Journal of Electrostatics 96 (2018) 111–118

Contents lists available at ScienceDirect

Journal of Electrostatics

journal homepage: www.elsevier.com/locate/elstat

Spark erosion in a metal spheres bed: Experimental study of the discharge stability and energy efficiency

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ARTICLE INFO

Keywords:
Discharge
Erosion
Granule
Metal
Pulse
Steel

ABSTRACT

Pulsed spark discharge in metallic granular beds in aqueous media was studied for the granular bed geometry affecting the discharge parameters, stability and powder production. Experiments were carried out in horizontal bed and columnar reactors filled with 4-mm steel spheres. The pulse energy and the powder production depend on the bed height, showing its maximum within 9–14 mm growing with the pulse repetition frequency from 200 to 800 pulses per second and degrading in spark erosion time due to the bed vibrational compaction and accumulation of the erosion products short-circuiting intergranular gaps.

1. Introduction

Spark discharges are generated by applying repetitive voltage pulses to a layer of millimeter-size metal pellets, facings or spheres of a conductive material submerged in liquid of low electric conductivity. The approach has been applied in a number of technologies: Berkowitz and Walter [1] described generation of ultrafine metal powders, Maiorov et al. [2] produced nanoparticles of magnetite, Zhang et al. [3] applied the method for production of silicon powders, and Cabanillas et al. [4] – for dispersion of the uranium-molybdenum alloy. The method was also used by Dvornik and Verkhoturov [5] for the reuse of hard alloys, and by Plotnikov et al. [6] in preparation of bioactive suspensions. Coreton and Hayhurst [7] used the method to produce powders of pure metals, their oxides, hydroxides, nitrides and carbides applied as catalysts. Berkowitz et al. [8] applied powders in production of ferromagnetic substances, and Monastyrsky et al. [9] – for shape-memory alloys. In water purification, spark discharge in granular beds was used by Danilenko et al. [10] for arsenic removal; Lobanova et al. [11] used the approach removing humic substances. The effect in water treatment was achieved due to adsorption of aqueous dissolved impurities on the surface of spark erosion products.

According to Berkowitz and Walter [1], high-temperature spark discharges appearing in gaps between adjacent metal pieces lead to local heating of the material followed by its melting and evaporation. Carrey et al. [12] described fine metal particles produced in this process having usually a particle size distribution ranging from several nanometers to tens of micrometers. Pfeiffer et al. [13] extensively reviewed principles of spark circuits and achievements in particle size control. The properties of powders, such as chemical composition, average particle size and particle morphology, can be controlled by the choice of process parameters.

For practical use of the method, maximum powder yield has to be achieved under repeatable and well-understood spark discharge conditions. However, only few works have been published regarding optimal discharge conditions and process parameters. Thus, Petrichenko et al. [14] determined the conditions of stable spark discharge in metal and graphite granular beds dependent on the capacitance of the output capacitor. Shcherba et al. [15] studied the influence of the discharge pulse repetition rate on the reactor impedance showing the equivalent resistance of the discharge growing with the pulse repetition frequency. Carrey et al. [12] used mechanical activation to obtain discharge stability in a “shaker pot” reactor. Liu et al. [16] applied ultra-sound for the discharge stabilization. Most publications, however, focused on the properties of powders produced by spark erosion, often disregarding the influence of discharge parameters and other process factors.

The present study aims to establish the dependence of the energy efficiency and the discharge stability in spark erosion on the reactor geometry and the discharge parameters. The experimental data on single-pulse and repetitive mode operation in different reactor configurations are reported. Spatial distribution of the discharge was studied and a simple electric equivalent circuit of the reactor was discussed and compared to the experimental results. Extended operation of a spark

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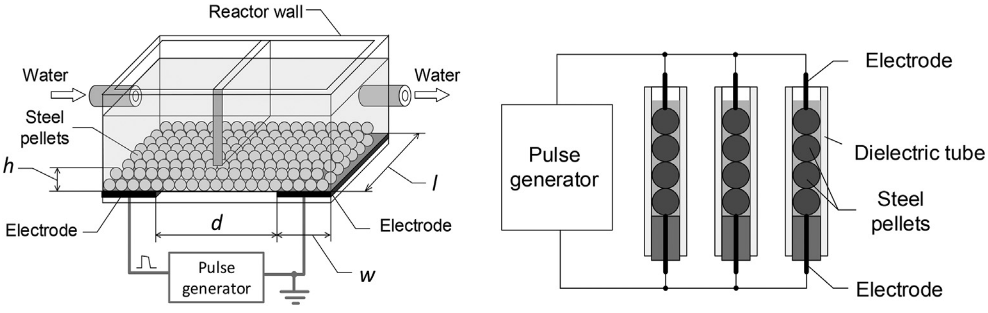
https://doi.org/10.1016/j.elstat.2018.10.008
Received 10 May 2018; Received in revised form 8 October 2018; Accepted 10 October 2018



(a) (b)

Fig. 1. Rectangular bed (a) and vertical tubular (b) reactors.

erosion reactor was studied, and parameters influencing the discharge stability were specified.

2. Materials and methods

Experiments were performed using spherical steel pellets sized from 3.8 to 4.2 mm in diameter obtained from Nazarovo Metallurg-Service Ltd. (Russia). According to manufacturer's specification, steel contains 0.8–1.2% of carbon, minimum 0.4% of silicon, 0.6–1.2% of manganese, less than 0.05% of sulfur and less than 0.05% of phosphorus. Reactors of two configurations were used: (i) a rectangular 6-L acrylic glass reactor (190 × 300 × 100 mm) with a steel spheres bed at its bottom (Fig. 1a) and (ii) a vertical tubular quartz reactor with metal spheres loaded in columnar form (Fig. 1b). Distilled water with the conductivity of 5 μS cm^{-1} and tap water with the conductivity of 340 μS cm^{-1} were used in the experiments at the starting temperature of 18–20 °C.

Voltage to the spheres bed in the rectangular reactor was fed through the pair of 1-mm thin rectangular stainless steel electrodes having width of 20 mm placed horizontally onto the reactor bottom. The electrodes were covered with the spheres bed providing reliable contact. Dimensions of the bed were varied to study the impact of geometry on the stability of spark erosion process. The layer length (*l*) was set to 150 and 300 mm, the interelectrode distance (*d*) was varied from 80 to 150 mm and the layer height (*h*) - from 4 to 25 mm. In all experiments, water was constantly pumped through the reactor with the flow rate of 150 L h^{-1} removing fine particles produced by the discharge. The integral amount of finely dispersed iron produced in the discharge was determined by filtering of 1 L of the output water through a paper filter with 2–3 μm pore size. The samples were dried at 105 °C in vacuum before balance measurement. Relative distribution of the particle size was studied using sedimentation analysis. The samples were collected in 2-L laboratory glass flasks, solid precipitates collected at sequential time intervals in three to five parallel experiments were dried in vacuum and weighted.

Spheres in the vertical tubular reactor used for the single-chain discharge studies were placed into the plastic transparent tubes with inner diameter of 5 mm and wall thickness of 2 mm. The length of spark channels chain was varied by the adjustment of the number of spheres in amount from 1 to 80. The height of the plastic tube was set accordingly from 100 to 400 mm. Electrical connections were arranged by welding wire electrodes to the top and bottom spheres. Before applying a voltage pulse, the tubes were filled with fresh distilled water to provide similar initial conditions in all experiments.

The power to the reactors was supplied using a thyristor-based pulse generator schematically shown in Fig. 2a. The mains AC voltage was converted to DC using a three-phase diode bridge rectifier A1 and an LC-filter consisting of an inductor L1 and a filter capacitor C1. A storage capacitor C_2 was charged to the voltage of 830 V using a thyristor VS_1, and discharged to the reactor via a thyristor VS_2 and a pulse transformer T_1. The latter provided galvanic isolation of the granular bed from the generator. The storage capacitance C_2 was set to 2.0, 4.0 or 6.0 μF, determining the pulse energy. The voltage and current diagrams for a single pulse are given in Fig. 2b. The generator was operated either in a single-pulse or in a repetitive mode with the pulse repetition rate of 100–1000 pulses per second (pps). The temperature of the treated water in the flow-through reactor inevitably grows by 1–5 °C after passing the discharge zone at given glow rate depending on the discharge power applied. In single-pulse experiments no significant change of water temperature was observed.

The top view photographic images of spark discharges in the rectangular reactor were obtained using Canon 60D digital camera (Canon, Japan). Photographs were taken in the single-pulse mode to study the spatial distribution of the discharge luminescence. A monolayer of spheres was used to provide optical transparency. The interelectrode distance was set to 60, 80 and 100 mm at the layer lengths of 150 and 300 mm; forty photographs were taken at each reactor geometry arrangement with the pulse electrical parameters registered for each photograph. A constant storage capacitance C_2 of 4.0 μF was used in all experiments photographed. Distilled water was pumped through the reactor.

Voltage and current waveforms were registered using Tektronix TDS 2014 digital oscilloscope (Tektronix Inc., USA), a compensated voltage divider and a resistive current sensor designed and calibrated by the authors. The discharge power was calculated using equation (1):

$$P = \int_{0}^{T} U(t)I(t)dt \tag{1}$$

where *U(t)* and *I(t)* represent voltage and current waveforms at the discharge reactor, respectively. The integral was found numerically using MathCad software.

Transmission electron micrographs of powders were taken with Jeol JEM-2100 microscope (Japan). The phase composition was studied using X-ray diffraction (XRD) analysis with Shimadzu XRD-7000 diffractometer (Japan). In XRD and TEM experiments, the powder particles were washed in acetone and ethanol straight after the spark erosion to preserve the particle structure and prevent further oxidation during drying.

3. Results and discussion

3.1. Photographic images of spark discharges

At the storage capacitance of 4 μF, the voltage pulse duration was 22 μs, the amplitudes of voltage and current were 300–600 V and 240–400 A respectively dependent on the reactor geometry. Analysis of multiple photographs shows that spark discharges usually align in chains between the electrodes, each chain being a series electrical connection of individual sparks. The discharge spark luminescence does not always propagate completely through the interelectrode distance,