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Study of Agglomeration Process of Nanocrystalline Powder ZrO2-Y2O3-CeO2 in Aqueous Media By Means Of Dynamic Light Scattering Technique.

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ABSTRACT

Discussion resumed. Creating model systems, reproducing different environment living organism need to explore changes to the properties of nanoparticles in biological objects. The previous study [19] explored the method for producing stable nanopowder dispersions used as biocompatible materials for toxicological studies. The present study presents the results of hydrodynamic diameter modification in ZrO2-2Y2O3-4CeO2 system, optionally modified with Al2O3 within varying periods of time under variable conditions. The change in electrostatic charge of the particles is performed by means of pH adjustment. The received data has shown that powders with aluminum oxide dopant appear to be more stable over the entire course of the experiment. The system with aluminum oxide proves to be more stable, while it is preferable that the dispersion is preliminarily cured in ethanol medium for 24 hours. Nanopowder dispersion in distilled water without aluminum oxide is stable when treated at natural pH. The results serve as a scientific basis for toxicological study design. To this end, it is necessary to develop a procedural framework for nanomaterials biological effect research. It is highly desirable to involve as much innovative activities as possible when dealing with biomaterials development, in order to implement a scientifically substantiated, integrated and standardized quantitative approach to artificial nanomaterials safety evaluation.
Keywords: Hydrodynamic diameter, ZrO2-Y2O3-CeO2-Al2O3 nanoparticles of system, dispersions, agglomeration state, toxicity, nanoparticles dispersion., staff. innovative activeness,

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INTRODUCTION

Nanoscale science and technology became a linchpin of the cutting edge 21st century scientific research and speculation. Nanotechnology penetrated next to all areas of our living, from equipment design and clothes manufacturing to household detergents, health care, power industry and environment protection. Historical reference suggests that the extensive nanotechnology growth, on top of immediate task of creating unique materials with targeted properties, poses a question of safety in regard of the said technology.

Medical science is one of the areas where nanotechnology comes into an immediate contact and close interaction with a man. Human life expectancy is gradually improving, causing the increase in aged population, who are the most frequent recipients of dental and orthopedic prosthetic care [1,2]. Novel nanomaterials are widely used for this purpose, particularly as implants. [3,4]. The scientists are cooperating with doctors to develop new solutions in terms of materials with unique characteristics and targeted properties. In the context of achieving the strategic goals of Russia's innovative development the formation of organizations' sustainable competitive advantages by encouraging their innovative activity is becomming of special importance.Creating new biocompatible materials requires significant effort in theoretical and clinical experimental study, but their growing practical value offsets the cost and provides a substantial background for the topical nature of the problem.

Currently the development of new biomedical nanomaterials is not sufficiently backed up with use of hazard free materials and nanomaterials toxicity check prior to the clinical research. Therefore, there is an ongoing demand to study the toxicity of biomedical nanomaterials and their health and environmental impact simultaneously with their development, since adverse impact of nanomaterials on human body may be both immediate and deferred in its nature [4-7].

Therefore, to study the changes of properties of nanoparticles to create model systems, fertile environment of a living organism. If we define the specific molecule contacted nanoparticle, we understand further its path in the body. The day today, many scientists are interested in the development of various standards determine the effects of nanoparticles on biological objects.

To meet this demand, specific regulations are being developed for new materials by respective European and US authorities, prioritizing the materials used for biomedical purposes. Designated institutions are put in charge of the matter, while public authorities appoint groups responsible for risk assessment and developing regulatory documentation for nanomaterials manufacturing. Among them are the United States Food and Drug Administration (FDA) and Environmental Protection Agency (EPA), European Food Safety Authority (EFSA), European Agency for the Evaluation of Medicinal Products (EMEA), Organization for Economic Co-operation and Development (OECD), and other national agencies [6,8-14].

Development of nanotechnology related standards is another important highlight. The activity of ISO/TC 229 Technical Committee is concerned with standardization tasks in the sphere of nanotechnology and attracts global professional attention. Multifaceted approach is implemented by the Committee for analysis of problems arising in the course of nanotechnology research and application. ISO/TC 229 activity is to a large extent based on the attitude of its member countries – world leaders in nanotechnology: USA, Great Britain, Japan, South Korea, China. Nanotechnology safety matters are crucial for the modern society, since their neglect or underestimation can result in severe impact on people's health and environment. In January the voting on the draft innovative technical report ISO/DTR 13121 "Nanotechnologies – nanomaterial risk evaluation" had been started among the members of ISO/TC 229. The report was developed in the scope of ISO/TC229/WG3 work group based on Nano Risk Framework standard published in June 2007 jointly by American Corporation DuPont and Environmental Defense Company. The sequential and pragmatic approach proposed by the corporate standard was supported by users in a number of countries. Therefore it was decided to extend the standard scope from corporate to international. Russian Rospotrebnadzor (Directorate for consumer rights and health protection), Russian Academy of Medical Sciences Nutrition R&D Institute, Russian Academy of Medical Sciences Epidemiology and Microbiology R&D Institute, Russian Academy of Sciences A.N.Bach Institute of Biochemistry, and F.F.Erisman Federal Scientific Center of Hygiene developed two regulatory documents that have already been approved by the Russian State Chief Medical Officer: procedural guidelines MU 1.2.2520-09 "Nanomaterials Toxicological and Hygienic Safety Evaluation";

procedural recommendations MR 1.2.2522-09 "Identification of nanomaterials presenting potential human health risk". Starting on January 1, 2016 a set of interstate nanotechnology standards will become optional for use in the Russian Federation. These are: GOST ISO/TS 80004-5–2014 “Nanotechnologies. Part 5. Nano-/bio-interface. Terms and definitions”, which is identical to the international document ISO/TS 80004-5:2011 “Nanotechnologies. Vocabulary. Part 5. Nano/bio interface”; - GOST ISO/TS 80004-7–2014 “Nanotechnologies. Part 7. Nanotechnologues in medical science. Terms and definitions”, which is identical to the international document ISO/TS 80004-7:2011 “Nanotechnologies. Vocabulary. Part 7. Diagnostics and therapeutics for healthcare”.

However, that figuratively to intensify scientific potential in the development of environmental and school-related problems, nanotechnologies, incentive to actors nanotechnology to develop environmentally sound technologies and new solutions in the field of ecology. Scientists must possess a combination of unique knowledge and skills.

Risk assessment is a classifying scientific description of risk factors potentially detrimental to health, arising as a result of hazardous agents impact on people and environment or in case of incident occurrence [5, 7]. Just as in relation to larger size chemical substances, risk assessment underlies nanomaterials research and establishment of guidelines on their safe treatment. It is performed by means of a comprehensive analysis of available data and knowledge in order to ensure timely protection of people’s health and environment.

Risk assessment implies:

1) Hazard identification – performing quantitative evaluation of various substances adverse effects;
2) Exposure estimation – exposure types determination (sources of exposure and environment), quantitative parameters or its levels;
3) Estimation of dose-response relationship – determining the relation between dosage and its harmful effect manifestations (extent of exposure);
4) Risk characterization – quantitative estimation of probability of health impairing effects manifestation under varying exposure conditions, including description of unaccounted factors.

The primary task in nanomaterial risks evaluation is to identify and describe potential hazards and estimate their probability and quantitative parameters of exposure. Probable consequences of contact with nanomaterials are determined based on the substances hazard class, including the dose-response relationship [7, 13-14]. By studying physical and chemical properties of nanomaterials (such as size, surface charge and agglomeration state) in aqueous suspensions and carrying out meticulously planned research in managed conditions, toxicological effect characteristics and related dose-response relationships for individual nanomaterials are being obtained.

Work objective

The purpose is to investigate the agglomeration process of nanopowders in dispersion for developing a productive method for stable dispersions of nanopowders used as biocompatible materials for toxicological studies.

Starting materials

In order to solve the original problem, powders ZrO_2-$2Y_2O_3$-$4CeO_2$ and ZrO_2-$2Y_2O_3$-$4CeO_2$-$3Al_2O_3$ were used as starting materials produced by the redeposition from inorganic precursors using the sol-gel technology. In order to synthesize nanopowders, yttrium nitrate $Y(NO_3)_3 \cdot 6H_2O$, zirconium oxychloride $ZrOCl \cdot 8H_2O$, cerous nitrate $Ce(NO_3)_3 \cdot 6H_2O$, aluminum nitrate $Al(NO_3)_3 \cdot 9H_2O$, ethanol, 25% ammonia water NH_4OH were used. Other chemical substances used in this study contain sodium chloride (NaCl), hydrochloric acid (HCl).

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METHODS

Hydrodynamic diameter of powder nanoparticles dispersions of ZrO_2-$2Y_2O_3$-$4CeO_2$ and ZrO_2-$2Y_2O_3$-$4CeO_2$-$3Al_2O_3$ were measured by Zetasizer Nano ZS (Malvern Instruments Inc, UK) using the dynamic light scattering (DLS) and electrophoretic light scattering (ELS).

RESULTS AND DISCUSSION

Studying nanomaterials properties for toxicological research is a fairly complicated process, since a wide variety of material parameters is to be considered, such as size, size distribution, shape and other morphological characteristics, as well as dispersion degree, surface charge, specific area and surface chemistry, and other physical and chemical properties. To this end, the procedural framework for nanomaterials biological effect research has to be developedTo this end, it is necessary to develop a procedural framework for nanomaterials biological effect research. It is highly desirable to involve as much innovative activities as possible when dealing with biomaterials development, in order to implement a scientifically substantiated, integrated and standardized quantitative approach to artificial nanomaterials safety evaluation.

Ecotoxicological testing of nanopowder obligatorily include the stage of preparation of aqueous suspensions. Proper preparation of materials (powders, dispersion, etc.) is crucial for toxicological research [5,6, 12-14]. For instance, use of improperly prepared (unstable) dispersions for toxicological tests can significantly alter the results of toxicity tests, which can eventually lead to faulty interpretation of probable hazard level of a nanomaterial. Surface charge and hydrodynamic size of disperse nanoparticles have to be studied likewise, since these characteristics can have considerable influence over the way a body reacts to nanoparticles [7, 14-16]. Particle size determines their interaction with biological systems, including absorption, distribution, metabolism and excretion.

In our previous research [17-18] we considered the impact of ultrasonic treatment and curing in ethanol on the agglomeration rate of nanoparticles in solution, as well as stability of nanoparticles dispersions in solution using variable stabilization types. The purpose of the present study is to expand on the important and challenging issue of stable dispersions preparation, and to identify the factors influencing ZrO_2-Y_2O_3-CeO_2-Al_2O_3 system nanocrystalline powder dispersions stability.

The research uses nanocrystalline powders of ZrO_2-Y_2O_3-CeO_2 and ZrO_2-Y_2O_3-CeO_2-Al_2O_3 systems. We studied the impact of curing in ethanol on agglomeration of nanoparticles in solution. The measurement method is based on dynamic light scattering theory. The preliminarily prepared dispersions were placed in a cuvette for dynamic measurement of hydrodynamic diameter. The designed conditions were set to perform measurement each 3 seconds during 2 hours. Thus we would be able to analyze the pattern of nanoparticles diameter variation in dispersion in the course of time. The obtained data can provide additional information regarding the behavior of system ZrO_2-Y_2O_3-CeO_2-Al_2O_3 nanoparticles in dispersion.

In the previous research [17-19] we also established that stable dispersions can be obtained at dispersed powder particles concentration of max. 1 g/l, preferably 0,5 g/l. Therefore we prepared a dispersion with powder concentration 0,5 g/l (500 ppm). The prerequisite for the two particles' agglutination in dispersed phase is sufficiently short distance between them for attraction forces to pull them together. If colloid particles collision frequency is low, the disperse system can be stable. This can happen provided that the disperse particles concentration is extremely low.

The standard framework for nanopowder dispersion preparation in distilled water for measurement by method of dynamic light scattering includes:

1) preliminary curing of nanopowder in distilled water;
2) ultrasonic treatment

Figure 1a presents dependency diagrams of ZrO_2-$2Y_2O_3$-$4CeO_2$ system powder nanoparticles hydrodynamic size at natural pH=4.1. Dispersion was prepared in distilled water, powder concentration in dispersion is 0,5 g/l (500 ppm). No additional adjustment of pH was performed. From Figure 1a it is evident

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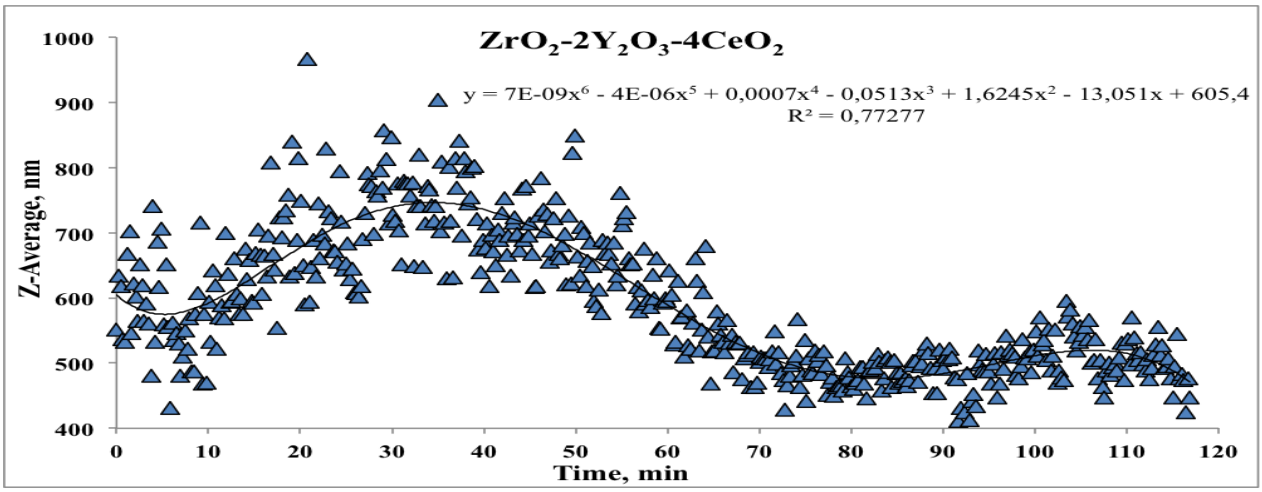
that hydrodynamic size of nanoparticles within first 10 minutes remains on the level of approximately 580 nm, but particle size tends to increase with time, reaching its peak of 750 nm in 35 minutes after the experiment start. Then the diameter goes gradually down until 65th minute when it turns flat at particles hydrodynamic diameter approximate value of 500 nm. The diagram shows that in the beginning of the experiment (immediately after the dispersion preparation and its sonification), the particles haven't agglutinated yet, but afterwards we observe growth of particle size. Actually it's not one big particle but an agglomerate of smaller particles. When the particles start to agglutinate, the measurement device captures the agglomerate size. Then the agglutinated particles flocculate, and the device captures smaller particles that remain suspended, their hydrodynamic size less than in the beginning of the experiment.

a



b

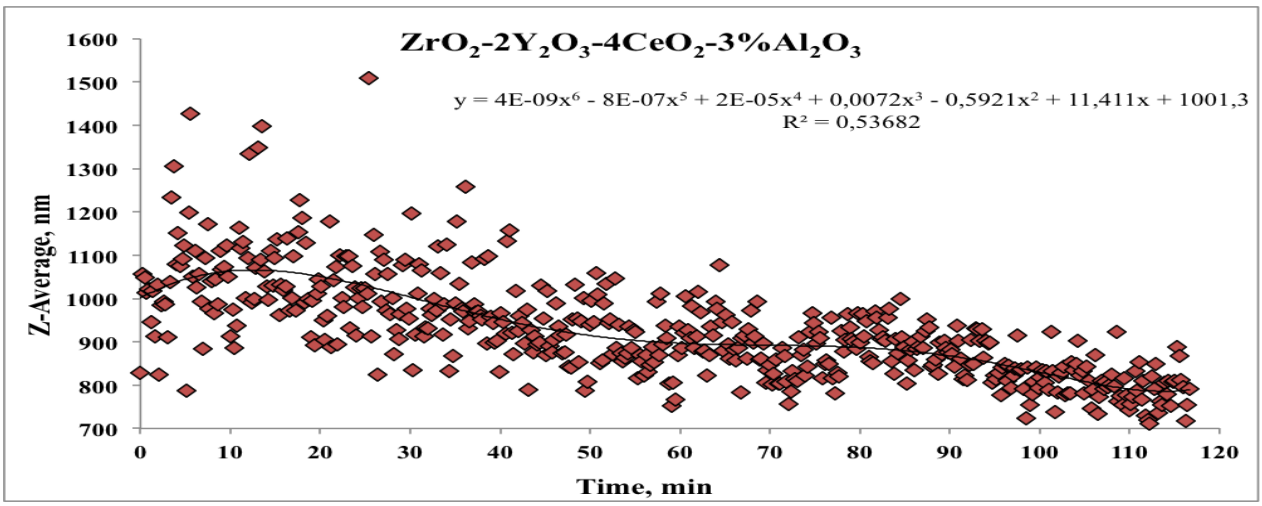


Figure 1. Variation of hydrodynamic diameter of nanoparticles dispersion in distilled water at natural pH during 120 minutes: a – dispersion of ZrO_2-$2Y_2O_3$-$4CeO_2$ system nanoscale powder; b – dispersion of ZrO_2-$2Y_2O_3$-$4CeO_2$-$3Al_2O_3$ system nanoscale powder

Figure 1b presents the results of hydrodynamic diameter variation in ZrO_2-$2Y_2O_3$-$4CeO_2$-3%Al_2O_3 system nanopowder in the course of time. The diagram shows that particle size increases when 3% aluminum oxide is added. Unlike the diagram in fig. 1a, particle size in the beginning of the experiment is already doubled and exceeds 1000 nm. Then the size smoothly decreases with time going down to nearly 800 nm at the end of the experiment. Like in figure 1b, it can be assumed that hydrodynamic diameter reduction may be caused by agglomeration of particles, resulting in weight increase and subsequent flocculation, the device capturing the smaller particles which remain suspended.

Our previous research [17] also included the effect of curing in ethanol and subsequent ultrasonic treatment on the nanoparticles agglomeration. We found that after curing in ethanol for approximately 24 hours and subsequent ultrasonic treatment of nanoparticles dispersion, the particle size decreases. This effect

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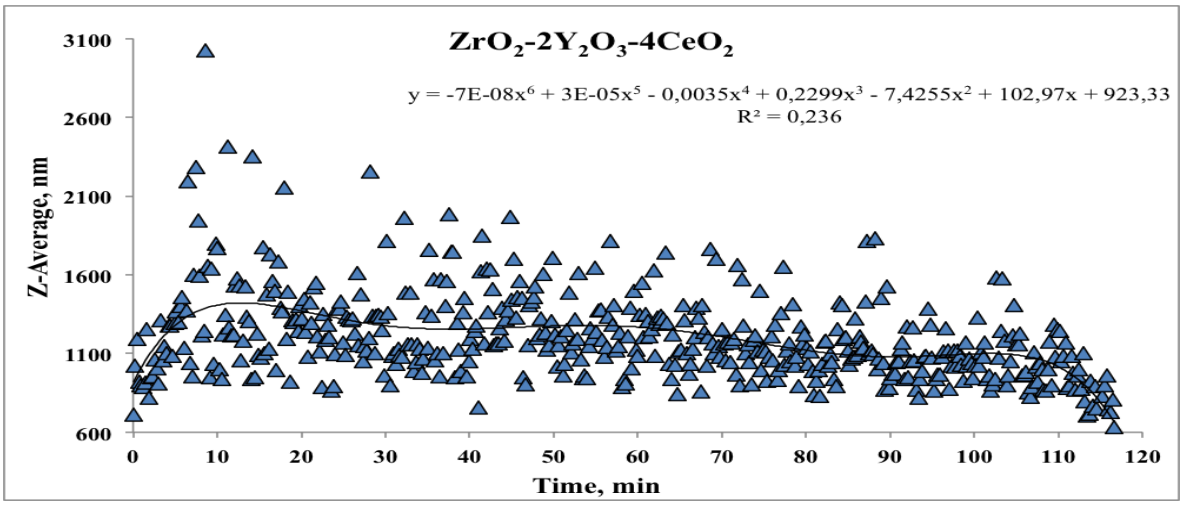
is caused by the properties of ethanol used for curing and dispersing, which meet a number of requirements: high cavitational ability for maximum efficiency of dispersing, easy separation from solid residue after treatment and ability to maintain purity of the treated material.

In view of the above, it was decided to conduct a similar experiment to the one presented in Figure 1, but powder curing and ultrasonic treatment were performed in ethanol medium. Measuring of hydrodynamic diameter was also performed for the nanoparticles dispersion in ethanol.

Figure 2 presents the results of hydrodynamic diameter measurement for ZrO_2-$2Y_2O_3$-$4CeO_2$ and ZrO_2-$2Y_2O_3$-$4CeO_2$-$3\%Al_2O_3$ systems nanopowders during 120 minutes. Powders were prepared by curing in ethanol and subsequent ultrasonic treatment; measurement was performed in ethanol medium as well. Nanopowder concentration was 0,5 g/l (500 ppm).

a



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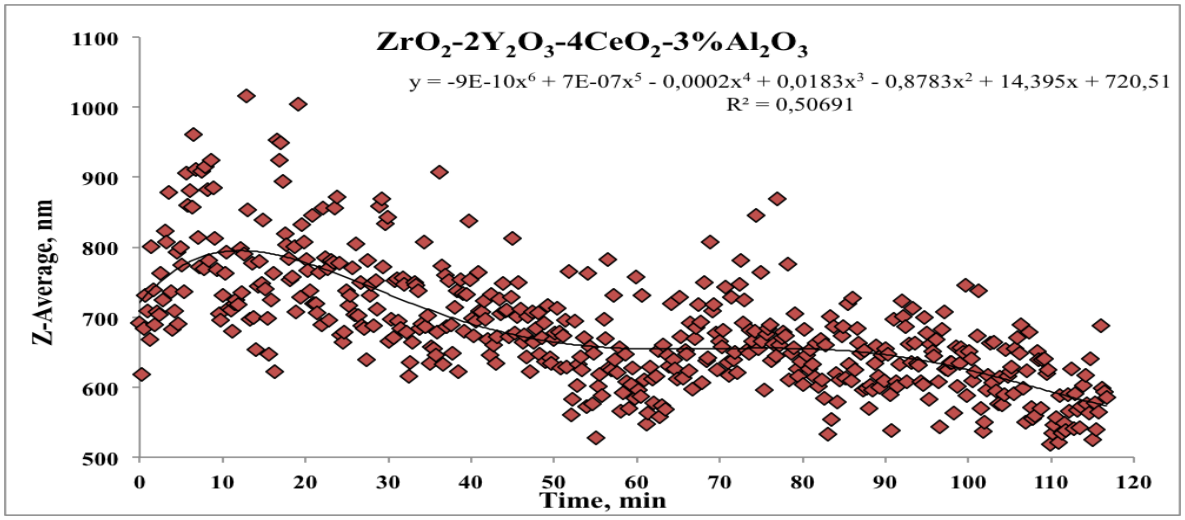

Figure 2. Variation of nanoparticles dispersion hydrodynamic diameter after curing in ethanol during 24 hours. Experiment duration – 120 minutes: a – nanoscale powder dispersion of ZrO_2-$2Y_2O_3$-$4CeO_2$ system; b – nanoscale powder dispersion of ZrO_2-$2Y_2O_3$-$4CeO_2$-$3Al_2O_3$ system

Figure 2a presents the variation of ZrO_2-$2Y_2O_3$-$4CeO_2$ system powder nanoparticles hydrodynamic size. The diagram shows that the dispersion can be considered relatively stable, since no significant variation in particle size is observed. Hydrodynamic diameter of particles throughout the experiment stays in the range between 1000 and 1300 nm. Probably it is the effect of curing in ethanol. Apparently the nanopowder particles still agglomerated but the size of agglomerates appeared to be uniform, they neither agglutinated with other agglomerates nor flocculated, remaining suspended throughout the entire experiment.

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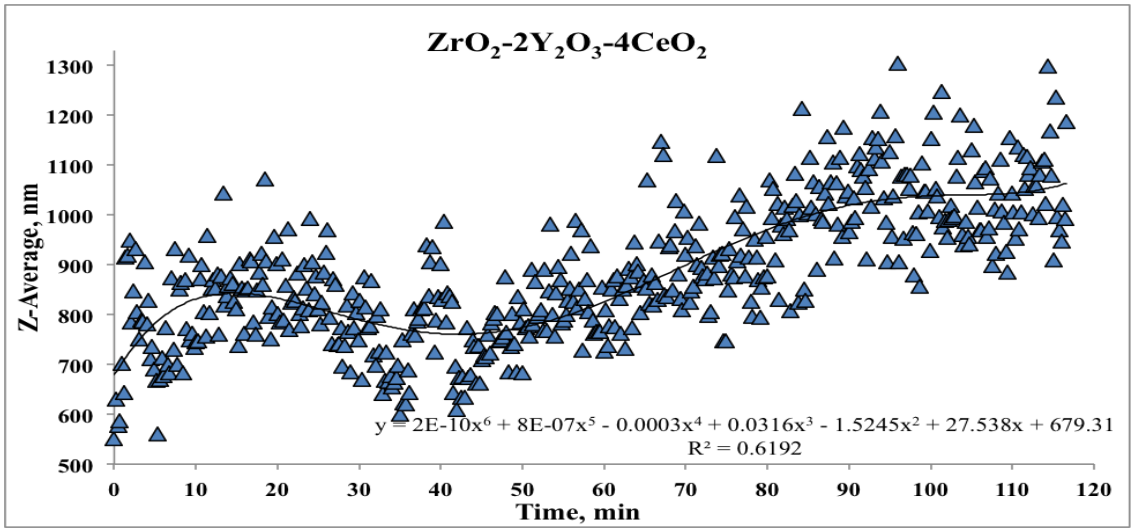
Figure 2b presents the variation of ZrO_2-$2Y_2O_3$-$4CeO_2$-3%Al_2O_3 system nanopowder hydrodynamic size. Following the previous measurement method (fig.1a), a low dose of aluminum oxide dopant gradually decreases the hydrodynamic diameter in the course of 120 minutes. In the beginning of the experiment, the size is approximately 800 nm, going down to less than 600 nm in the end of the experiment. The curve signature suggests that probably particles in the system with aluminum oxide dopant tend to agglomerate more than without the dopant. Again, we assume that the hydrodynamic diameter reduction in the course of time is caused by agglomeration of flocculating particles; then the measurement device captures remaining suspended particles only.

In our previous published research [17-19] we studied the ways to stabilize the nanoparticles dispersion in ZrO_2-$2Y_2O_3$-$4CeO_2$ and ZrO_2-$2Y_2O_3$-$4CeO_2$-3%Al_2O_3 systems. In the scope of the present study we aimed to verify if electrostatic stabilization was possible for dispersion cured in ethanol for 24 hours. Figure 3 presents the results of experiments directed at stabilization of nanoparticles dispersion in ethanol. Nanopowder concentration amounted to 0,5 g/l (500 ppm). Electrostatic stabilization was performed by adding NaCl/HCl solution at 10 mmol concentration and pH=2 to the dispersion.

a



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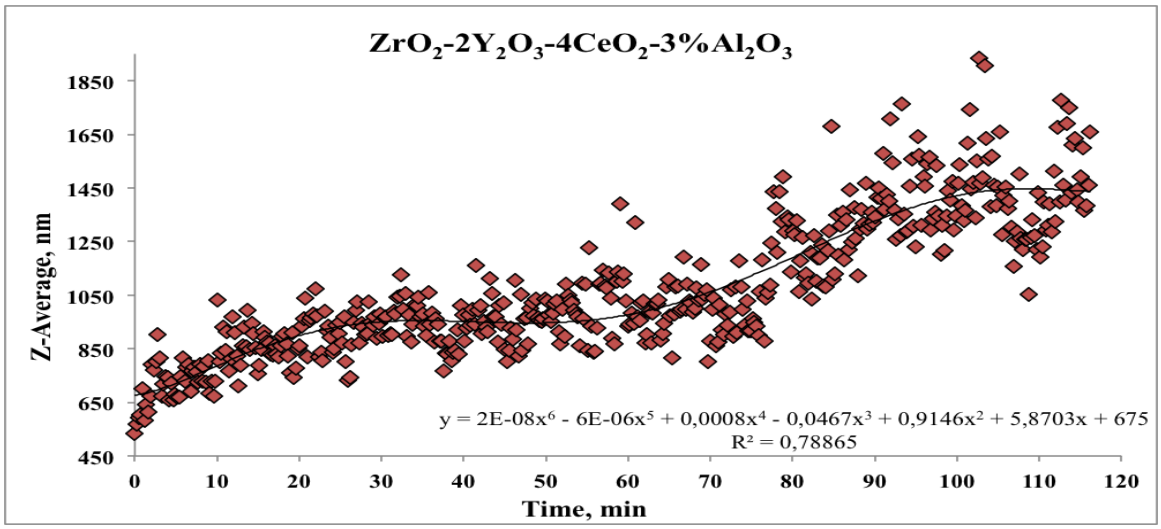

Figure 3. Variation of nanoparticles dispersion hydrodynamic diameter in ethanol stabilized by electrostatic method during 120 minutes: a – dispersion of ZrO_2-$2Y_2O_3$-$4CeO_2$ system nanoscale powder; b – dispersion of ZrO_2-$2Y_2O_3$-$4CeO_2$-$3Al_2O_3$ system nanoscale powder

The diagram presented in Figure 3a shows that gradual growth of hydrodynamic diameter of nanoparticles in dispersion occurs. In the beginning of the experiment, the particle size was approximately 700

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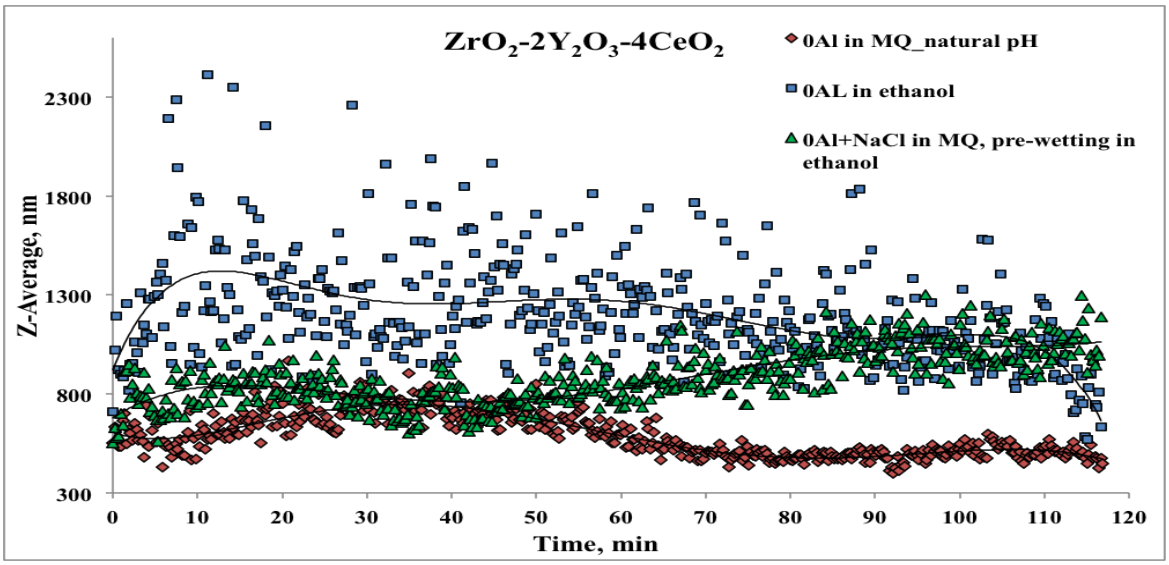
nm, while towards the end of the experiment it amounted to nearly 1000 nm. Based on comparison with diagrams for nanopowder dispersion without aluminum oxide (Fig. 3a) and with aluminum oxide, it is apparent that the curve signatures are similar and pointing at active agglomeration of particles causing the growth of hydrodynamic diameter of particles. As per the diagram in figure 3b, in the beginning of the experiment the size equaled to approximately 650 nm, while by the end it increased up to 1450 nm. In other words, the disperse particles size in the end of the experiment reflected in Figure 3a is nearly twice less than particle size in Figure 3b. Apparently this is the result of aluminum oxide dopant impact.

Based on the experiment results reflected in diagrams presented in Figure 3 we may observe that electrostatic stabilization does not occur; on the contrary, the particles actively agglutinate and gradually form agglomerates as NaCl/HCl solution is being added to dispersion.

To conclude, and in order to facilitate the comparison analysis of hydrostatic diameter, Figure 4 presents the results of all conducted experiments (at natural pH, cured in ethanol and after electrostatic stabilization with NaCl/HCl solution), one diagram per each powder.

a



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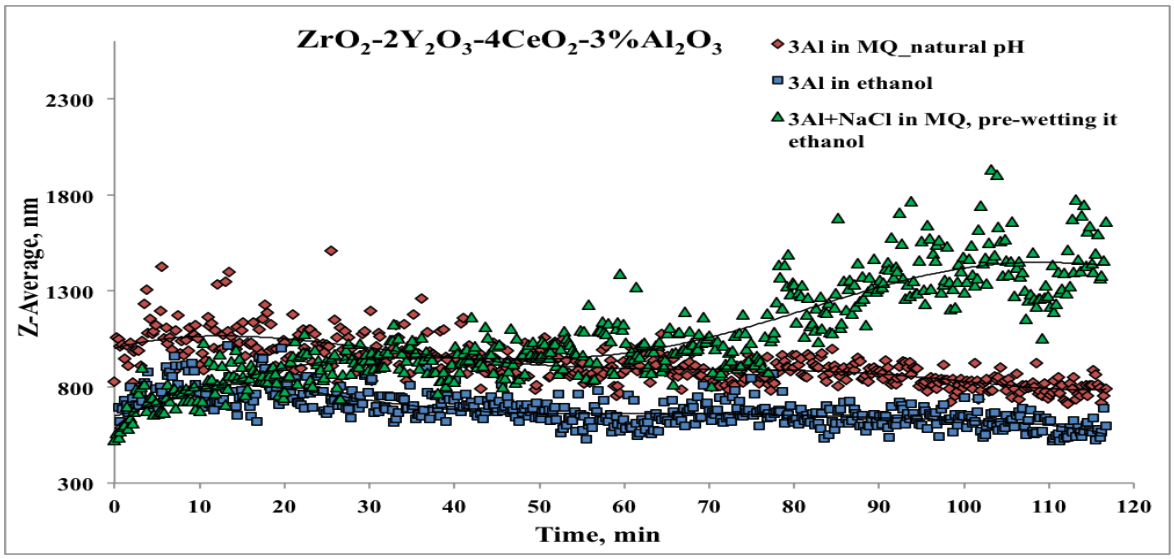

Figure 4. Variation of nanoparticles dispersion hydrodynamic diameter during 120 minutes in variable conditions: a – ZrO_2-$2Y_2O_3$-$4CeO_2$ system nanoscale powder dispersion; b – ZrO_2-$2Y_2O_3$-$4CeO_2$-$3Al_2O_3$ system nanoscale powder dispersion.

Based on the data presented in Figure 4a we may observe that the biggest size (from 1000 to 1300 nm) is manifested by particles prepared by curing in ethanol and measured in ethanol medium. It is also apparent that the range of hydrodynamic diameter values for this curve is the most extensive. The other two curves reflecting the variation of hydrodynamic diameter (dispersion at natural pH and after electrostatic stabilization) in the beginning of the first 50 minutes remain in the range between 500 and 800 nm. Further on, after 60 minutes of the experiment, they start to diverge.

From Figure 4b it is evident that nanopowder dispersion with aluminum oxide dopant is more stable versus the system without aluminum oxide dopant. From the beginning of the experiment to 70th minute, all curves remain in the range between 600 and 1000 nm, while after the 70th minute the hydrodynamic diameter growth occurs in dispersion that was electrostatically stabilized by NaCl/HCl solution.

SUMMARY

- Nfluence of pH on the stability of surface charge and aggregation hydrodynamic size dispersed nanoparticles
- Shows that powders with addition of aluminum oxide are more stable during the whole experiment. the values span more pronounced on the graphs of dispersion without aluminium oxide Nanopowders.
- Particle size in electrostatically stabilized dispersion starts to increase and reaches 1450 nm by the end of the experiment,
- Particle size in dispersion prepared at natural pH decreases down to 750 nm by the end of the experiment.
- From the beginning of the experiment to 70th minute, all curves remain in the range between 600 and 1000 nm, while after the 70th minute the hydrodynamic diameter growth occurs in dispersion that was electrostatically stabilized by NaCl/HCl solution.

In other words, it is logical to assume that the system with aluminum oxide is more stable, and it is preferable to use dispersion prepared by curing in ethanol during 24 hours. Besides, it is notable that nanopowder dispersion without aluminum oxide in distilled water is stable when treated in natural pH. The data is quite consistent with other studies [13-15]. Other important factors impacting the disperse nanoparticles that are mentioned in the said studies are ionic force of solution, pH, particles and surface chemistry.

Knowledge about the determinants of dispersion parameters status would have significant consequences in the preparation of the sample for toxicological studies and interpretation of biological response.

The establishment of such a model system that play different environment living organism will look more closely into the properties and behavior of nanoparticles in humans. In the same way, it may become essential elements in the development of various standards determine the effects of nanoparticles on biological objects.

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