Synthesis of Magnetic Particles Using Electric Explosion of the Wire at the Boundary with the Liquid

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Abstract. The article describes an installation for producing nanopowders by the method of electrical explosion of a wire. The powders are supposed to be used as a basis for magnetorheological fluids. The article describes the functional installation and the model of the power converter. The electric explosion of the wire was carried out at a voltage of 500 V and 1000 V. The experimental data coincide with the results of the study on the model. The pulse duration is ~ 10⁻⁴ s, and the power is in the range from 1.5 MW to 4 MW. Spherical particles are obtained in the size of 500-5000 n with such parameters of an electric explosion. The surface of the particles was examined on a Tescan VEGA II electron microscope.

1. Introduction
Nanoscience and nanotechnology are currently one of the most rapidly developing areas of science and technology. In recent years, highly dispersed metal nanoparticles have attracted much attention due to their properties and are widely used in various fields, such as electronic devices, microfluidic devices, biomedical, etc. [1-3]. For various applications of magnetorheological fluids, certain requirements are imposed on their properties. The properties of magnetically controlled liquids strongly depend on the composition of the colloidal system [4-9].

2. Description of the Installation for the Production of Nanopowders by the Method of Electric Explosion
In fig. 1 shows a functional diagram of an installation for producing nanopowders by the method of electric explosion. In fig. 1 shows: SC - control system, PC - power converter, C - capacitive storage element, VS - voltage sensor, CS - current sensor, R - reactor, WFM - wire feeding mechanism, S - power switch, W - wire.
Figure 1. Functional installation diagram.

The algorithm of the installation is as follows: the wire introduced into reactor $R$ by the $WFM$, in which it closes the electrodes $E1$ and $E2$. After the electrodes are closed, the control system enables the operation of the power converter, which charges capacitor $C$ to a predetermined voltage level. When a given voltage on a capacitor is reached, the control system closes the key $S$, and an electrical explosion of the wire in the reactor $R$.

3. Power Converter Model

The power converter model is shown in Fig. 2. In fig. 2 shows: $U_{grid}$ - single-phase voltage; $T1$ - step-up transformer 220/1500 V; the elements $D1$, $D2$, $C1$ and $C2$ form a voltage multiplier; $R$ - current limiting resistor; $C3$ - 160 microfarad capacitive energy storage; $R_{Wire}$ - active resistance of the exploding wire; $VT1$ - IGBT transistor; $U_{goal}$ - voltage setting at which the discharge occurs; $ControlSys$ - control system.

Figure 2. Power converter model.

The model allows to obtain oscillograms of current and voltage with different resistance $R_{Wire}$, which depends on the geometrical dimensions of the wire. The maximum length of the wire for the implementation of an electrical explosion is determined by [10]:

\[ l = \frac{2\pi}{d^2} \frac{C U^2}{e_s \rho K}, \]

where \( l \) - the length of the wire, mm; \( d \) - the diameter of the wire, mm; \( e_s \) - the specific energy of wire sublimation, J/g; \( \rho \) - the wire density; \( C \) - the capacity of the storage element, F; \( U \) - the voltage on the storage element, V; \( K \) - the safety factor from 1 to 3.

The resulting simulation data allows you to calculate the necessary energy for the effective explosion of a wire with a known length and diameter. This energy value determines the minimum voltage for charging the capacitor.

4. Simulation Results
In fig. 3-4 shows the oscillograms of voltage and current during the process of electrical explosion of a wire at various set discharge voltages obtained during the experiment (Fig. 3b, 4b). The capacitor charge voltage was 500 V and 1000 V. Alloy steel AISI 316 was used as a wire. The wire length in the reactor was \(~3\) cm, diameter \(~0.3\) mm.

![Figure 3. Oscillograms of voltage and current at a capacitor voltage of 500 V: a) simulation; b) experiment.](image)

![Figure 4. Oscillograms of voltage and current at a capacitor voltage of 1000 V: a) simulation; b) experiment.](image)
Current and voltage waveforms recorded with a Tektronix TDS2014B oscilloscope. The current was measured on the current shunt, and the voltage on the voltage divider. The obtained experimental data coincide with the results of research on the model. The pulse duration is \( \sim 10^4 \) s, and the power is in the range from 1.5 MW to 4 MW.

The electrical explosion of the wire was carried out over the surface of the solution of vacuum oil with the addition of oleic acid (7% by weight) in an inert atmosphere of nitrogen. The resulting explosion is condensed in the liquid phase, covered with surface-active substances, which leads to a decrease in the coagulation of particles and increase the stability of the colloidal system. The surface of the particles was examined using a Tescan VEGA II electron microscope, which revealed that the particles have a spherical shape and size in the range of 300-5000 nm (Figure 5).

![Figure 5](image)

**Figure 5.** Photos of particles of a magnetorheological fluid.

Figure 6 shows photographs of the formed structures of a magnetoreological fluid under the action of a magnetic field.
5. Conclusion
From the obtained simulation results it follows that the effective production of metal particles can be carried out at a relatively low voltage (500-1000 V). Using a low voltage installation allows you to simplify the equipment used. Experimental results obtained by exploding a wire above the surface of a liquid confirm the simulation data. With the wire injection, spherical particles with a size of 500–5000 nm with high sedimentation stability and redispersibility are obtained. Thus, the results obtained are of interest as the basis for the technology of obtaining magnetorheological fluids.

References
[1] Kotov Yu A 2009 Electric wire explosion - a method of obtaining low-aggregated nanopowders Russian nanotechnology 4 40-51
[2] Ivanov V V, Efimov A A, Mylnikov D A, Lizunova A A, Bagazeev A V, Beketov I V, Shecherbinin S V 2016 High-efficiency synthesis of nanoparticles in a repetitive multigap spark discharge generator Technical Physics Letters 48 876-878
[3] J de Vicente, Klingenberg D J, Hidalgo-Alvarez R 2011 Magnetorheological fluids: a review Soft matter 8 3701-3710
[4] Vollath D 2008 Plasma Synthesis of Nanopowders Journal of Nanoparticle Research 10 39-57
[5] Hutten A, Sudfeld D, Ennen I, Reiss G, Wojczykowski K, Jutzi P 2005 Ferromagnetic FeCo nanoparticles for biotechnology J. Magn. Mater 293 93 - 101
[6] Wieckleder M S, Schlecht S, Preis W 2006 Trendbereicht: Nanoskalige Festkorper, Nachrichten aus der Chemie 54 236 – 237
[7] Lorenz M R, Holzapfel V, Musyanovich A, Nothelfer K, Walther P, Landfester K, Schrezenmeier H, Mailander V 2006 Uptake of functionalized, fluorescent labelled particles in different cell lines and stem cells Biomaterials 27 2820 – 2828
[8] Landfester K, Ramirez L 2003 Encapsulated magnetite particles for biomedical application J. Phys. Condens. Matter. 15 1345 – 1362
[9] Belyaev E S, Ermolaev A I, Titov E Yu, Tumakov S F 2017 Technologies for creating and using magnetorheological fluids for controlled vibration isolators NNSTU n.a. R E Alexseev (N Novgorod)

[10] Nazarenko O B, Tikhonov D V 2008 Formation of nanoparticles under conditions of electrical explosion of conductors Publishing house of Tomsk Polytechnic University (Tomsk)

Acknowledgments
The results of the research work were obtained with the support of a grant from the President of the Russian Federation for state support of young Russian scientists (MK-590.2018.8 agreement № 075-15-2019-660).