

Dedicated to the 115th anniversary of B.A. Arbuzov's birth

Hybrid Systems Based on Surfactant-Stabilized Carbon Nano- and Microparticles

G. A. Gainanova^{a*}, F. G. Valeeva^a, R. A. Kushnazarova^a, E. A. Bogoslov^b, and M. P. Danilaev^b

^a *A.E. Arbuzov Institute of Organic and Physical Chemistry, FRC Kazan Scientific Center, Russian Academy of Sciences, ul. Akademika Arbuzova 8, Kazan, Tatarstan, 420088 Russia*

**e-mail: ggulnara@bk.ru*

^b *Tupolev Kazan National Research Technological University, Kazan, Tatarstan, Russia*

Received September 13, 2018

Abstract—The influence of the nature of stabilizing amphiphilic additives on the dispersion and precipitation of carbon nanoparticles was evaluated. The stabilized systems were tested for adsorption properties with respect to spectral probes and drugs for which purpose the degree of removal and the amount adsorbed were determined spectrophotometrically for dye Orange OT and anti-inflammatory drug indomethacin.

Keywords: surfactant, carbon particles, adsorption, Orange OT, indomethacin

DOI: 10.1134/S1070363218110191

The idea of using amphiphilic compounds as stabilizing agents for colloid systems with a solid dispersed phase is applied internationally in research aimed to develop drug delivery systems based on carbon nano- and microparticles [1–4]. Those studies focus mainly on carbon nanoobjects, single- and multi-walled carbon nanotubes, and employ various approaches involving covalent or noncovalent modification of the particle surface. Successful examples include the recently reported noncovalent self-assembly of amphiphilic compounds [5, 6], as well as covalent attachment of long-chain alkyl groups of an organic ammonium onto a carbon carrier [7] with the aim to increase the stability of multi-walled nanotubes dispersion. The resulting stable systems, where sedimentation is negligible, are characterized by extremely large interfacial area and high adsorption capacity. Presumably, in such hybrid systems surfactants cannot only act as stabilizing agents but also provide additional drug solubilization in the area of the monolayer formed on the carbon particle surface and promote their permeation through biomembranes.

Apart from nanotubes, other recently discovered new carbon modifications, fullerenes and graphene, have unique properties making them highly promising

for applications of nanotechnology in medicine. The same is also true of carbon nanoparticles produced by pyrolysis of monomers (e.g., benzene, styrene, acrylonitrile) [8, 9] or of the products of decomposition of polymers [e.g., polystyrene, poly(methyl methacrylate)] [10] in gas discharge plasma. The type of the resulting carbon particles depends on their preparation conditions (discharge current density, concentration of the pyrolysis products in the discharge chamber, pressure and temperature in the pyrolysis chamber, monomer/polymer type) [11, 12]. For example, styrene vapor pyrolysis in a barrier gas discharge by the procedure described in [8] yielded conglomerates of nanoscale carbon particles (including graphene particles) in dendritic form. Benzene vapor pyrolysis in atmospheric-pressure glow discharge gave microsized agglomerates of carbon nanoparticles (primarily amorphous soot particles and a small amount of fullerenes). However, the ability of such carbon particles to form stable hybrid systems with amphiphilic compounds has been little studied. There is currently insufficient information to assess the suitability of this kind of systems as effective adsorbents or as drug delivery agents. The aim of this study was to evaluate the influence of the nature of stabilizing amphiphilic additives both on the carbon

particle dispersion and precipitation processes and on stability of the colloidal dispersions of these particles possessing drug-binding properties.

In our studies of the effect of surfactants on stability of colloidal dispersions of carbon particles we used amphiphilic compounds of different nature: cationic cetyltrimethylammonium bromide and cetyltriphenylphosphonium bromide and anionic sodium dodecyl sulfate and sodium dodecyl benzenesulfonate, as well as nonionic Twin-80. The experiment involved preparation of a dispersion of carbon particles in surfactant solutions using an ultrasonic bath, followed by spectrophotometric estimation of the precipitation rate of the carbon particles in solutions. As indicator of the content of dispersed particles in solutions we chose the optical density of the samples at a wavelength of 400 nm. The conditions were optimized by varying the nature and concentration of the surfactants, the content of carbon particles, and the sonication time. The stability of the resulting dispersions was assessed by following optical density data as a function of time. As applied to the specific performance characteristics of the spectrometer, the aqueous solutions containing 0.02 wt % of carbon particles whose optical density fell in the range from 0.2 to 2 rel. units proved to be best suited to our purposes. However, the main properties (precipitation rate, relative saturation of dispersions) determined at this concentration were also reproduced at a higher content of particles of up to 0.2 wt %. Figure 1 shows that the highest saturation level of dispersions was achieved with the use of cationic surfactants. For example, cetyltrimethylammonium bromide introduced at twice the critical micelle concentration (CMC) provided a 9-fold increase in the content of the carbon particles in the system relative to water, all other conditions being the same. An even greater effect, specifically a 15-fold increase in the content of dispersed particles, was achieved with the use of cetyltriphenylphosphonium bromide.

Stabilization of dispersed particles in micellar solutions is presumably due to the occurrence of the hydrophobic radicals of ionic surfactants on the particle surface, whereby sticking of the particles is precluded by electrostatic repulsion of the charged head groups of the adsorbed surfactants. Nonionic surfactants are incapable of charge stabilization, and thus Twin-80 proved to be the least efficient among the surfactants studied. Additional stabilization by surfactants containing aromatic moieties can be achieved via π -like stacking of the benzene rings of the

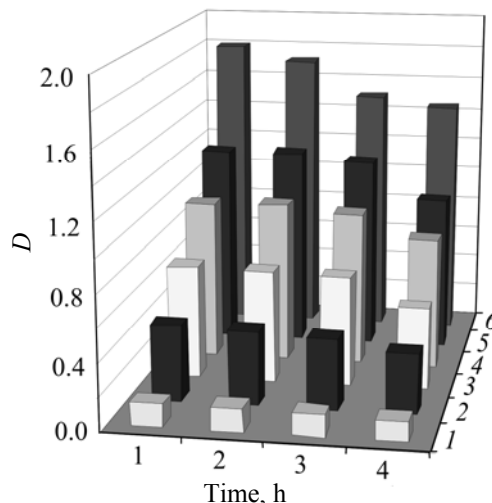


Fig. 1. Optical density of the 0.02 wt% dispersion of the carbon dendrites in the (1) aqueous and (2) micellar solutions Twin-80, (3) sodium dodecyl sulfate, (4) sodium dodecyl benzenesulfonate, (5) cetyltrimethylammonium bromide, and (6) cetyltriphenylphosphonium bromide, obtained by sonication (20 min), recorded for (1) as prepared dispersion and (2) dispersion kept for (2) 1, (3) 5, and (4) 24 h (0.2 cm optical pathlength).

surfactant onto the carbon particle surface [13]. This may be one of the reasons why cetyltriphenylphosphonium bromide dispersed the carbon particles better than cetyltrimethylammonium bromide, and sodium dodecyl benzenesulfonate, better than sodium dodecyl sulfate.

The degree of particles dispersion can be additionally increased by sonication, as illustrated by Fig. 2 presenting the data obtained for the micellar solutions of cetyltrimethylammonium bromide and sodium dodecyl benzenesulfonate. Based on analysis of the sonication efficiency versus exposure time, a 20-min ultrasonic treatment of samples was chosen for further experiments. The resulting dispersed systems were fairly stable, with predominance of particles with hydrodynamic diameter of 150–200 nm and polydispersity index of 0.2–0.3, as revealed by dynamic light scattering examination (Table 1).

Observations over time revealed precipitation of the carbon particles, but this process was slow, with $\leq 10\%$ particles precipitated within one day (Fig. 1). The solid phase could be effectively isolated by centrifugation of the samples, if necessary. For example, 80–90% carbon particles could be precipitated within 20 min at a 10000 rpm speed; repeated centrifugation of the supernatant under the same conditions enabled 95–

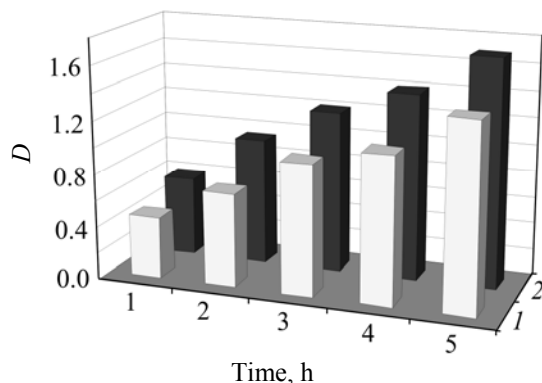


Fig. 2. Optical density of the 0.02 wt % dispersion of the carbon dendrites in the micellar solutions of (1) cetyltrimethylammonium bromide and (2) sodium dodecyl benzenesulfonate, prepared by sonication for different times: (1) 0, (2) 10, (3) 20, (4) 30, and (5) 60 min (0.2 cm optical pathlength).

97% separation. The isolated precipitate, alongside carbon particles, contained a certain amount of the adsorbed surfactant. For cetyltriphenylphosphonium bromide and sodium dodecyl benzenesulfonate taken as examples, spectrophotometric examination revealed a 15–20% decrease in the surfactant concentration in the micellar solutions due to adsorption of the surfactant on the carbon particles. This confirmed the formation of hybrid carriers consisting of carbon particles and a surfactant, which can exist in aqueous media as stable suspensions or can be isolated as a precipitate by centrifugation.

The adsorption properties of these systems were tested using hydrophobic spectral probe Orange OT and nonsteroidal anti-inflammatory drug indomethacin.

Table 1. Hydrodynamic diameter (D_h) and polydispersity index (PDI) of the carbon dendrite particles in water and micellar solutions

| Dispersion medium (c_{surf} , M) | D_h , nm | PDI |
|--|--------------|-------|
| Water | 148.0±29.84 | 0.234 |
| Cetyltrimethylammonium bromide (2 mM) | 202.5 ±56.26 | 0.314 |
| Cetyltriphenylphosphonium bromide (0.2 mM) | 166.8 ±81.59 | 0.270 |
| Sodium dodecyl sulfate (20 mM) | 188.8 ±33.23 | 0.384 |
| Sodium dodecyl benzenesulfonate (5 mM) | 237.2 ±147.1 | 0.377 |
| Twin-80 (0.3 mM) | 154.6± 24.26 | 0.449 |

These compounds exhibit characteristic spectra in the UV and visible regions, which allows determining their concentration in solution based on the absorption intensity. In our experiments, the dye or the drug was added to the aqueous or aqueous micellar system prepared by ultrasound-assisted dispersion of the carbon particles and kept for 20–60 min, whereupon the adsorbent was isolated by centrifugation.

The adsorption efficiency was quantitatively characterized via comparative analysis of the absorption spectra of the compounds in the micellar solutions before and after contact with the carbon particles. The residual concentration of the test substance in solution (c_{res}) was estimated from the optical density (D) of the sample using Eq. (1):

$$c_{\text{res}} = D/\varepsilon L, \quad (1)$$

where ε is the molar extinction coefficient of the absorbing substance, $\text{L mol}^{-1} \text{cm}^{-1}$.

The degree of removal (Γ , %) was determined by formula (2):

$$\Gamma = [(c - c_{\text{res}})/c] \times 100\%, \quad (2)$$

where c is the initial concentration of the substance, M.

The amount of test substance adsorbed (a) was calculated by formula (3):

$$a = (c - c_{\text{res}})V/m, \quad (3)$$

where V is the volume of the solution, L, and m , mass of the sorbent, g.

The first series of experiments was carried out using dye Orange OT. Figure 3 shows examples of the spectra of this compound in the solutions of cetyltriphenylphosphonium bromide and sodium dodecyl benzenesulfonate, as well as in the samples of the supernatant, after isolation of the carbon particles.

The residual concentration of Orange OT in solution was determined from the absorption near 495 nm [$\varepsilon = 17400 \text{ L mol}^{-1} \text{cm}^{-1}$], exhibited by the suspensions containing 0.02 or 0.2 wt % dispersed particles. Table 2 lists the adsorption characteristics calculated on the basis of the data obtained. It is seen that the highest degree of the dye removal was achieved with the use of the hybrid systems containing cetyltriphenylphosphonium bromide and sodium dodecyl benzenesulfonate. This characteristic could be improved by increasing the content of the carbon particles in the system, though in parallel with a decrease in the amount of the dye adsorbed, reflecting

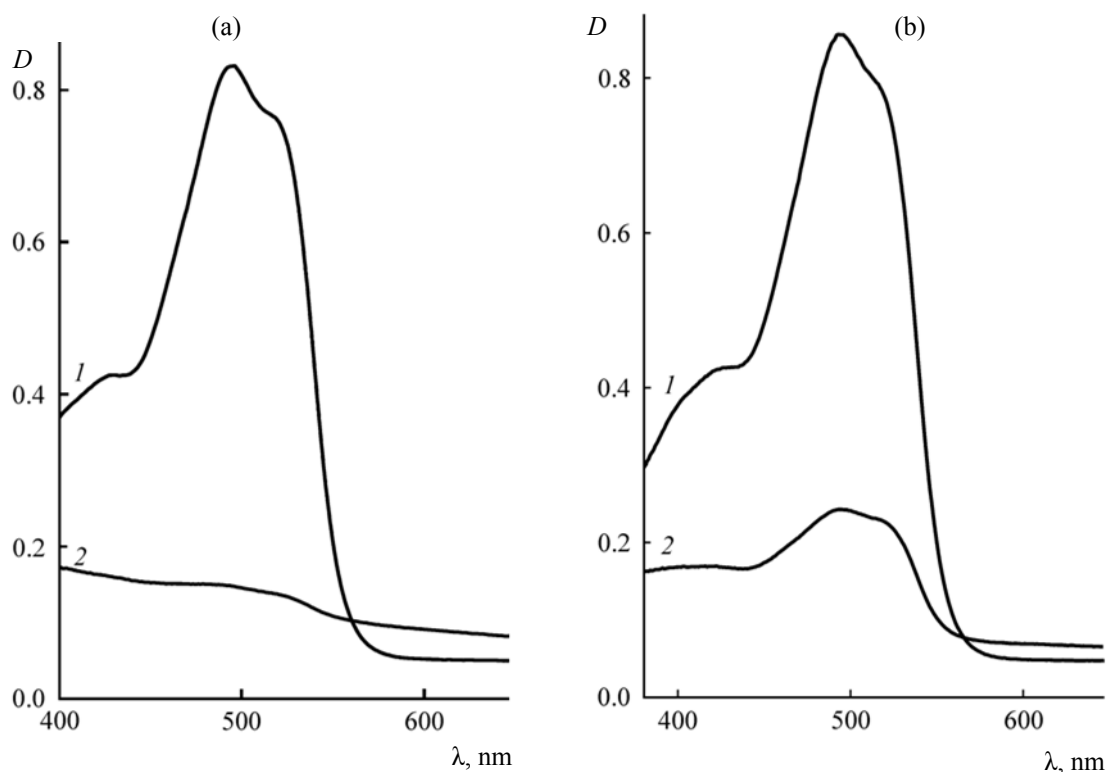


Fig. 3. Spectra of Orange OT (0.1 mM) in the solutions of (a) cetyltriphenylphosphonium bromide and (b) sodium dodecyl benzenesulfonate (1) before and (2) after adsorption on the carbon particles (0.02 wt %) (0.5 cm optical pathlength).

the efficiency of the adsorbent. Yet another option was increasing the adsorbent–dye contact time, but the gain did not exceed 10%. An increase in the surfactant concentration in the system also caused only slight improvement of the adsorption characteristics. Based on the above results, the experimental conditions were optimized as follows: 0.02 wt % content of dispersed carbon particles in the system, surfactant concentration twice the CMC, adsorbent–dye contact time 20 min,

separation by centrifugation at 10000 rpm speed for 20 min. Specifically under these conditions the carbon particles were tested for their adsorption properties towards drug indomethacin. Cetyltrimethylammonium bromide, cetyltriphenylphosphonium bromide, and sodium dodecyl benzenesulfonate in whose solutions the carbon particles showed the best adsorption characteristics in the previous series of the experiments were chosen as stabilizing surfactants. Figure 4

Table 2. Adsorption characteristics of Orange OT (0.1 mM) on the carbon particles in solutions based on various surfactants

| Surfactant | c_{surf} , mM ^a | a , mM/g | | | |
|-----------------------------------|-------------------------------------|----------------------------|---------------------------|------|-------|
| | | carbon particles 0.02 wt % | carbon particles 0.2 wt % | | |
| Cetyltrimethylammonium bromide | 2 | 32 | 0.16 | 61 | 0.035 |
| Cetyltriphenylphosphonium bromide | 0.2 | 87 | 0.43 | 89 | 0.045 |
| Sodium dodecyl sulfate | 20 | 16 | 0.08 | 35 | 0.018 |
| Sodium dodecyl benzenesulfonate | 5 | 79 | 0.39 | 82 | 0.041 |
| Twin 80 | 0.3 | 27 | 0.14 | 57.5 | 0.02 |

^a The surfactant concentration was twice the CMC.

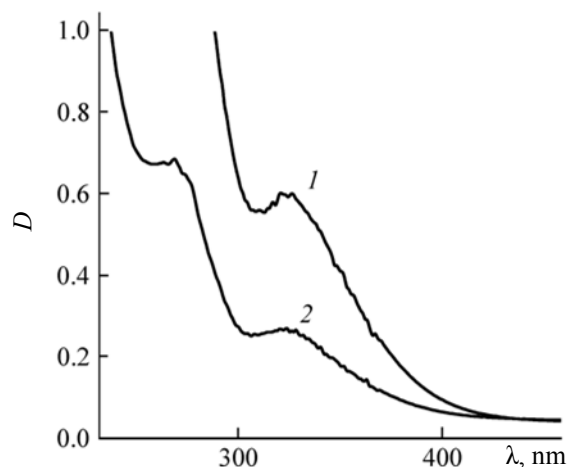


Fig. 4. Spectra of indomethacin in the solutions of cetyltriphenylphosphonium bromide (1) before and (2) after adsorption on the carbon particles (0.02 wt %).

demonstrates how the optical density of the micellar solutions of cetyltriphenylphosphonium bromide containing indomethacin changed upon treatment with the carbon particles. Table 3 lists the adsorption characteristics that were determined spectrophotometrically for the systems tested.

A weak adsorption effect produced by the system containing sodium dodecyl benzenesulfonate can be explained by the fact that indomethacin, with $pK = 4.5$ [14], exists predominantly in the anion form in neutral aqueous solutions and shows no affinity for the negatively charged surface layer formed by this surfactant. Cationic surfactant cetyltrimethylammonium bromide proved to be somewhat more effective, but the best performance was demonstrated by the system based on carbon particles and cetyltriphenylphosphonium bromide. Adding the latter in even small amounts allowed preparation of stable hybrid systems with a high content of carbon particles possessing strong adsorption properties, which may serve as a basis for the development of drug-delivery systems.

EXPERIMENTAL

Commercial samples of the surfactants, as well as of dye Orange OT and of indomethacin (Sigma Aldrich), containing 99% of the main substance, were used in the experiments. Solutions were prepared using bidistilled water obtained on a Direct-Q5 UV water purification unit ($pH = 6.8-7$, $\chi = 2-3 \mu S/cm$). Carbon particles were produced by mechanical dispersion of annealed carbon dendrites. The carbon dendrites were obtained by pyrolysis of styrene vapor in barrier-discharge plasma (a.c. voltage source frequency ~ 40 kHz) [8, 9, 15]. The flow rate of the plasma-forming gas (argon) was 200 mL/min and was controlled accurately to within 10%. The electrode system of the discharge chamber had a point-to-point configuration and consisted of two stainless steel electrodes with a tip radius of 0.5 mm. In the experiments, the condition $T_e/T \sim 10$ was provided, where T_e is the electron temperature in the barrier discharge plasma, and T , thermodynamic temperature near the point electrode. As the T_e/T ratio decreased due to a decrease in the electron temperature or to an increase in the temperature, carbon dendrites ceased to grow. The characteristic temperature was $\sim 1000^\circ C$ as controlled by a pyrometer with a measurement error of no greater than 5%. Carbon dendrites grew from the surfaces of the points toward each other until discharge gap closing. The dendrite structure was analyzed by scanning electron microscopy on a JAMP-9510F Auger electron spectrometer (JEOL, Japan) in an ultrahigh vacuum (1×10^{-9} mmHg) at $23^\circ C$, as well as by infrared spectroscopy (carbon dendrite surface on a FrontierDTGS Fourier-transform spectrometer) and by optical spectroscopy using a StellarNet EPP2000 spectrometer with a resolution of 0.5 nm.

In the cross section of the carbon dendrite, three regions can be distinguished: the core, the intermediate layer, and the outer shell. The regions differ in structure [8]; specifically, the core consists of disordered layers of graphene flakes, and the inter-

Table 3. Adsorption characteristics of indomethacin on the carbon particles in solutions based on various surfactants

| Surfactant | c_{surf} , mM | c_{ind} , mM | Γ , % | a , mM/g |
|-----------------------------------|-----------------|----------------|--------------|------------|
| Cetyltrimethylammonium bromide | 2 | 0.4 | 5 | 0.10 |
| Cetyltriphenylphosphonium bromide | 0.2 | 0.4 | 47.5 | 0.95 |
| | 0.2 | 0.2 | 66.5 | 1.3 |
| Sodium dodecyl benzenesulfonate | 5 | 0.4 | 2.5 | 0.05 |

mediate layer and the outer shell, of undecomposed products from styrene pyrolysis. To remove the intermediate layer and the outer shell, the dendrites were annealed at $1500 \pm 100^\circ\text{C}$ and a pressure of $\sim(1 \pm 0.5) \times 10^{-5}$ mmHg for 4 ± 0.5 h. The annealed carbon dendrites were dispersed mechanically to ~ 1 μm sizes on a Retsch PM 100 planetary ball mill. The resulting agglomerates of the particles contained both amorphous carbon particles and graphene flakes.

The samples were sonicated in an ELMASONIC S15H ultrasonic bath (Elma, Germany) providing temperature-controlled ultrasonic operation at the ultrasound frequency of 37 kHz and sweep function for an optimized sound field distribution in the bath. The sonication time was varied from 5 to 60 min depending on specific tasks; the temperature was 25°C .

Electronic spectra of the solutions were recorded using a Specord 250 Plus spectrophotometer (Germany). The samples were placed in quartz cells (optical pathlength L 0.1 to 1 cm) and kept at 25°C . The concentration of the solubilizate (c) was calculated using the optical density (D) of the sample by Eq. (1). The size of the aggregates was determined on a Malvern ZetaSizer Nano photon correlation spectrometer (Malvern Instruments, UK) by using dynamic and electrophoretic light scattering techniques. The laser radiation source was a He–Ne gas laser operated with a power of 10 mW at a wavelength of 633 nm; the scattering angle was 173° . The pulse accumulation time was 5–8 min. The signals were analyzed using a single-board multichannel correlator coupled with an IBM PC compatible computer equipped with a software package for estimating the effective hydrodynamic radius of the particles.

ACKNOWLEDGMENTS

This study was financially supported by the Russian Foundation for Basic Research [project nos. 18-43-160015 (study of the adsorption properties, G.A. Gainanova, F.G. Valeeva, and R.A. Kushnazarova) and 18-48-160024 (synthesis of carbon dendrites, E.A. Bogoslov and M.P. Danilaev)] and by the Government of the Republic of Tatarstan.

CONFLICT OF INTERESTS

No conflict of interests was declared by the authors.

REFERENCES

- Miriyala, N., Ouyang, D., Perrie, Y., Lowry, D., and Kirby, D.J., *Eur. J. Pharm. Biopharm.*, 2017, vol. 115, p. 197. doi 10.1016/j.ejpb.2017.03.002
- Yang, J., Gao, G., Zhang, X., Ma, Y.H., Jia, H.R., Jiang, Y.W., Wang, Z., and Wu, F.G., *Nanoscale*, 2017, vol. 9, no. 40, p. 15441. doi 10.1039/c7nr05613c
- Itatahine, A., Mehdi, Y.A., Fizir, M., Qi, M., Dramou, P., and He, H., *New J. Chem.*, 2018, vol. 42, p. 1326. doi 10.1039/C7NJ04609J
- Jeevanandam, J., Barhoum, A., Chan, Y.S., Dufresne, A., and Danquah, M.K., *Beilstein J. Nanotechnol.*, 2018, vol. 9, p. 1050. doi 10.3762/bjnano.9.98
- Qiao, M., Ran, Q., and Wu, Sh., *Appl. Surf. Sci.*, 2018, vol. 433, p. 975. doi 10.1016/j.apsusc.2017.10.138
- Kim, S., Tserengombo, B., Choi, S.-H., Noh, J., Huh, S., Choi, B., Chung, H., Kim, J., and Jeong, H., *Int. Commun. Heat Mass Transfer*, 2018, vol. 91, p. 95. doi 10.1016/j.icheatmasstransfer.2017.12.011
- Maggio, M., Marrazzo, R., Acocella, M.R., Granata, V., and Guerra, G., *Carbon*, 2018, vol. 127, p. 228. doi 10.1016/j.carbon.2017.11.011
- Danilaev, M.P., Zueva, E.M., Bogoslov, E.A., Pudovkin, M.S., and Pol'skii, Y.E., *Tech. Phys.*, 2018, vol. 63, no. 6, p. 857. doi 10.1134/S1063784218060105
- Kozak, D., Shibata, E., Iizuka, A., and Nakamura, T., *Carbon*, 2014, vol. 70, p. 87. doi 10.1016/j.carbon.2013.12.076
- Danilaev, M.P., Bogoslov, E.A., Morozov, O.G., Nasybullin, A.R., Pashin, D.M., and Pol'skii, Y.E., *J. Eng. Phys. Thermophys.*, 2015, vol. 88, no. 3, p. 774. doi 10.1007/s10891-015-1250-2
- Poklonski, N.A., Ratkevich, S.V., and Vyrko, S.A., *J. Phys. Chem. A*, 2015, vol. 119, p. 9133. doi 10.1021/acs.jpca.5b03573
- Rafique, M.M.A. and Iqba, J., *J. Encapsul. Adsorpt. Sci.*, 2011, vol. 1, p. 29. doi 10.4236/jeas.2011.12004
- Islam, M.F., Rojas, E., Bergey, D.M., Johnson, A.T., and Yodh, A.G., *Nano Lett.*, 2003, vol. 3, p. 269. doi 10.1021/nl025924u
- Nokhodchi, A., Javadzadeh, Y., Siahi-Shadbad, M.R., and Barzegar-Jalali, M., *J. Pharm. Pharm. Sci.*, 2005, vol. 8, p. 18.
- Hemawan, K.W., Gou, H., and HemLey, R.J., *Appl. Phys. Lett.*, 2015, vol. 107. doi 10.1063/1.4934751