The usage of low-voltage AC plasma torch for polystyrene gasification

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Abstract. The article describes the plasma-chemical process of polystyrene processing by air low voltage AC plasma torch with a power of up to 500 kW. Polystyrene is a highly toxic compound, so its processing is very important. In this case, it consists mainly of carbon and hydrogen. The thermodynamic calculation of plasma gasification of polystyrene using air plasma and steam was carried out. It is established that the maximum concentration of steam in the gasifying agent is 50%wt. In this case, the plasma enthalpy of 12 MJ/kg is sufficient for the implementation of this process.

1. Introduction

The problem of recycling waste is becoming increasingly important. This is due to the growing population of the planet and the consumption of biological and other natural resources. There are a number of solutions to this problem: heat treatment is the main method of recycling; biogas production [1]; recycling into useful materials. Thermal processing can be carried out in the mode of combustion and pyrolysis. In the first case, the raw material is incinerated in an excess of oxidant (usually air). The products of the process are ash and combustion products (carbon dioxide and water). However, in most cases, to achieve complete combustion of organic matter does not work. As a result, a large number of toxic compounds are formed that adversely affect the environment and human health. During pyrolysis, the process is carried out with a lack of oxidizing agent. In this case, a combustible gas is formed containing a large amount of resinous components and a soot. Combustible gas can be used to generate electrical energy, chemical synthesis, and individual compounds. With the development of energy, the gasification method is becoming increasingly important. In this case, organic fuel (or waste) is subjected to partial oxidation with the formation of synthesis gas (hydrogen + carbon monoxide) and ash. The produced synthesis gas can be used to generate electrical energy with high efficiency. However, this process requires additional energy. In industry, for this purpose, the heat from the combustion of a part of the fuel (partial oxidation with air or pure oxygen [2]) or preheated high-temperature steam [3] is used. With the development of plasma technology and electrical engineering, it became possible to use plasma to process waste [4] and produce new...
materials [5] and coatings [6]. Plasma torches of various types are used to study plasma gasification: direct current, alternating current and microwave. Currently, DC plasma torches are the most common in the world, since stabilization of the DC arc is much simpler [7] [8]. Microwave plasma torches have a very high power, which ensures a very high performance of plasma-chemical installations [9, 10]. However, low efficiency, high capital costs significantly limit their use. AC plasma torches are explored and developed in the spirit of types: high-voltage [11] and low-voltage [12, 13]. High-voltage plasma torches have a high electrode lifetime, since to obtain the same power, a smaller current value is required [14]. However, low voltage plasma torches are much safer.

The article [15] considers gasification of tire powder (200 and 600 μm) using a radio frequency plasma torch (13.56 MHz). The installation capacity is 1600-2000 W, the plasma reactor is a quartz tube with an inner diameter of 16 mm, an outer diameter of 18 mm and a length of 500 mm. Nitrogen with a volume flow rate of 800 ml/min was used as the carrier gas; the feed speed of the tire powder was 0.2 g/min; the pressure in the reactor ranged from 3,000 to 8,000 Pa. The degree of conversion of the raw materials was in the range of 34.4-78.4%, the hydrogen productivity reached 99 ml/min.

For the processing of medical waste, an AC plasma torch was studied [16]. The study of gasification was carried out on an experimental setup, the main components of which were a plasma torch with a capacity of 70 kW and a plasma reactor, whose capacity was up to 30 kg/h of waste. The reaction volume of the reactor was 0.016 m³. Specific power consumption for the treatment of waste range from 3.5 to 4.6 kWh/kg. The total concentration of synthesis gas (CO + H2) was 69.6% vol.

However, the hydrogen content was 6.2% vol., due to the high requirements for the process of neutralization.

AC high voltage plasma torches of alternating current (10 kV) showed high efficiency in the processing of wood waste in a reactor of the inverted type [17]. The plasma torch consists of three electric arc channels with end electrodes in each channel. The electric arc ignites as a result of the breakdown between the electrode and the plasma torch case. The plant capacity is up to 150 kg/h, the total power of the plasma torches of the plant was 120 kW. The main composition of the synthesis gas was as follows: \( H_2 \) - 32.2, \( CO \) - 26.1 \( N_2 \) - 33.4, \( O_2 \) - 0.27, \( Ar \) - 0.4, \( CO_2 \) - 7.64% vol.

2. Estimated part

Thermodynamic calculations were performed using the Chemical Workbench 3.5 program to study the use of low-voltage AC plasma torch with power up to 500 kW [18]. This device consists of two plasma torches: a low-power high-voltage plasma torch that provides air ionization (Figure 1, [19]) and a large low-voltage plasma torch (Figure 2). In a low-voltage plasma torch there are two electrodes on the surface of which the arc binding moves. By moving the arc binding, the life of the electrodes is increased.

![Figure 1. High-voltage single-phase plasma torch: 1 - housing; 2 - electrode holder; 3 - end electrode; 4 - nozzle.](image1)

![Figure 2. Low-voltage three-phase plasma torch.](image2)
The main technological parameter of the plasma torch is its power. The dependences of the plasma torch power and plasma enthalpy on the plasma gas flow and electric current are presented in Figures 3 and 4 [20].

![Figure 3](image1.png) ![Figure 4](image2.png)

**Figure 3.** The dependence of the thermal power of the plasma torch on the electric current and the flow of plasma-forming air.

**Figure 4.** The dependence of plasma enthalpy on electric current and plasma-forming air flow.

Polystyrene was chosen as a raw material with high toxicity and a tendency to polymerization. Polystyrene together with polyvinyl chloride is the main polymeric environmental pollutant. The elemental composition of the raw material is presented in Table 1 [21]. The net calorific value is assumed to be 38.19 MJ/kg.

The main gasification agent is air (air plasma), and the secondary agent is saturated water vapor (120 °C). The composition of the mixture gasifying agent is presented in Table 2.

| Table 1. The composition of the raw materials for plasma gasification. |
|---------------------------------------------------------------|
| **Element** | **Concentration,%wt** |
|----------------|---------------------|
| Carbon         | 87.1                |
| Hydrogen       | 8.4                 |
| Oxygen         | 4.0                 |
| Nitrogen       | 0.2                 |
| Sulfur         | 0                   |
| Ash            | 0.3                 |

| Table 2. The composition of the mixture gasifying agent for the calculation. |
|--------------------------------------------------------------------------------|
| **Calculation number** | **O₂** | **N₂** | **Ar** | **CO₂** | **H₂O** |
|-------------------------|--------|--------|--------|---------|---------|
| 1                       | 23.11  | 75.38  | 1.29   | 0.05    | 0.17    |
| 2                       | 22.01  | 71.79  | 1.23   | 0.05    | 4.92    |
| 3                       | 21.01  | 68.53  | 1.17   | 0.05    | 9.25    |
| 4                       | 20.10  | 65.55  | 1.12   | 0.04    | 13.19   |
| 5                       | 18.49  | 60.30  | 1.03   | 0.04    | 20.14   |
| 6                       | 17.12  | 55.84  | 0.96   | 0.04    | 26.05   |
| 7                       | 15.94  | 51.99  | 0.89   | 0.03    | 31.15   |
| 8                       | 14.91  | 48.63  | 0.83   | 0.03    | 35.59   |
| 9                       | 14.01  | 45.68  | 0.78   | 0.03    | 39.50   |
The calculations were carried out at constant pressure (1 atm) and temperature (1500 K). The dependence of the equilibrium composition of the reaction products on the flow rate of the gasifying agent was determined. The end of the calculation was considered to stop the formation of solid carbon materials (graphite).

### 3. Results and its discussion

As one would expect, with increasing concentration of water vapor in the reaction products, the content of hydrogen and carbon monoxide increased, and the concentration of nitrogen fell (Figure 5). From this it can conclude that it is possible to significantly increase the heat of combustion of synthesis gas by increasing the consumption of steam.

![Figure 5. The dependence of the composition of the main products of gasification on the concentration of steam in the gasifying agent.](image)

With an increase in the concentration of steam in the gasifying agent, the lower heat of combustion of synthesis gas increases (Figure 6). This is due to an increase in the concentration of hydrogen and carbon monoxide. However, an increase in lower calorific value is provided by an increase in energy consumption for the chemical process. This consumes relatively expensive electrical energy. The dependence of the enthalpy of air plasma and the specific consumption of air and water vapor are shown in Figure 7.
As can be seen from the Figure, with increasing steam concentration, the required enthalpy of air plasma increases. This is due to the fact that the reaction of the interaction of steam and carbon-containing substances is highly endothermic, in contrast to partial oxidation by atmospheric oxygen. At the same time, the specific consumption of gasification agents is reduced. The main reason for this fact is the high content of ballast nitrogen in the air, which is not involved in a chemical reaction. The removal of nitrogen from synthesis gas is a very energy-intensive process, which can significantly reduce the economic effect in the processing of polystyrene. Figure 6 shows the dependence of the lower heat of combustion of synthesis gas on the concentration of water vapor in the gasifying agent.

However, the possibility of using additional water vapor for the gasification of polystyrene is determined by the electrical power and plasma enthalpy obtained in the plasma torch. Therefore, it is necessary to compare the desired plasma enthalpy and plasma enthalpy obtained in the plasma torch. The maximum value of the plasma enthalpy obtained in the plasmatron is 12 MJ/kg, which corresponds to the concentration of steam in the gasifying agent about 50\% wt. From this, it follows that the total capacity of a hypothetical plasma installation consisting of a single plasma torch will be 110 kg/h of polystyrene.
4. Conclusion
Polystyrene gasification using an AC low-voltage air plasma torch is possible not only at 100% air concentration, but at also when steam with a concentration of 50%wt introduced as a gasifying agent. This increases the content of hydrogen and carbon monoxide in the synthesis gas, the lower heat of combustion of the synthesis gas. It is especially important that with an increase in the concentration of steam in the gasifying agent, the concentration of nitrogen, which is the main ballast gas, reduces the economic efficiency of this method. One the plasma torch has sufficient capacity to ensure processing of 110 kg/h of polystyrene with the formation of high-calorific synthesis gas.

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