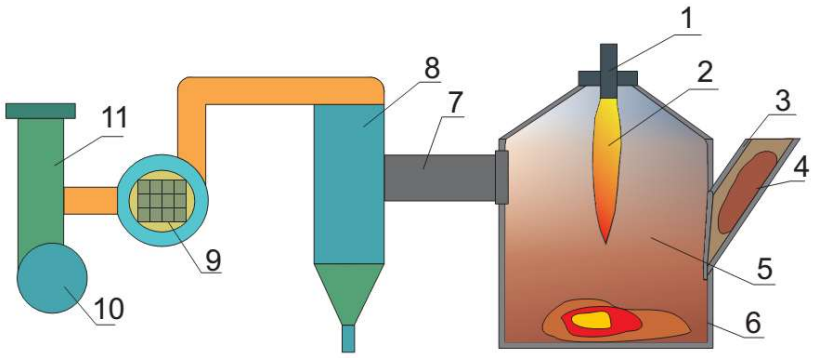

Figure 1. Scheme of the experimental installation for PET plasma gasification: 1 – electric arc plasma torch, 2 – plasma jet, 3 – pipe for loading briquetted waste, 4 – briquetted PET, 5 – PET gasification zone, 6 – plasma reactor, gas cleaning unit, 7 – exhaust gas cooling section, 8 – cyclon combustion chamber, 9 – gas cleaning unit with bag filter, 10 – exhaust fan engine, 11 – ventilation pipe.

Based on the results of PET plasma gasification experiments, the operating modes of the plasma reactor were determined, and the composition of the exhaust gases and condensed products was analyzed for residual carbon content. Once the plasma torch was turned off and the reactor cooled, condensed products were collected. In order to estimate the residual carbon content in the condensed product samples, the absorption and weighing method was used. A 65.8%-66.0% degree of PET carbon gasification was observed. The specific energy consumption for the PET gasification process in the plasma reactor varied from 2.4 to 2.7 kW h/kg. The total yield of combustible gases ($CO+H_2+CH_4$) varied within the range of 55.7 to 60.8%. According to the gas analysis data, no harmful impurities were detected in the gaseous products of PET plasma gasification. When PET is burned, inert gas (CO_2, H_2O and N_2) is formed with physical heat between 176 and 249 MJ/h, depending on PET consumption. As a result of plasma gasification of PET, combustible gas is obtained with a thermal power in the range of 425 to 557 MJ/h. In accordance with this, the thermal power of plasma gasification products is more than twice that of PET combustion. A comparison of the calculation results and the experiment selected based on the maximum concentration of combustible gases (60.8%) is presented in Table 1. The discrepancy between the experiment and the calculation for the target product (combustible gas) did not exceed 9%, the degree of carbon gasification – 7%, and the specific energy consumption for the process – 12.5%. Calculations and experiments showed the absence of harmful impurities in the PET plasma gasification products.

Table 1 – Comparison of experimental and calculation results for PET plasma gasification.

Method	CO, Vol.%	H_2, Vol.%	CH_4, Vol.%	CO_2, Vol.%	N_2, Vol.%	T, K	X_C, %	Q_{SP}, kWh/kg
Test	23.1	21.5	16.2	13.6	25.6	1704	60.8	2.4
Calculation	42.1	23.9	0.1	0.3	33.9	1704	64.8	2.1

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