

Aggregative Characteristics of Nanocarbon and of a Stabilizing Surfactant in the Aqueous-Polymer Matrix versus Optical Power Limiting Performance

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By the example of single-walled carbon nanotubes (SWCNT) stabilized by sodium deoxycholate in “water + polyvinyl alcohol” medium, the impact of aggregative peculiarities of a stabilizer on the efficacy of dispersing the photoactive agent is investigated. This feature is collated with respect to alternative common anionic surfactants in SWCNT suspensions. The temporal stability of dispersions of the nanocarbon (SWCNT vs carbon black) stabilized by sodium deoxycholate in a medium with controlled viscosity is juxtaposed. The optical power limiting characteristics of these dispersions versus concentration of a polymer dopant (0–3 wt%) is also monitored. In particular, the resistibility of such materials regarding bleaching phenomena in a pulse-periodic regime (pulse repetition rate 10 Hz) of nanosecond laser irradiation (wavelength 532 nm) is addressed. It is demonstrated that optimal concentration of a polymer dopant (≈ 1.0 wt%) ensures elimination of bleaching with respect to the irradiation conditions studied.

form of suspensions, which can manifest nonlinear optical power limiting (OPL) of high-intensity laser irradiation^[2]). Noteworthy is, however, the fact that neat CNPs cannot be dissolved in water insofar as they are hydrophobic and their suspensions sediment rapidly. Suspensions must therefore be stabilized; one of common routines being wrapping of CNPs by surfactants. The latter form the microenvironment around the carbon species, thereby encumbering particle agglomeration and subsequent sedimentation, with the CNP electronic structure staying intact.^[3] Hereof comes the first physicochemical issue of processing suspensions, viz, the choice of the effective surfactant, which would feature as a dispersant and a suspension stabilizer. Once it is chosen, next steps would be

either preparation of films or gels basing on such suspensions, or study/usage of such materials per se. Although the fluid state of the said materials is inferior versus solid and solid-like films in terms of usage convenience, they turn out to be more germane to rejuvenation of such optical material regarding the break-down damage upon passage of high-intensity laser light by virtue of convection processes.

The OPL manifests itself as a drastic drop in the optical transmission of the system when a certain threshold of incident-light intensity is surpassed. There are several mechanisms of the OPL effect, viz., saturable and reverse saturable absorption, multiphoton absorption, photorefraction, and photo-induced light scattering.^[4] For fluid CNP suspensions (set aside fullerene ones), the main effect is the photo-induced scattering on submicro-scale inhomogeneities, formed during the propagation of a laser beam across the material. OPL parameters under such circumstances are hugely dependent upon the properties of the liquid matrix (surface tension, viscosity, heat of the matrix vaporization, etc.) and sizes of the photoactive particles. Therefore, optimization of the matrix physico-chemical properties in this aspect and establishing a relevant mechanical regime of processing the best size-distribution of CNP would show up as the second and the third problem one should tackle. Particles should be sufficiently small to ensure the temporal stability of the material, and yet big enough to effectively convert optical energy into heat, generating scattering centers.

1. Introduction

Condensed-phase systems containing carbon nanoparticles (CNP) evoke researchers' interest during the last decades.^[1] Apart from fundamental reasons, it is connected with their applications, in part, potential ones. One of the latter consists in processing optical filters and switches (in particular, in the

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Although CNP suspensions are promising materials, because they can provide broadband limiting in the optical range,^[5] they have a serious drawback. It consists in a parasitic bleaching effect (local deterioration of the limiting power of suspensions under high-power pulse-periodic radiation^[6]). Bleaching is caused by depletion of the focal volume with nanocarbon material under exposure to infrasound temperature and pressure waves in the focal volume. These surges are generated by transients of heat production on the surfaces of the carbon nanospecies along the optical path of laser irradiation, a frequency of their emergence being modulated by the laser-pulse repetition rate. The suspension bleaching aggravates the OPL properties of the material and makes it unfit for practical application. A possible way to overcome this drawback is to modify the structural and transport matrix properties using polymers. As it has been observed earlier,^[7,8] polyvinyl alcohol (PVA) is a suitable dopant, which can easily alter viscosity of the system. The latter, for its part, controls depletion and replenishing fluxes of CNPs regarding the focal volume; an increase in viscosity suppressing each of the both. We have established that for carbon black (CB) suspensions stabilized by sodium dodecylbenzenesulfonate in aqueous solutions of PVA, there is an optimal amount of doping polymer, which provides elimination of the bleaching phenomenon. So, in projection of the three issues of processing fluid suspensions of CNPs for the OPL study, we report in this article on the following matters. An anionic surfactant sodium deoxycholate has a reputation of a quite superior one as a dispersant/stabilizer of CNPs. We set an assignment to track thermodynamic properties of its micellar aggregation in “water + PVA” mixtures in correlation with its efficacy as a stabilizing agent of SWCNT against some of the widely used stabilizers. We additionally collated temporal stability of SWCNT versus CB dispersions stabilized by sodium deoxycholate. Next, we studied by z-scan methodology the OPL and bleaching in suspensions of CB and SWCNT in aqueous suspensions doped with PVA (concentrations spanning from 0 to 3 wt%). Eventually we revisited^[9,10] the impact of the SWCNT aggregation degree on the stability and OPL performance of their suspensions.

2. Results and Discussion

2.1. Thermodynamics of Stabilizers’ Micellization: Its Effect on the Efficacy of SWCNT Dispersing and Stability of CNP Suspensions

It is noteworthy that micellization of sodium deoxycholate (SDOC) in aqueous media was in focus of quite a number of studies.^[11–13] Their results make appearance as controversial ones. That is, in ref. [13], two critical micellar concentrations (CMCs) are registered by fluorescence measurements: one corresponds to formation of “primary”, small micelles, due to a combination of solvophobic effect and formation of surfactant intermolecular hydrogen bonds, whereas the second one reflects the aggregation of primary micelles mostly due to intramolecular bonding. Another group of sources^[11,12] asserts existence of a single CMC. These sources give polythermal CMC data obtained by a series of isothermal titration calorimetry experiments; a salient feature of a reciprocal CMC versus temperature

being in a non-monotonous character with a minimum. To get a certain insight, we used a technique of the latter sources and performed calorimetric titration of pure water with a solution of SDOC, whose concentration was set deliberately above both of the anticipated CMCs. For the temperatures tried (298.2 and 308.2 K) titration curves showed two jumps of the heat flux. For example, at room temperature, they corresponded to the content of SDOC 1.4 and 6.2 mmol L⁻¹, accordingly. It is in satisfactory agreement with ref. [13], where the corresponding values were registered as 2.4 and 6.5 mmol L⁻¹. Henceforth, we focus on determining thermodynamic characteristics of SDOC micellization in the proximity of the first micellar aggregation, denoting a corresponding concentration as a CMC. In first place, we obtained polytherms of the CMC by electric conductance measurements and tensiometry. It gave us grounds to obtain values of standard thermodynamic functions of micellization: Gibbs energy, the entropy jump and enthalpy, via pseudo-phase separation model (to the end of notation simplicity we omit the zero superscript for thermodynamic functions):^[14]

$$\Delta G_{\text{mic}} = RT \ln \text{CMC}, \quad \Delta S_{\text{mic}} = -\frac{\partial \Delta G}{\partial T}, \quad (1)$$

$$\Delta H_{\text{mic}} = \Delta G_{\text{mic}} + T \Delta S_{\text{mic}}$$

CMC is in a mole fraction concentration scale of a surfactant. **Table 1** gives data about the said parameters in the present study; they are juxtaposed with the data from the ref. [13]. Apart from the fact of a satisfactory agreement between the two sources, one could notice a predominance of the enthalpy increment into the Gibbs energy of aggregation. It must be reflecting the fact that the aggregation of SDOC is, to a high extent, a phenomenon promoted by surfactant inter-molecular hydrogen bonding, rather than by solely a hydrophobic effect. This state of affair singles out a surfactant in view from other CNP stabilizers presented by anionic surfactants. **Table 2** gives thermodynamics of micellization in aqueous solutions of sodium dodecylsulfate (SDS) and sodium dodecylbenzenesulfonate (SDBS), bases on the CMC data from the ref. [15]; herein an entropic term is obviously predominant. The latter fact reflects a primacy of the operating hydrophobic effect.

It seems to be quite a natural consequence of the aggregation thermodynamics that SDOC is a superior dispersant/stabilizer of SWCNT in aqueous medium. The conjecture would be that a primary layer of the surfactant on the SWCNT trunk forms, at least, in part, due to enthalpy-driven stacking on the p-orbitals

Table 1. Thermodynamic parameters of micellization in aqueous solutions of SDOC: columns denoted by (1) refer to the present work; columns denoted by (2) present the values from the ref. [13].

T [K]	CMC [mmol L ⁻¹]		ΔG_{mic} [kJ mol ⁻¹]		$T \Delta S_{\text{mic}}$ [kJ mol ⁻¹]		ΔH_{mic} [kJ mol ⁻¹]	
	1	2	1	2	1	2	1	2
288	–	2.3	–	–24.16	–	9.91	–	–14.25
298	1.05	2.4	–26.84	–24.89	8.52	10.25	–18.41	–14.64
303	1.24	–	–26.97	–	8.67	–	–18.3	–
308	1.34	3.4	–27.21	–24.82	8.81	10.6	–18.4	–14.27
310	1.41	–	–27.25	–	8.87	–	–18.39	–
318	–	3.8	–	–25.33	–	10.94	–	–14.39

Table 2. Thermodynamic characteristics of micellar aggregation in aqueous solutions of SDS and SDBS, calculated from the data of ref. [15] in accord with Equation (1).

T [K]	ΔG_{mic} [kJ mol ⁻¹]	$T\Delta S_{mic}$ [kJ mol]	ΔH_{mic} [kJ mol]
SDS			
303.15	-22.29	18.49	-3.8
313.15	-22.9	19	-3.8
SDBS			
303.15	-25.62	16.37	-9.25
313.15	-26.16	16.91	-9.25

of the graphene-curved surface of the SWCNT; further on, it is combined with followup positioning of the upcoming SDOC molecules on the primary layer due to the hydrophobic effect. **Figure 1** shows optical absorption spectra of SWCNT dispersions stabilized by all of the three surfactants mentioned, given the same protocol of mechanical processing of materials. Clearly, a suspension stabilized by SDOC contains bigger amounts of nanotubes; characteristic peaks corresponding to van Hove singularities being by far more distinct.

The aggregative behavior of SDOC in mixed water–PVA solutions is summed up in **Table 3**. Therein, we consider 1, 2, and 3 wt% solutions of PVA as the media for aggregating SDOC. One would see that aggregation of SDOC in mixed media is

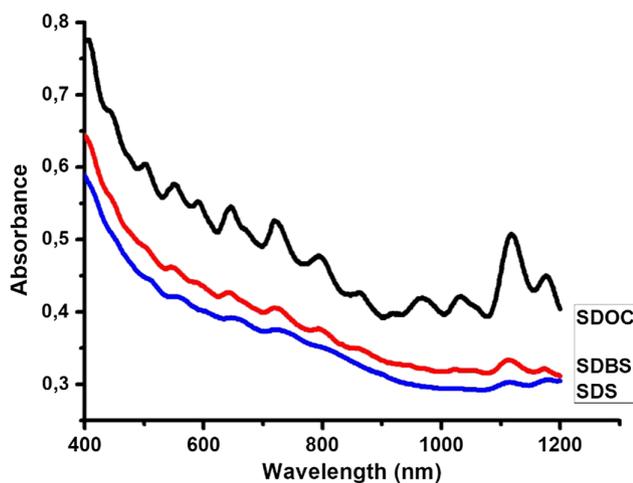


Figure 1. Absorption spectra of SWCNT dispersions stabilized by SDOC (upper curve), SDBS (middle curve), and SDS (bottom curve).

Table 3. Thermodynamic parameters of micellar aggregation in mixed aqueous–PVA solutions of SDOC.

T [K]	ΔG_{mic} [kJ mol ⁻¹]/ ΔH_{mic} [kJ mol ⁻¹]			
	SDOC–H ₂ O	SDOC–H ₂ O–PVA 1%	SDOC–H ₂ O–PVA 2%	SDOC–H ₂ O–PVA 3%
295	–	-25.91/-20.72	-25.88/-21.31	-25.39/-10.11
298	-26.94/-18.41	-26.04/-20.80	-25.89/-21.27	-25.36/-9.92
303	-26.97/-18.30	-26.06/-20.73	-25.94/-21.24	-25.64/-9.95
308	-27.21/-18.40	-26.13/-20.71	-26.03/-21.26	-26.03/-10.08
310	-27.25/-18.39	-26.24/-20.78	-26.12/-21.32	–

still strongly thermodynamically profitable as is witnessed by Gibbs energies of aggregation.

Basing on the CMC determinations by measurements of electric conductance, we estimated degrees of counter-ion binding by SDOC micelles. They are weakly dependent on temperature, and for the contents of PVA studied, they are confined in the interval 0.1–0.2. These values are smaller than those reported in ref. [13], where they are within the interval 0.2–0.3. Hereof, one can infer that micelles of SDOC in the media considered are strongly charged. It gives grounds to conclude that SDOC micro-environment around carbon nanomaterial sustains this feature, thereby providing both mechanisms of dispersion stabilization, viz., a steric and a charge one.

Temporal stability of CB and SWCNT dispersions stabilized by SDOC was verified and compared by monitoring spectra of their optical absorption just after processing and upon 4-month's storage. Results given in **Figure 2** and **3** show that on the said time-scale dispersions show up as fairly stable ones. However, temporal stability of the SWCNT dispersion manifests superior characteristics, which might be connected with a greater graphene non-defect surface on this type of CNP. The latter is more relevant for manifestation of the enthalpy increment into stabilization of the solvophobic dispersion with the discussed surfactant.

2.2. Doping Aqueous Dispersions of CNP with PVA and Its Effect on Bleaching Resistibility

Basing on our previous study, where we demonstrated bleaching resistibility of aqueous suspensions of CB stabilized with SDBS and doped with 1 wt% PVA,^[8] we processed CB and SWCNT dispersions stabilized by SDOC and doped with 1, 2, and 3 wt% of PVA. Developing of suspensions was in accord with a standard protocol of ultrasonification (see Experimental Section). We examined their temporal stability as it is mentioned earlier and performed z-scan determination of their OPL characteristics.

Figure 4 gives the reciprocals of the transmitted energy versus the cuvette displacement from the focus waist of the z-scan setup. The z-scan curves of each of the suspensions in a single-shot and a pulse-periodic regime (repetition rate of 10 Hz) are juxtaposed to pin down the bleaching effect. Under experimental conditions, the coincidence of the curves shows the absence of bleaching, whereas an increase in the transmission (in the pulse-periodic mode) would herald its emergence. One can easily notice bleaching in all the suspensions, setting away those containing any of the CNP studied with the addition of 1 wt% PVA. When the PVA concentration grows up to 2 wt%, bleaching shows up as an increase

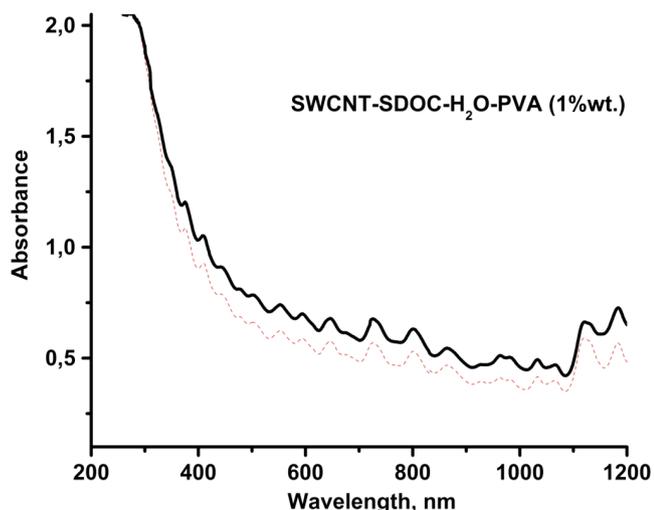


Figure 2. Absorption spectra of SWCNT dispersion in water–PVA (1 wt%) media, registered just after processing (solid curve) and upon 4-month's storage (dashes).

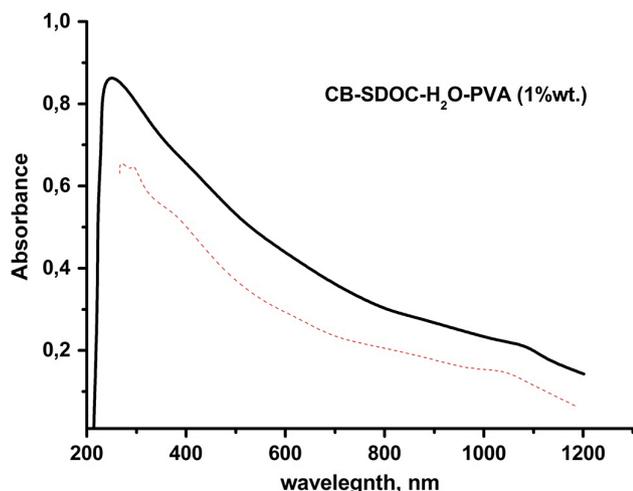


Figure 3. Absorption spectra of CB dispersion in water–PVA (1 wt%) media, registered just after processing (solid curve) and upon 4-month's storage (dashes), a suspension of SWCNT being definitely a superior one in terms of stability.

in the transmission in the proximity of the laser light waist ($Z = 0$). With a further increase in the PVA concentration (3 wt% of polymer doping were examined solely in the CB dispersions), bleaching is even more salient.

The particle sizes of the studied solutions were monitored by dynamic light scattering (DLS). In the systems “water–PVA–SDOC” with varying PVA content, the DLS method shows three modes in the range of surfactant concentrations surpassing the CMC: size of 1–2 nm corresponds to individual SDOC micelles; size of ≈ 20 nm corresponds to PVA unimer tangles; and a diffuse peak (≈ 90 nm) corresponds to a small number of polymer agglomerates, which are likely due to the effect similar to the salting-out action exerted by a monomeric surfactant populace.^[16,17] The DLS results for the systems “water–PVA–SDOC–CB” show

that the mode corresponding to CB confined in its micro-environment does not substantially shift against the concentration of PVA: it spans 110–140 nm (0–3 wt% PVA, accordingly).

The data on micelle sizes and the absence of bonding between the surfactant and PVA, which was shown by conductance measurements, indicate the absence of adsorption of SDOC micelles on the polymer chains. Therefore, it is quite unlikely to presume a change in a nomenclature of supra-species identities stemming from the addition of PVA to aqueous solutions.

Complementarily, we measured the dynamic viscosity in the PVA–water systems, it increases with an increase in the polymer concentration. Dynamic viscosity values at $T = 25^\circ\text{C}$ are the following (values in braces give the PVA content): 1.891 mPa·s (1 wt%), 4.232 mPa·s (2 wt%), and 9.926 mPa·s (3 wt%). One would easily notice a significant increase in viscosity with an increase in the polymer concentration. Insofar, as we presently have no evidence of the change in the suspension structure (for example, formation of PVA coacervates), we can presume that in a pulse-periodic regime, the ratio of outflux of nanocarbon material from the focal volume to a replenishing influx from the suspension bulk, the both being counteracted by the system viscosity, gets optimal value for the PVA concentration ≈ 1 wt% at pulse durations and repetition rates studied.

2.3. Degree of CNP Aggregation and Its Effect on the OPL

The third option to control OPL parameters of aqueous-based CNP dispersions resides on the idea of “auto-synergism” in materials containing the CNP agglomerates.^[9,10] In a scoop, it means that agglomeration enhances conversion of optical energy into heat, which, in turn, generates inhomogeneities scattering the incident light. On the flipside, it is well known in the theory of hydrophobic dispersions that they can show up stable, provided the particle sizes do not exceed ≈ 100 nm.^[18] To make ends meet in between the two opposing circumstances, viz, efficacy of the optical energy conversion and stability of the material, we processed aqueous suspensions of SWCNT varying preparation regimes and, thereby, controlling the degree of debundling. Samples were ultrasonicated during 5, 15, or 60 min and ultra-centrifuged in a standard regime (150 000 g, 1 h); SDOC being a stabilizing agent. The dependency of optical and OPL parameters upon the degree of SWCNT debundling was previously investigated with SDBS as a stabilizer.^[9,10] OPL measurements in the present study were performed using a setup similar to that described by Venediktova et al.^[6]

Absorption spectra of the aqueous suspensions of SWCNT with varying sonication time are given in **Figure 5**. As stated in the previous subsection, these systems showed pretty stable absorption spectra on the time-scale of several months. It is evident from **Figure 5** that optical absorption intensity increases monotonously with a growth of ultrasonication duration; the fact indicating the growth of carbon nanomaterial concentration. Simultaneously, the resolution of characteristic peaks of SWCNT improves, and the ratio of characteristic peaks absorption to background absorption grows with an increase in ultrasonication duration, which evidences the rise of the debundling degree and the growth of concentration of isolated SWCNT and their fine bundles at longer ultrasonication duration.

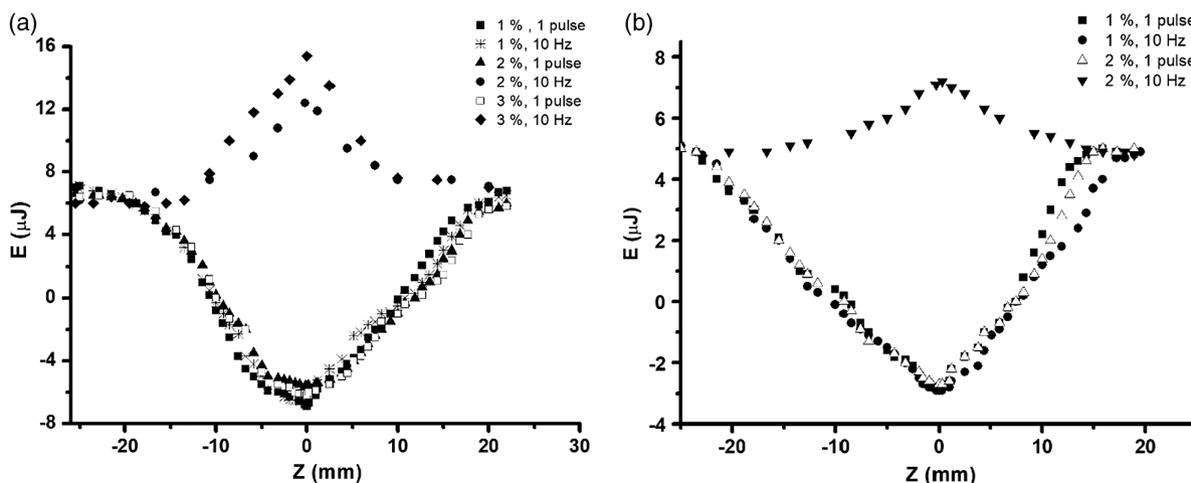


Figure 4. Dependence of the laser-pulse energy transmitted through the cell with the a) CB-SDOC-PVA-water and b) SWCNT-SDOC-PVA-water quaternary systems versus the cell position (Z) with respect to the optical-system focus at different PVA concentrations: (squares) 1 wt%, single-pulse mode; (stars) 1 wt%, pulse-periodic mode with a repetition rate 10 Hz; (triangles) 2 wt%, single-pulse mode; (circles) 2 wt%, 10 Hz; (open squares) 3 wt%, single-pulse mode; and (diamonds) 3 wt%, 10 Hz.

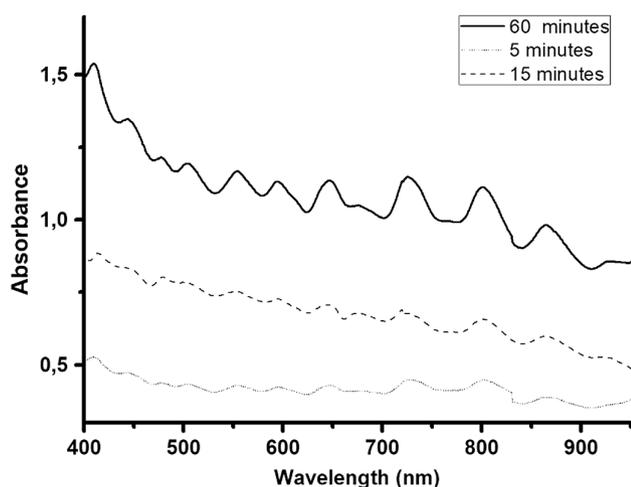


Figure 5. Absorption spectra of SWCNT suspensions in water prepared with different ultrasonication times: (solid curve) 60 min, (dashed curve) 15 min, (dotted curve) 5 min.

The aforementioned results are confirmed by results obtained by cryogenic transmission electron microscopy (Cryo-TEM) methodology. Cryo-TEM was used to determine bundle sizes. **Figure 6** shows images of suspensions ultrasonicated during a) 5 min, and b) 60 min. An increase of ultrasonication duration leads to the reduction of the average bundle diameter: in case of 5 min ultrasonication, bundles have average diameter ≈ 6 –8 nm; the average diameter in a suspension ultrasonicated during 1 h is ≈ 2 nm. A decrease in average diameter is accompanied with a growth of nanotube concentration. The SWCNT in 1 h sample are shorter and more kinked than in a 5 min sample; therefore, one can assume a growth of the defect concentration on the graphene surface of SWCNT alongside an increase in the ultrasonication duration.

The latter conclusion is in line with the data previously obtained for arc-discharge SWCNT by Raman spectroscopy and discussed in ref. [9]. Therein, basing on the analysis of the D - and G - bands intensities in Raman spectra of SWCNT,^[19] it was inferred that longer ultrasonication duration of suspensions causes an increase in defectiveness in the sp^2 -hybridized orbital of a nanotube: intercarbon bonds break in some instances, and atoms with sp^3 -hybridized orbitals emerge. So, in ref. [9], it was observed that reduction in the degree of the SWCNT association gives rise in the defectiveness with an increase in the ultrasonication time.

Eventually, the OPL behavior of the suspensions with different times of ultrasound treatment was checked. The E-scan curves are given in **Figure 7**. The best OPL parameters are demonstrated by the sample with the biggest average diameters of bundles and the lowest ultrasound treatment durations; the weakest OPL parameters are shown by the system with 1 h ultrasonication duration and the smallest average bundle diameters. These results give grounds to conclude that conversion of laser light energy into heat goes more effective in suspensions with bigger average bundle diameters and lower concentration of defects on them due to the growth of probability of cross-system energy transitions.

3. Conclusions

Thermodynamic analysis of micellar aggregation of SDOC in aqueous solutions of PVA reveals a commensurable role of both the hydrophobic effect and the formation of hydrogen bonds between molecular species of the aggregate; high degree of micellar ionization being the case. These circumstances make this surfactant a superior stabilizing agent of SWCNT particles among the low molecular weight anionic surfactants in the said fluid solutions. Addition of PVA in an optimal amount (≈ 1 wt%) to the aqueous fluid matrix of CNP dispersions procures them highly resistible with respect to bleaching phenomenon in a

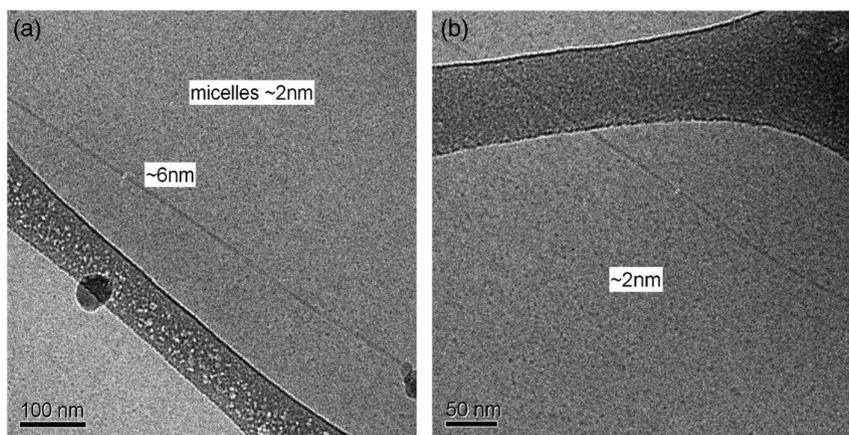


Figure 6. Cryo-TEM images of SWCNT suspensions prepared with ultrasonication time: a) 5 min and b) 60 min.

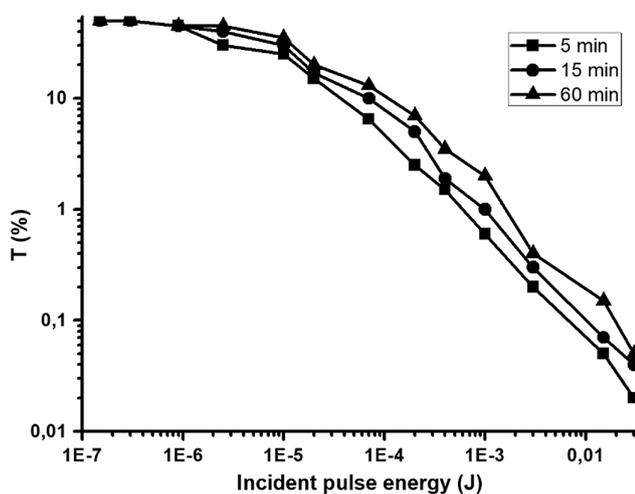


Figure 7. E-scan OPL curves of transporence (T) in SWCNT aqueous suspensions processed with different ultrasonication times: (triangles) 60 min, (circles) 15 min, (squares) 5 min.

pulse-periodic regime (repetition rate 10 Hz) of high-intensity laser irradiation. Enriching SWCNT dispersions with a bigger fraction of agglomerated material (bundles) renders their limiting factor enhanced.

4. Experimental Section

We used HiPco SWCNT (Carbon Nanotechnologies Inc., Houston, TX, purity > 85%) and CB (Sigma Aldrich, $d < 50$ nm, purity > 99%). Net concentration of nanoparticles was 0.05 wt%. For nanomaterial stabilization, SDS (Acros Organic, 99%), SDBS (Sigma Aldrich, 98%), and SDOC (Helicon, 99%) were chosen. These are common anion surfactants, though SDOC molecular architecture differs significantly from SDBS and SDS. In the present study into aggregative properties of the stabilizer, we pinpointed at SDOC, whereas SDS and SDBS (alongside with SDOC) were used for processing CNP dispersions and registering the OPL properties of the latter. SDOC molecules are shell-like with a concave hydrophilic surface and a convex hydrophobic side. Such molecule geometry may cause changes of aggregative mechanism. To process suspensions,

neat CNPs were dispersed in an aqueous solution of a chosen surfactant (1 wt% concentration) and then ultrasonicated during 1 h. SWCNT suspensions were ultra-centrifuged during 1 h at acceleration 150 000 g (Sorvall WX 80+ Ultracentrifuge). CB suspensions were centrifuged during 20 min at 4000 rpm. To process samples in mixed media, PVA (molecular mass ≈ 60 000, Air Products and Chemicals, Inc.) was used. The concentrated PVA solution was prepared separately. PVA solid grains were previously dissolved at a temperature of ≈ 90 °C, then a specified amount of the surfactant was introduced into the solution. Next, the SWCNT–PVA–surfactant–water and CB–PVA–surfactant–water suspensions were obtained with PVA concentrations of 1, 2, and 3 wt%; surfactant concentration was maintained constant and equal to 1 wt% (24.1 mM for SDOC, 28.7 mM for SDBS, and 34.6 mM for SDS). All processed samples were characterized by optical absorbance spectroscopy (Shimadzu UV-3600, 1 cm quartz cuvette).

CMC were determined by three methods: conductivity measurements, tensiometry, and isothermal titration calorimetry. The conductivity method is based on the analysis of the concentration dependence of the electrical conductivity of solutions. When aggregation of the surfactant begins, a noticeable change in the run of electrical conductivity dependency upon concentration appeared. According to the break point in the dependencies, the value of CMC was determined. To measure electrical conductivity, we used Sartorius RR-50 ionomer-conductometer with a PY-C02 cell. The cell had four circular platinum electrodes. The cell constant was 1.14 cm⁻¹; the relative error was $\pm 0.5\%$.

The tensiometry method is based on the analysis of the concentration dependence of the surface tension. The surface tension was measured using a Du Noüy ring on a Sigma 702 tensiometer (Finland). We used a platinum–iridium ring with a radius of 0.9545 mm and a wire radius of 0.185 mm.

To determine CMC by means of isothermal titration calorimetry, we used the TAM III isothermal titration system with a 3201 nanocalorimeter (TA Instruments, USA).

The sizes of particles in the suspensions were measured by a Zetasizer Nano ZS analyzer (Malvern Instruments, Great Britain) in 12 mm polystyrene cells with a square cross section (DTS0012). The detection angle was 173°. The results were processed using the commercial Zetasizer Software 6.20 code.

The nonlinear optical limiting of the suspensions was investigated by means of z-scanning technique: energy transmitted through the samples was measured as a function of the cell position (Z) with respect to the optical system focus ($Z = 0$). We used a set-up analogous to that described in ref. [8]. To study the OPL behavior of the suspensions with different degrees of SWCNT aggregation, we used an E-scan set-up, similar to the one described in ref. [6].

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

carbon black dispersion, carbon nanotubes, mixed solvents, surfactants, SWCNT dispersion

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