Industrial testing and analysis of activated carbons derived from electric arc plasma

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Abstract. The article presents the results of study of activated carbon produced by thermal destruction in electric arc plasma. There are measurement methods such as density measuring, measuring of total and summary porosity, porous surface microscopy, laboratory methods and industrial testing of sorption activity.

Key words. Sorbent, porosity, density (true, apparent, bulk), pore volume, specific surface, surface microscopy, electric arc plasma treatment.

1. Introduction
At present time, carbon absorbent (activated carbon) is used in many processes of chemical technologies. Gas and wastewater treatment is mainly based on activated carbon adsorption [1]. Characteristics of adsorption capacity are important for studying of carbon nature and for solving of many technical problems. Thermal destruction is the basic process of obtaining the target product [2].
Use of low temperature plasma is a new method of thermal activation of carbon [3]. Water purification enterprises and water treatment systems usually located at power stations, power plants are main consumers of activated carbon. Sewage treatment is complicated by the fact that this water is a complex heterogeneous system and consists of various substances in different states [4]. In the article there are investigation results of structure and properties of coal after electric arc plasma treatment. The possibility of industrial use of these sorbents for sewage treatment is explored.

2. The experimental setup and methods of research
The use of electric arc plasma can significantly intensify heat treatment of coal, increase yield of desired synthesis product (sorbent) and thereby reduce production costs and considerably improve environmental performance. To investigate carbon activation process universal plasma modular installation of combined type has been created which opens possibility for integrated approach to the production of activated carbon and gas synthesis combined in unified process of carbon plasma treatment [3]. In the article sorption properties of coal mine “Okinoklyuchevsky” were investigated treated by means of electric arc plasma in the plasma reactor of combined type. Coal with the following characteristics was applied (see Table1).

In the experiment, coal passed through plasma chemical reactor with an arc rotating by magnetic field. In uniform rotation of anode arc spot between the annular cathodes in the reactor continuous plasma environment is formed with average temperature 2500-3000K. Due to this, coal particles supplied from the top into the reactor fully undergo plasma thermochemical treatment. The residence time of coal particles in plasma zone depends on the size of fraction and is regulated by installation of
diaphragm in the bottom of the plasma reactor and ranges from 0.1 to 1 sec. The temperature and
speed of rotation is adjusted by alteration of plasma current power source and coil. While passing
through plasma zone all coal particles are exposed to short plasma treatment that leads to its thermal
destruction. Treated solid particles fall into the bottom part of the plasma reactor - activation chamber.
Generated synthesis gas is removed from the reaction zone by exhaust device. This principle of
construction of plasma systems allows reaching industrial production level of carbon sorbents [3, 5].

In electric arc zone of the reactor of described type electric power loaded in the camera in the arc is
converted into heat. Thus, electric arc zone is zone of generating thermal energy, its absorption, it
covers entire section of the chamber, allows to adjust dwell time of coal dust, concentration power and
hence temperature. This area is limited in height by planes perpendicular to the chamber axis and
passing through the electrode end (top), and through the middle of the electromagnetic-solenoid coil
(lower) [6]. Thermal energy is generated by the rotating arc in the zone and under influence of gas
flow resulted from thermal effect on coal dust, is distributed throughout its entire volume.

Power of generating zone was determined by condition of its even distribution. In calculations the
diameter of the reactor chamber was taken as key size and all basic regularities in the electric arc zone
were expressed by means of it. It makes possible to extend the experiment results received for small
reactors to geometrically similar reactors of larger power and hence larger diameter chambers [7].

Reactor current \( I_p \) is expressed by current density relevant to sectional area of the camera:

\[
I_p = \Delta i_p \pi \frac{D_k^2}{4}.
\]

(1)

Accordingly, current density \( I_p = \Delta i_p \pi \frac{D_k^2}{4} = 1.132 \frac{A}{cm^2} \)

Reactor voltage \( U_p \) is represented by means of voltage gradient of the electrode gap:

\[
U_p = E_p \frac{D_k}{2} = 1.132.
\]

(2)

Where \( \frac{D_k}{2} \) - interelectrode gap, which includes arc voltage for determining voltage gradient (in reactor
with rod cathode).

Accordingly, voltage gradient \( E_p = \frac{2U_p}{D_k} = 26.7 \frac{V}{cm} \)

As a result, taking into account expressions for \( I_p \) u \( U_p \) formula for reactor power is derived:

\[
P_p = U_p \cdot I_p = \pi \cdot \frac{1}{2E_p \Delta i_p Dk^3} \approx 0.39E_p \Delta i_p Dk^3.
\]

(3)

Which is equal to: \( P_p \approx 0.39E_p \Delta i_p Dk^3 = 0.39 \cdot 26.7 \frac{V}{cm} \cdot 1.132 \frac{A}{cm^2} \cdot (15)^3 cm^3 = 40 kW \).

As a result it can be concluded that generated in volume of zone heat power equal to loaded
electrical power is proportional to the cube of the chamber diameter, it is also proportional to the
current density \( \Delta i_p \) and voltage gradient \( E_p \) or volumetric power \( W_p \), released in the zone. Value \( W_p \),
determining temperature level is, obviously, a constant for given production for geometrically similar
reactors:

\[
W_p = \text{const}.
\]

(4)

Consequently, it is possible to adopt as constants \( \Delta i_p \) and \( E_p \):

\[
\Delta i_p \approx \text{const}.
\]

(5)

\[
E_p \approx \text{const}.
\]

(6)

The value of \( \Delta i_p = I_d / Dk^2 \) is determined by using models [8] provided high technological
indicators of conditions in high-performance unit. Then, for given diameter of the reactor its value is
provided by selection of current.

3. Results and discussion
At the initial stage of the study of sorption properties of coal, ablation of coal was determined and sorption activity was analyzed. Analysis results are presented in Table 1.

| №  | Coal ablation, % | Sorption activity by iodine, cm$^3$/g | Sorption activity by benzene, cm$^3$/g | Sorption activity by iron, mg/g | Sorption activity by methylene blue, mg/g | Fractional composition |
|----|-----------------|-------------------------------------|--------------------------------------|-------------------------------|------------------------------------------|-----------------------|
| 1  | 12.3            | 0.082                               | 21.1                                 | 25                            | 63                                        | 12                    |
| 2  | 15.6            |                                     |                                      |                               | 50                                        |                       |
| 3  | 72              | 17.8                                | 0.085                                | 3.10                          | 123.85                                    | 8                     |
| 4  | 72              | 20.3                                | 0.133                                | 2.60                          | 123.89                                    | 12                    |
| 5  | 72              | 19.4                                | 0.157                                | 2.24                          | 123.9                                     | 13                    |
| 6  | 72              | 19.1                                | 0.192                                | 2.54                          | 133.5                                     | 11                    |
| 7  | 15.6            | 0.046                                | 14.52                                | 58.3                          | 38                                        | 61                    |

As it can be seen from Table 1 ordinary low-grade coal (or a mixture of coal), treated by low temperature plasma has sorption properties. The quality of carbon sorbents in general was determined by nature of porous structure directly dependent on the following factors: true density of coal $\rho_a$, apparent density of coal $\rho_{ap}$, and bulk density of coal $\rho_b$ [9]. Results $\rho_a$, $\rho_{ap}$ and $\rho_b$ are shown in Table 2.

| №   | $\rho_a$ (g/cm$^3$) | $\rho_{ap}$ (g/cm$^3$) | $\rho_b$ (g/cm$^3$) |
|-----|---------------------|------------------------|---------------------|
| 1   | Before treatment    | 1.45                   | 1.24                | 0.67                |
| 2   | After treatment     | 1.66                   | 0.78                | 0.42                |

The received data allows us to estimate alteration of porous structure of sorbents. With this data important indicators of porous structure can be determined: effective porosity $P_{ef}$, total volume of open pores $V_o$, as well as one of the most important characteristics of sorbents - total porosity $V_\Sigma$. For layer of dispersed carbon materials interparticle porosity can be distinguished (Pd.i.) or interparticle pore volume ($V_v$) [2, 10]. Determination data $P_{ef}$, $V_o$, $P_{d.i.}$, $V_v$ and $V_\Sigma$ shown in Table 3.

| №   | $P_{ef}$, % | $V_o$ (cm$^3$/g) | $P_{d.i.}$, % | $V_v$ (cm$^3$/g) | $V_\Sigma$ (cm$^3$/g) |
|-----|-------------|------------------|--------------|------------------|----------------------|
| 1   | Before treatment | 14.5    | 0.12          | 46              | 0.7                   | -                    |
| 2   | After treatment   | 53.0    | 0.70          | 46              | 1.10                  | 0.70                 |

During testing it was observed that if to put coal treated by low-temperature plasma in water with steam supply (regular tap water was used), it separates into fractions: heavy fraction precipitated at the bottom (line 7, Table 2), as well as light fraction (line 6 Table 2) floated to the surface of water. Small part of coal particles were in water column. The analysis of sorption properties revealed that heavy
(settling) fraction exhibits good chemisorption properties (sorption activity by iron 14.52 mg / g) and light (floating) fraction has good oil absorption properties.

Subsequently, possibility of industrial application of plasma treated sorbents at wastewater treatment plant LLC “Hydros” was studied.

It should be noted that all waste waters are complex heterogeneous systems typically contaminated by various substances in different states, namely: substances in undissolved, dissolved and colloidal conditions. Also all wastewaters have organic, inorganic and biological compounds.

To study sorption activity, chemical water analysis was conducted in compliance with procedures PNDF 14.1.2.3. and PNDF 14.1-95 of State environmental control.

Initially, fraction of 1 mm was investigated, but due to its lightness the fraction floated to the surface so it was carried over with waste water making impossible to use this fraction.

At the next stage of investigation, fraction from 2 to 5 mm was taken. For testing a water sample prior to chlorination was taken, this sample was tested before and after passing the column with activated carbon. Investigation results of wastewater before and after sewage are shown in Table 4.

Table 4. The results of waste water investigation before and after sewage

| Chem. substances, mg/dm$^3$ | Without sorbent | After passing through sorbent | Purification, % |
|----------------------------|-----------------|-------------------------------|-----------------|
| Iron                       | 0.08            | 0.04                          | 50              |
| Nitrite                    | 0.144           | 0.0395                        | 72              |
| Nitrates                   | 21.90           | 11.48                         | 48              |
| Phosphates                 | 2.20            | 1.73                          | 21              |
| Ammonia                    | 0.34            | 0.105                         | 69              |

At the final stage, investigation of pore surface of coal treated by plasma thermal activation was conducted by means of computer of 3D-modeling. When analyzing coal pore surface by 3D-modeling, samples of both initial and treated by thermal destruction in plasma were used. The analysis was carried out by means of optical microscope metallographic Altami MET 2 use. Micrographs of coal particles before and after heat treatment provides volumetric 3D interpretation of data surfaces of simulation using software environment analysis scans Image J. This 3D-simulation enabled to graphically evaluate nature of porosity of the surface, and to compare them before and after thermal activation in plasma [11, 12].

4. Conclusions

Thus, samples of carbon sorbents fraction of 2-5 mm, produced by electric arc plasma showed good chemisorption properties (Table 2, 5), which allows to make conclusion about appropriateness of its use as sorbents for wastewater treatment and water treatment. Presented samples have high sorption properties: total porosity $V_\Sigma = 0.70$ cm$^3$/g, total volume of open pores $V_o = 0.70$ cm$^3$/g, interparticle porosity and interparticle pore volume $P_{d.i} = 46\%$, $V_c = 1.10$ cm$^3$/g, total porosity $P_{ef} = 53\%$, making it correspond to parameters of industrial coal type BAU, KAD. The obtained data is in good agreement with the literature data [2, 4, 10].

Acknowledgement

The work was supported by the project of the Russian Federation Science order # 2014/23

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