Co-gasification of lignite and used car tires by H₂O/air thermal plasma

V E Popov¹, D I Subbotin¹²³, A V Surov¹, S D Popov¹, E O Serba¹, E P Godina¹², A A Kiselev¹

¹ Institute for Electrophysics and Electric Power of the Russian Academy of Sciences (IEE RAS), Dvortsovaya emb. 18, St. Petersburg, 191186, Russia
² St. Petersburg State Technological Institute (Technical University), Moskovsky prospect, 26, St. Petersburg, 190013, Russia
³ St. Petersburg State University, Universitetskaya Emb., 7/9, St. Petersburg, 199034, Russia
derwinter@mail.ru

Abstract. The article considers a high-voltage AC plasma torch working on a mixture of water vapor and air up to 90 kW. A thermodynamic calculation of the co-gasification of used automobile tires and lignite is presented. Assessment of the operation of the plasma torch working on mixtures of H₂O/air at co-gasification of lignite and used car tires shows prospect of these processes implementation.

Keywords: plasma torch; thermal plasma; co-gasification; synthesis gas

1. Introduction

The problem of processing used tires is very relevant. They are processed into fuel based on tires, materials for the construction of roads and buildings foundations, etc. One of the methods for processing tires is gasification. A number of gasifiers for the realization of this process are proposed: entrained gasification, fluidized-bed gasification and bed gasification. The first two methods are complicated in hardware design, but they have high performance. Bed gasification of car tires is not possible, because the formation of a reducing layer (carbonized residue) is required for the normal operation of the plant. The same problem is noted for plastics and other polymer materials. When these substances are heated without access of air, practically the whole mass is converted into volatile substances and a small amount of ash. In the absence of a reducing layer, instead of the material gasifying, pyrolysis takes place with the formation of a large number of liquid organic substances, the processing of which is a complex technological task. To solve this problem, co-gasification of materials with a high yield of volatile substances and materials traditionally used in bed gasification is used [1]. Various types of coals are often used as such materials, including lignite (low-grade coal with a low calorific value).

Air, oxygen, steam and carbon dioxide are used as an oxidizer. Carbon dioxide refers to a gasifying agent with low economic efficiency, steam requires high energy inputs, and oxygen is highly flammable. The advantage of air is its relative cheapness, however, the produced syngas contains a large amount of nitrogen (ballast gas) [2].
To increase the hydrogen yield and the molar ratio $H_2/CO$, energy is required to be supplied to the gasifier. This can be realized using powerful plasma torches [3]. A number of plasma gasification methods using DC plasma torches have been proposed [4, 5]. At the same time, high-voltage AC plasma torches have higher thermal efficiency [6]. Air plasma torches of this type have shown their effectiveness in gasification of biomass [7], and multigas plasma torches allow to process natural gas [8] and organochlorine compounds [9].

The theoretical estimation of a high-voltage AC plasma torch work at co-gasification of the used tires and lignite with use of the thermal air-steam plasma is considered in the article.

2. AC plasma torches operating on mixtures $H_2O/\text{Air}$

The major disadvantage of the air plasma gasification is high concentration of nitrogen in product gas. It increases the cost of synthesis gas treatment. At steam gasification the concentration of ballast gases is relatively low. However, as noted above, the electrodes erosion in the presence of steam is much higher than at usage of air, carbon dioxide or inert gases. It is proposed to use these gases as protective gases (steam is the main gasifying agent) for the problem solution. Air can be provided as gasifying agents: when using steam the low air flow rate will result in a small amount of nitrogen in the product gas.

On this basis it is advisable to use air-steam plasma for gasification of organic substances. The plasma torch operating parameters using mixture of steam and air in different ratios were also previously investigated [10, 11]. Its operating electrical characteristics, dependence of the thermal efficiency on arc current, flow rates and composition of the plasma-forming mixture were determined. Steam flow rate is 3.55 - 5.8 g/s, air flow rate is 1 - 3 g/s, arc current is 28 - 29 A, arc voltage drop is 1.15 - 1.85 kV, power is 57.6 - 87.5 kW, thermal efficiency is 94.3 - 95.3%. The photograph of this plasma torch is shown in Fig. 1.

![Figure 1. Multi-gas three-phase electric arc AC plasma torch](image)

3. Estimation of lignite and used tires co-gasification

Thermodynamic estimation of co-gasification of used car tires and lignite was carried out to evaluate the work of the plasma torch as part of a plasma gasifier. Lignite, a low-calorie fuel, was chosen deliberately to show the effectiveness of plasma gasification. If it is used better fuel, the results will be much better. Available enthalpy of blowing agent without regard to heat loss was 12.5 MJ/kg (steam: air = 5: 1 wt.). Further experiments are planned to carry out in the downdraft reactor, it was therefore it was provisionally selected the ratio of used car tires: lignite 30% to 70% wt. The efficiency of the gasification process is directly influenced by the granulometric characteristics of the fuel; therefore, imparting certain form of crushed waste is a necessary part of the technological chain of their
preparation. The requirements for the size of the granules of fuel obtained in the granulator are determined from the conditions of a uniform distribution of the gas flow over the cross section of the layer of granular material, which is observed when the ratio of the layer diameter to the characteristic particle size is in the range of 20-40 mm.

The inorganic portion of used car tires is assumed for iron and ash lignite is assumed for silicon dioxide. It is assumed that used car tires are pre-cleaned from large metal particles. Element composition of mixed fuel and composition of blowing agent are shown in Table 1 and 2 respectively.

Table 1. Elemental composition of raw materials, % wt.

| Chemical element | Used car tires | Lignite | Mixed fuel |
|------------------|----------------|--------|------------|
|                  | Used car tires |        |            |
| C                | 60.16          | 26.99  | 36.94      |
| H                | 5.66           | 4.48   | 4.83       |
| O                | 10.74          | 52.92  | 40.27      |
| N                | 0.77           | 0.43   | 0.53       |
| Fe               | 18.30          | -      | 5.49       |
| S                | 4.37           | -      | 1.31       |
| Si               | -              | 15.19  | 10.63      |

The computation was performed in the adiabatic mode at temperature of 1500 K and pressure 101325 Pa. Thus the thermal balance was calculated from the mass balance data, plasma enthalpy and the lower heating value of mixed fuel per 1 kg of fuel.

Table 2. Gasifying agent composition, % wt.

| Substance | Gasifying agent (H2O : air = 5:1 mass) |
|-----------|----------------------------------------|
| N2        | 12.58                                  |
| O2        | 3.86                                   |
| Ar        | 0.22                                   |
| CO2       | 0.01                                   |
| H2O       | 83.33                                  |
| Total     | 100                                    |

Lower heating value of mixed fuel was calculated using the formula:

\[ Q_{LHV}^g = \frac{33.5 \cdot C^{fg} + 1256 \cdot H^{fg} - 105 \cdot O^{fg} - S_1^{fg} - 25 \cdot 14 \cdot 9 \cdot H^{fg} + W^F}{LHV_{fg} + LHV_C}, \text{kJ/kg}. \]  

(1)

where \( Q_{LHV} \) – the lower heat value of mixed fuel, MJ/kg; \( Q_{fg} \) – heat removed with synthesis gas MJ/kg of mixed fuel; \( Q_w \) - heat removed with water, MJ/kg of mixed fuel; \( Q_{ash} \) - heat removed with ash, MJ/kg of mixed fuel; \( Q_c \) - heat removed with fixed carbon, MJ/kg of mixed fuel; \( LHV_{fg} \) – lower heat value of syngas, MJ/kg of mixed fuel; \( LHV_C \) – lower heat value of fixed carbon, MJ/kg of mixed fuel.

Composition of products depending on the gasifying agent flow rate for its different types is shown in Fig. 2 (impurities content is not shown, but are taken into account in the computation). Step of computation - 0.1 kg of gasifying agent per 1 kg of mixed fuel. Initially fixed carbon (graphite) is the main product for lack of gasifying agent (pyrolysis). Pyrolysis is terminated at flow rate of the gasifying agent of 0.3 kg/kg for steam/air.

As the flow rate of the gasifying agent increases various solids are produced: iron carbide, iron oxides, silicon dioxide and metallic iron. Because of the made simplifications their composition is not reliable. Required enthalpy of gasifying agent calculated from the heat balance is shown in Fig. 3. Maximum of enthalpy of a gasifying agent corresponds to the transition from pyrolysis to gasification and maximum hydrogen content in the products.
Figure 2. Dependence of product composition at co-gasification when using a mixture of steam and air

Figure 3. Dependence of enthalpy of gasifying agent versus specific consumption of gasifying agent

Unfortunately, at the moment the developed plasma torches do not have plasma enthalpy corresponding to the best parameters of the synthesis gas (taking into account the minimum excess of
oxidizer), however, from the economic point of view, they can be better. The results of computation are presented in Table 3. In this case, the plasma enthalpy obtained in plasma torches takes into account heat losses (9-10%).

As can be seen, for 1 kg of mixed fuel it is necessary to supply about 8.3 MJ of energy, the synthesis gas is substantially free of ballast gases (nitrogen, argon), lower heat value of product gas is 10 MJ/kg, the total concentration of H₂ + CO is about 74% (in dry condition is 90%). In the case, if more high calorie fuel applies the results will be significantly better, in the first place, the water content in the product gas will be less. Subsequently, more powerful facilities on the basis of developed plasma torches operating with a wide range of gasifying agents can be designed, that allows producing synthesis gas with higher molar ratio of H₂/CO.

| Parameters                  | Unit       | H₂O:Air |
|----------------------------|------------|---------|
| Enthalpy of gasifying agent | MJ/kg      | 11.71   |
| Mass balance               |            |         |
| Raw materials              | kg/kg of mixed fuel | 1.00   |
| Air                        |            | 0.12    |
| Steam                      |            | 0.58    |
| Carbon dioxide             |            | -       |
| Syngas                     |            | 1.12    |
| Condensed water            |            | 0.28    |
| Ash                        |            | 0.30    |
| Energy balance             |            |         |
| LHV of the raw materials   | MJ/kg      | 13.25   |
| Plasma                     |            | 8.20    |
| Inlet sum                  |            | 21.45   |
| Chemical energy of the syngas | MJ/kg of mixed fuel | 17.45 |
| Heat energy of the syngas   |            | 2.85    |
| Heat energy of condensed water |            | 0.75    |
| Heat energy of ash         |            | 0.40    |
| Total yield                |            | 21.45   |
| Syngas Composition         | % vol.     |         |
| H₂                         |            | 44.32   |
| CO                         |            | 29.49   |
| N₂                         |            | 3.68    |
| CO₂                        |            | 4.49    |
| Ar                         |            | 0.04    |
| H₂S                        |            | 0.44    |
| COS                        |            | 0.01    |
| H₂O                        |            | 17.53   |
| LHV of the dry syngas      | MJ/Nm³     | 9.56    |

4. Conclusion
It is established that using the developed AC plasma torch, it is possible to conduct plasma co-gasification of used automobile tires and lignite. In this case, low-grade coal was chosen for the calculation, therefore, the results of the process will be much better for gasification of higher quality
coal. The plasma installation test with the proposed parameters will be presented in subsequent publications.

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References
[1] Kamińska-Pietrzak N, Smoliński A 2013 *Journal of Sustainable Mining* **12** 4 6-13
[2] Mozafari A, Tabrizi F F, Farsi M, Mousavi S A H S 2017 *Journal of Analytical and Applied Pyrolysis* **126** 415-422
[3] Messerle V E, Ustimenko A B, Lavrichshev O A 2016 *Fuel* **164** 172–179
[4] Hlina M, Hrabovsky M, Kavka T, Konrad M 2014 *Waste Management* **34** 1 63–66
[5] Galvita V, Messerle V E, Ustimenko A B. 2007 *International Journal of Hydrogen Energy* **32** 16 3899–3906
[6] Rutberg Ph G, Safronov A A, Popov S D, Surov A V, Nakonechnyi G V 2006 *High Temperature* **44** 2 199-205
[7] Rutberg Ph G, Bratsev A N, Kuznetsov V A, Popov V E, Ufimtsev A A, Shtengel’ S V 2011 *Biomass and Bioenergy* **35** 495-504
[8] Rutberg Ph G, Bratsev A N, Kuznetsov V A, Nakonechny G V, Nikonov A V, Popov V E, Popov S D, Serba E O, Subbotin D I, Surov A V 2014 *Technical Physics Letters* **40** 9 725-729
[9] Surov A V, Popov S D, Popov V E, Subbotin D I, Obraztsov N V, Kuchina J A, Serba E O, Nakonechny Gh V, Spodobin V A, Pavlov A V, Nikonov A V 2017 *Journal of Physics: Conference Series* **825** 1 012015
[10] Rutberg F G, Kuznetsov V A, Serba E O, Nakonechnyi G V, Nikonov A V, Popov S D, Surov A V 2013 *High Temperature* **51** 5 608-614
[11] Rutberg Ph G, Kuznetsov V A, Serba E O, Popov S D, Surov A V, Nakonechny Gh V, Nikonov A V 2013 *Applied Energy* **108** 505-514