PRODUCTION TECHNOLOGY AND FILTERING PROPERTIES OF CARBON BLOCK CARTRIDGES

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In the present paper, the information on the influence of various factors on the carbon block cartridges production technology and their potential impact on the properties of the finished product is presented. The possibilities of increasing the sorption-filtering efficiency of carbon block cartridges are presented. The technical and exploitation characteristics are influenced by the size of the mixture components granules, the physicochemical properties of active carbon and binder polymers, their ratio in the mixture, and the addition of bactericidal additives into the composition. The study of this topic is relevant, as evidenced by the analysis of the increasing number of publications on this matter over the past ten years. However, the production technology of carbon block cartridges is the know-how of manufacturing companies. This information is confirmed by the analysis of the technical characteristics of sixty carbon block cartridges from nine world manufacturers, whose products are WQA certified according to the NSF/ANSI 42 standard. The recommendations given by a number of authors on the size of activated carbon granules in the range from 40 to 120 mesh and polyethylene particles from 80 to 160 mesh with a flow rate of 1.4-3 g/10 min, can be taken as "reference points" in the development of extrusion mixtures with different components ratio. The following factors play an important role in obtaining effective cartridges: the quality of pre-extrusion mixing of the composition, its resistance to delamination during the "transition" from the mixer to the extruder loading zone, extrusion temperature regimes by zones, product cooling temperature, backpressure on the billet leaving the extruder. The information given in this article will be useful when producing new carbon block cartridges, improving the parameters of existing technologies, as well as in the research development of cartridges with new properties.

***Key words**: activated carbon, binder, carbon block, compression molding, extruder, water treatment*

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1. Introduction

Activated carbon is an adsorbent that is widely used in modern water treatment to purify water from chlorine, including chlorine derivatives, organic impurities, metals, as well as to improve water organoleptic properties. In water treatment, granular (GAC) (particle size 0.2–5 mm) and powder (particle size less than 0.045 mm) types of activated carbon are used. Coal coke, petroleum coke, wood, coconut shells, peat, plant pits and others are usually used as raw materials for their production. Depending on the type of raw material and production technology, 1 gram of activated carbon can hide a contact surface of 500 to 2200 m^2 (Mason 2002).

There are two mechanisms by which activated carbon removes contaminants from water - adsorption and catalytic oxidation. The main indicators that determine the efficiency of using activated carbon in water purification are the volume fraction of macro-, meso- and micropores, surface area, mechanical strength, particle size distribution and surface charge (Mason 2002).

Granular activated carbon has a wide range of advantages (National Research Council 1980), but being in a filling cartridge or adsorber loses a number of its advantages due to hydrodynamic processes that take place when water flows through a layer of granules. The literature outlines the following five main problems that arise when using GAC:

- low linear water flow rates are required to increase the efficiency of sorption treatment (Gray 2018);

- loading of GAC in cartridge filters is not subjected to back and direct flushing. This promotes the formation of longitudinal channels. As a result, water flows along the path of least resistance, and a certain part of the activated carbon remains unused (Bommi 2009);

- the development of chlorine-resistant bacteria, which belong to the genus Pseudomonas and Bacillus, in the isolated from the water flow areas of the cartridge (Patent Ripudaman 2016);

- the absence of an effective microfiltration regime in the granular load (Michael 2001);

- the inability to increase the efficiency of adsorption by reducing the size of activated carbon granules in standard cartridges is caused by the increase in layer resistance (Haftka 2004).

The above-described disadvantages of cartridges with GAC initiated in the early 70s of the previous century the development of solid porous blocks of various sizes from powdered activated carbon. A fundamentally new cartridge structure was proposed (Bommi 2006, Haftka 2004), that is presented in the form of a porous cylinder, which is obtained as a result of the effect of temperature and pressure on a mixture of activated carbon powder and a polymer low-melting binder placed in a special form. The technology was called compression moulding, and the product was named carbon block.

Interest in this topic is growing every year, which is confirmed by the statistics of publications shown in Figure 1 over the past ten years.

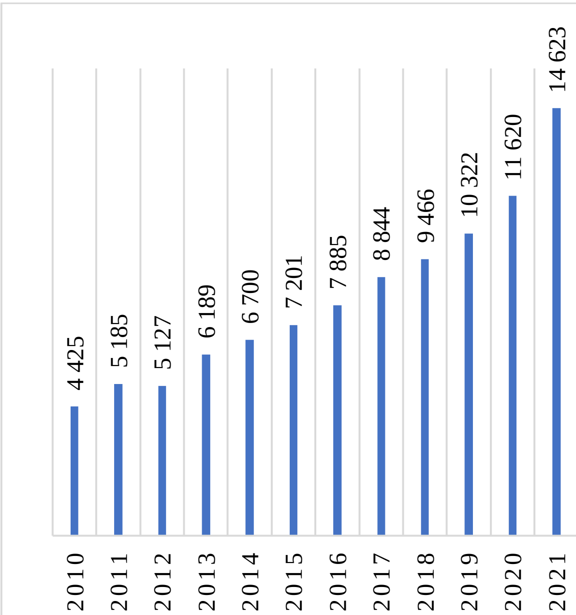


Fig. 1. *Number of articles published on the Carbon block topic in the last ten years (Science Direct)*

Such an increased interest is explained by a number of advantages of this product, namely:

- carbon block is made using activated carbon granules 7-20 times smaller than in filling cartridges. This allows increasing the sorption surface significantly, the time of contact with contaminants, and, as a result, the cleaning efficiency.

- the granules in the carbon block are fixed with a binder, which allows them to maintain their stable position relative to each other. Therefore, the formation of longitudinal channels is physically impossible and water flows uniformly through the bulk porous structure.

- certain brands of carbon block cartridges provide the ability to filter very small particles ranging in size from 0.5 to 10 microns. Such cartridges simultaneously purify water from a wide range of chemical pollutants, such as chlorine, chloramines, pesticides, drugs, radionuclides, organic solvents, oil products, lamblia cysts, mercury, lead and improve the organoleptic properties of water (unpleasant taste and odour, turbidity, colour) (Carbon Block Filter Buyer's Guide 2022).

Today, analysing the situation in the carbon block cartridge market, it is necessary to note the number of units sold worldwide. For instance, in the European market - this number is 15 million units or 90 MUSD in retail prices, in the American - 20 million units or 120 MUSD in retail prices, and in the CIS market this figure reaches 5 million units or 15 MUSD at retail prices per year. There are many different manufacturers of carbon block cartridges in the world. Their number is increasing every year as a result of high demand. For example, according to the Made-in-China website, there are 465 manufacturers in the Chinese market (Made-in-China 2022).

2. Product characteristics

Carbon filter performance is evaluated by manufacturers using laboratory tests in accordance with standards developed by NSF International (NSF) and American National Standards Institute (ANSI). Standard 42 applies to carbon filters. This standard guarantees the removal of chlorine and an acceptable water taste and odour. All tests are carried out in certified laboratories on specially designed stands (Carbon Block Filter Buyers' Guide 2022, NSF/ANSI 42, 53 and 40: Filtration Systems Standards 2019).

Several generally accepted criteria have been introduced in the world for assessing the filtering and sorption characteristics of carbon block cartridges. These characteristics include nominal filtration rating (NFR), resource, flow rate, initial pressure difference at the recommended flow rate for effective cartridge performance, and cartridge lifetime, which is determined by the resource.

The NFR indicates the size of particles which can hold a cartridge efficiency of at least 85%.

The resource indicates the total volume of dechlorinated water obtained during the period of cartridge operation at an input concentration of free chlorine in water of 2 mg/l. Moreover, the cartridge is considered effective until the efficiency is maintained by 50% from the beginning.

Since the market for carbon block cartridges is very diverse, the cartridges have different technical characteristics and work effectively under certain operating conditions. To confirm this, Table 1 provides a technical characteristics analysis summary of sixty cartridges produced by nine world manufacturers by standard sizes ranging from 2.5"×10" to 4.5"×20" (Pentauir 2022, Water filtration innovation 2022, CB Tech Carbon Block Filter Cartridges 2022, H_2O Distributors 2022, Atlas Filtri 2022, Aquafilter 2022).

Table 1. *Generalization of technical characteristics of sixty carbon block cartridges by standard sizes*

Cartridge type	NFR, _μm	Q, dm^3 /min	ΔP, bar or (bar/dm^3 /min)	Resource, dm^3	Term of use, month
2,5"x10"	0,5-10	2,8-3,8	0,07 - 0,26	4 500 - 11 500	from 3 to 6
2,5"x 20"	0,5-10	5,7-7,6	0,03-0,42	9 000 - 33 000	from 3 to 6
4,5"x10"	0,5-10	3,8-11,4	0,07-0,61	15 000 - 60 000	from 3 to 6
4,5"x 20"	0,5-10	7,6-26,0	0,5-0,7	30 000 - 130 000	from 3 to 6

Analysis of the data in Table 1 demonstrates the range of flow rates which is applicable to a particular standard size of a cartridge for water purification, the pressure losses that will occur in this case, and most importantly, the volume of water purified from free chlorine which can be calculated using a cartridge from 3 to 6 months. It should be noted that the smallest resource values are characteristic of cartridges with an NSP of 0.5 µm, and the highest with an NSP of 10 µm. An increase in sizes from 2.5"×10" to 4.5"×20" leads to an increase in flow rate, resource, and lifespan, which allows correct assessment of the cartridge utilizing place. Also, from Table 1 it is clear that cartridges of the same standard size may have different technical characteristics, but currently, there is no information in the literature on the reason for such significant differences, as long as this is a subject of know-how.

The purpose of this work is to analyse the information on the influence of various factors on the technological and operational characteristics of carbon block cartridges, as well as to assess the ways and possibilities of increasing their efficiency.

3. Factors and processes

The carbon block is a dense, porous cylinder, the surface of which is protected by a layer of non-woven filter material. Above and below, there are plastic covers for organizing a cross-flow of the filtered medium from outside to inside through the cartridge body and drainage of the filtrate from the core through the outlet (Fig. 2) (Bommi 2009, Herbert 1988, Herbert 1991).

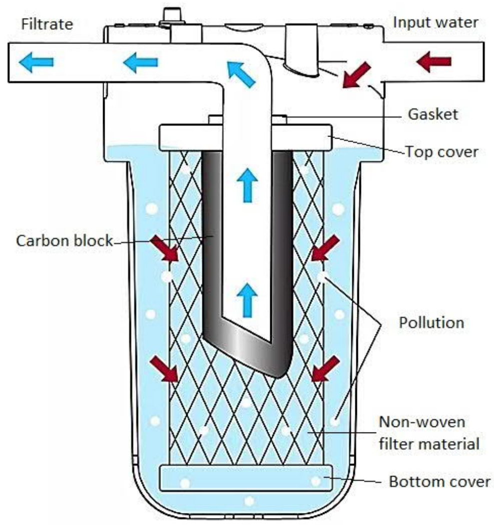


Fig. 2. *Schematic diagram of the carbon block cartridge*

The technology for producing carbon blocks is complex as it requires a delicate balance of a number of different factors and competing processes. This range includes:

- properties and particle size of activated carbon;
- characteristics of the binder and its mass fraction in the mixture;
- production technology;
- features of mixing components and maintaining the homogeneity of the mixture;
- the influence of the modes of the cartridge structure formation (extrusion or compression moulding);

- modification of the mixture composition to impart new properties to the cartridges.

Next, we will analyse the influence of each factor in more detail.

Particle size requirements of activated carbon are one of the key factors that determine the final characteristics of the finished product. It is known that smaller particles of activated carbon improve the sorption-filtering effect of the cartridge because they provide more surface area and create smaller pores in the carbon block structure that can trap smaller impurity particles. Unfortunately, the use of activated carbon with a particle size of less than 145 mesh (98 microns) causes certain problems. A dense block of coal not only traps smaller particles of impurities but also significantly limits the rate of water flow, which as a result reduces the volume of water that can be recycled per unit of time (Gray, 2018). An increase in the proportion of small particles of activated carbon creates problems in the production of carbon blocks using extrusion technology since a high degree of grinding of coal particles worsens the binding effect of the polymer filler, which is necessary for the manufacture of a durable coal block. As a result, cracking and destruction of coal blanks can occur, which leads to a low yield of the product (Ripudaman 2016).

The factor of the binder in the composition for the production of carbon block is one of the determining factors. The term "binder" refers to a polymeric material that promotes the adhesion of the activated carbon particles. It can soften and become “sticky” at higher temperatures and harden when cooled. When this technology is implemented, the loss of the active surface of coal in the finished product can be from 15 to 25%. The loss of the active surface is directly related to the physicochemical properties of the polymer binder, namely: the melt flow rate (MFR), molecular weight, melting and crystallization temperatures, and, of course, its concentration in the mixture. A high molecular weight leads to a limitation of the fluidity of the molten polymer, which is very important for ensuring reliable “spot adhesion” of activated carbon particles, but not their total coverage by the melt. The binder should become “sticky but not liquid” during the melting process. An increase in the concentration of a binder with a high melt flow index can lead to catastrophic consequences - the loss of the active surface for iodine up to 70% (Belikova 2007, Gray 2018, Ripudaman 2016).

For the production of carbon block cartridges, two methods are used, known as extrusion technology and compression moulding (Bommi 2009, Lee Yongbok 2017).

In extrusion technology, a mixture of small granules of active carbon and a polymer binder, previously prepared in a mixer, is added into the loading zone of a screw extruder, where the binder, being transported by a screw along the working cylinder, is melted, mixed with coal granules and squeezed out through a cylindrical matrix cooled by water or air. As a result, a long cylindrical blank is obtained, which, after solidification, is cut into cylinders of the required size in order to assemble filter cartridges from them (Bommi 2009).

In the compression moulding technology, the same principle is used, namely: preliminary mixing of activated carbon and binder granules, positioning the mix in the mould, heat treatment with melting of the binder under pressure, cooling the mould, removing blanks, trimming the ends, if necessary, assembling filter cartridges. The main advantage of compression moulding is the ability to vary the size of the activated carbon and binder granules. As a result, various porosities of carbon blocks are provided in the pore size range from 0.5 to 20 microns. This method allows the use of a wider range of thermoplastic binders and finer activated carbon granules. This method also allows the creation of blocks that can withstand higher pressures and have better performance and efficiency in water treatment (Lee Yongbok 2017, Bommi 2009).

It should be noted that extrusion moulding is more productive than compression moulding and, with multiple lines, allows for mass production of cartridges (Bommi 2009).

As the technology of extrusion moulding is more productive and is widely used in the modern production of carbon block cartridges, the next step will be to analyse in more detail the factors influencing the implementation of this particular process.

Figure 3 presents the hardware design of the extrusion technology. It includes mixing the initial components (1), transferring the mixture to the conveyor-dispenser (2), which ensures its supply to the feed hopper of the extruder (3) with a forming head, a device for cooling the continuous tubular billet (4) and a device for cutting (5). Further transformation of the blank into a filter cartridge is a simple semi-automatic operation and is not presented in the diagram (CTO Active Carbon Block Filter Cartridge Making Machine Introduction).

Mixing components evenly and maintaining a homogeneous mixture is not an easy task, because the mixture of particles of activated carbon and a binder has a different density and a different particle size distribution. Disruption of the homogeneity of the mixture leads to a violation of the stability of extrusion in terms of productivity, jamming of the screw, low strength of the workpieces and, as a result, the inconsistency of the cartridges with the filter-sorption characteristics declared by the manufacturer. Delamination of the mixture when mixed is a major hazard. Stratification is possible when the mix enters the feed hopper, at the hopper-extruder junction, as well as in the process of mixing and melting the mixture passing along the axis of the extruder.

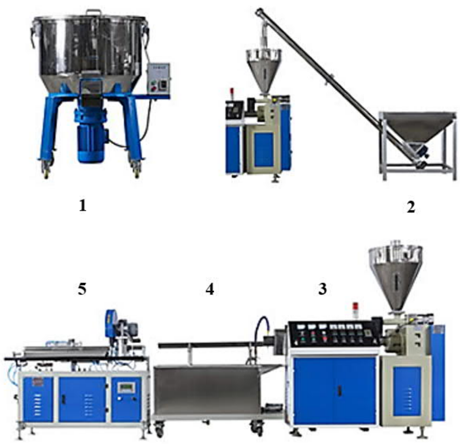
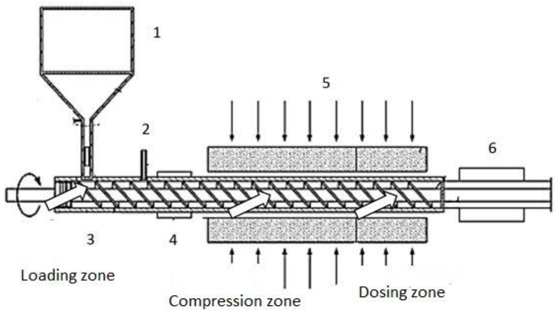


Fig. 3. *Hardware design of extrusion technology (Wuxi AJMS Filter Machinery Co., Ltd., China) for receiving carbon block cartridge*

The extruder is the main link in the technological chain for the production of carbon blocks and both the percentage of the yield of suitable products and their quality depend on its design and operation modes (Herbert 1991). When processing the mixture, the extruder screw plays a decisive role. Traditionally used extruders for polymer materials have three zones (Fig. 4): a feed zone, a compression zone and a dosing zone, each of which has important processes (Bommi 2009).



1 - loading hopper, 2 - gas outlet, 3 - loading zone, 4 - loading zone cooling, 5 - heating of the compression and dosing zone, 6 - forming head.

Fig. 4. *Extruder devise for the production of carbon block cartridges by the extrusion method*

The use of standard extrusion machines for the cartridges production initiates the grinding of coal particles, which leads to disruption of the technology and rejection of the finished product. Therefore, there is a significant number of inventions in the design of the auger (Herbert 1991, Erukov 2001, Yong 2018), the essence of which lies down in changing the geometry and pitch of the auger screw. This makes it possible to ensure high-quality mixing of the composition without crushing the activated carbon granules.

4. Recommendations for correlating influencing factors

The literature provides examples of the correlation of factors affecting the quality of carbon blocks. Some of these solutions are presented below.

According to Quenen (2010), if take into account filtration and sorption characteristics and the percentage of the output of final filters, the optimal composition of the mixture is with an average particle size of 210 mesh (70 μm) and a deviation (in size) up and down by no more than 7-7.5%. The particles of activated carbon and binder can form a block being of different sizes, but often the sizes of the particles of coal and binder are controlled and depend on the purpose of the carbon block. The literature (Herbert 1991) also recommends keeping the same size of the mixture components. In the production of more porous products by extrusion technology, the distribution of activated carbon granules is maintained in the range from 40 to 120 mesh (from 400 to 125 μm). For example, a carbon block that is targeted at removing volatile organic solvents and cysts should have smaller bore pores and be made from granules (200 to 320 mesh (74 to 45 μm) (Bommi 2009). Also, in a number of works (Herbert 1991, Herbert 1988), gradient blocks are shown in which the outer part of the cartridge body is made on the basis of 20-40 mesh active carbon particles and serves as a pre-filter, and the inner part of 80-400 mesh for particles of micron impurities with a size of 1 micron and less.

According to Herbert (1988), it follows that for the production of a high-quality cartridge it is necessary to focus on coconut coal with a low ash content and an active iodine surface of at least 1100-1200 m^2/g. This is due to the fact that during the formation of the block, a part of the active surface and specifically the transport pores are blocked by a polymer binder.

According to Bansode (2011), and Siddhansh (2016), polyethylene with an MFI in the range from 1.4 to 3 g/10 min and a particle size of 80-160 mesh (177-94 μm) or its mixture with polyethylene with ultra-high molecular weight and MFI less than 0.1 g / 10 min are usually used as a binder. The coal-binder ratio is usually maintained at 80:20 wt%, respectively (Hyukwon 2013).

The importance of uniform mixing of the components and maintaining the homogeneity of the mixture has already been noted previously. In order to achieve positive results, the following solutions are given in the literature for fixing particles of active carbon and binder between themselves before moulding:

- Carrying out acid treatment of coal and its further drying to a residual moisture content of 4%. And then mixing with a binder when heated by a non-contact heat source until the surface of the binder begins to melt and it adheres to the surface of the activated carbon particles (Hyukwon 2013);
- treatment of the binder before mixing with a plasma discharge in order to create a surface charge (Bommi 2009);
- the use of a binder in the form of a mixture of polyethylene powder with polypropylene fibres, as well as activated carbon fibres. This makes it possible to qualitatively prepare the mixture and prevent its stratification during mixing and transfer to the extruder hopper (Erukov 2001).

Also, in a number of works (Wu 2017, Ramadanoff 1958, Kiryang 2010, Kyunghee 2013 Hyoseop Oh 2015) the importance of continuous inactivation of pathogenic microorganisms that can accumulate in a filter cartridge with their subsequent removal into drinking water is highlighted. In a number of works, it is proposed to add additives such as silver, copper and zinc salts to the activated carbon-binder mixture to impart bactericidal properties to carbon block cartridges (Kiryang 2010, Kyunghee 2013 Hyoseop Oh 2015). Also known are cartridges that are modified with catalysts, which in turn helps to simultaneously decompose organic impurities to mineral substances, as well as remove heavy metals (Tae-ho Choi 2019).

5. Conclusions

To summarize, it is important to note that today carbon block cartridges solve many problems in modern water treatment.

The production technology of carbon block cartridges is the know-how of manufacturing companies that is confirmed by the analysis of the technical characteristics of sixty carbon block cartridges from nine world manufacturers, whose products are certified by WQA according to the 42 NSF/ANSI standards.

The present paper analyses the information on the influence of various factors on the production technology of carbon block cartridges and their potential impact on the properties of the finished product.

It is established that the size of mixture components granules, physicochemical properties of activated carbon and binder polymers, their ratio in the mixture, addition of bactericidal additives to active carbon while forming carbon block increases the quality, technical, and operational characteristics of carbon block cartridges.

The data given by a number of authors on the preferred sizes of activated carbon granules from 40 to 120 mesh and polyethylene particles with a flow index of 1.4-3 g/10 min from 80 to 160 mesh can be taken as "reference points" when working out extrusion mixtures with different components ratio.

The quality of pre-extrusion mixing of the composition, its resistance to delamination during the "transition" from the mixer to the extruder loading zone, extrusion temperature zones, product cooling temperature and “back pressure” on the workpiece coming out of the extruder play a significant role in obtaining carbon blocks with high performance characteristics.

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ТЕХНОЛОГІЯ ВИРОБНИЦТВА ТА ФІЛЬТРУЮЧІ ХАРАКТЕРИСТИКИ КАРТРИДЖІВ КАРБОНБЛОК

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У даній роботі наведено інформацію про вплив різних факторів на технологію виробництва картриджів з вугільних блоків та їх потенційний вплив на властивості готового виробу. Показано можливості підвищення сорбційно-фільтрувальної ефективності вугільних блочних картриджів. Встановлено, що на техніко-експлуатаційні характеристики готового виробу впливають такі фактори: розмір гранул компонентів суміші, фізико-хімічні властивості активного вугілля і полімерів, їх співвідношення в суміші, додавання до складу бактерицидних добавок. Вивчення цієї теми є дуже актуальним, про що свідчить аналіз кількості публікацій за останні десять років. Проте, технологія виробництва картриджів карбон-блоків є ноу-хау компаній виробників. Цю інформацію підтверджує аналіз технічних характеристик шістдесяти картриджів карбон-блок від дев'яти світових виробників, продукція яких сертифікована WQA за стандартом NSF/ANSI 42. Наведені рядом авторів рекомендації щодо розміру гранул активованого вугілля в діапазоні від 40 до 120 меш і поліетиленових частинок від 80 до 160 меш з витратою 1,4-3 г/10 хв можна прийняти як «еталонні» при розробці екструзійних сумішей з різним співвідношенням компонентів. Виявлено, що для отримання ефективних картриджів важливу роль відіграють такі фактори: якість передекструзійного змішування композиції, її стійкість до розшарування при «переході» із змішувача в зону завантаження екструдера, температурні режими екструзії по зонах, температура охолодження продукту, тиск на заготовку, що виходить з екструдера. Інформація, наведена у даній статті, буде корисна при створенні нових виробництв картриджів карбон-блок, при покращенні параметрів існуючих технологій, а також при науково-дослідній розробці картриджів з новими властивостями.

Ключові слова: *активоване вугілля, водопідготовка, екструдер, зв'язуюче, карбонблок, компресійне формування*