Physicochem. Probl. Miner. Process. 51(1), 2015, 137−150

www.minproc.pwr.wroc.pl/journal/

Physicochemical Problems of Mineral Processing

ISSN 1643-1049 (print)
ISSN 2084-4735 (online)

Received April 29, 2014; reviewed; accepted July 26, 2014

FINITE ELEMENT METHOD BASED SIMULATION OF ELECTRICAL BREAKAGE OF IRON-PHOSPHATE ORE

Seyed Mohammad RAZAVIAN, Bahram REZAI*, Mehdi IRANNAJAD

* Department of Mining and Metallurgical Engineering, Amirkabir University of Technology, Tehran, Iran, rezai@aut.ac.ir; b_rezai@hotmail.com

Abstract: In this study, the effect of minerals composition, particle size and shape as well as electrodes distance from iron-phosphate ore samples, was investigated by using a commercial software. Comparison between high voltage pulses and conventional crushing showed that minerals of interest in the electrical comminution product are better liberated than in the conventional comminution. In order to elucidate and confirm the experimental results, numerical simulation of electrical field distributions/intensity were performed. The software uses the finite element method, a numerical technique for calculating approximate solutions of partial differential equations with known boundary conditions. Magnetite, apatite and quartz were the basic minerals of iron-phosphate ore components, and the main material property used in the simulations was electrical permittivity. The results showed that the induced electrical field was strongly dependent on the electrical properties of minerals, the feed particle size and the location of the magnetite mineral (due to higher permittivity) in the ore. The angle of particle contact surface with high voltage electrode was an important factor in the intensity of electrical field. Smaller contact angle resulted in higher intensity of the electrical field. Electrical discharge within the material was converted to electrohydraulic discharge within the surrounding water environment by increasing the distance between the high voltage electrode and the material contact surface.

Keywords: *finite element method, numerical simulation, electrical breakage, iron-phosphate ore, COMSOL Multiphysics*

Introduction

The term high voltage usually means electrical energy at voltages high enough to inflict harm or death upon living organisms. Equipment and conductors that carry high voltage warrant particular safety requirements and procedures. In certain industries, high voltage means voltage above a particular threshold. One of the high voltage terms is pulse (or impulse) voltage. High-voltage pulses are used to test electrical equipment and to simulate system-generated over voltages and lightning surges in power distribution systems and lightning-protection equipment. In experimental physics,

http://dx.doi.org/10.5277/ppmp150113

high-voltage pulses are used to generate strong pulsed electrical fields to study processes of electrical breakdown, to produce short bursts of X radiation (10^{-7} to 10^{-6} s), to generate pulsed electron and ion beams, and to provide power supply for spark chambers, image converters, Kerr cells, and charged-particle accelerators (Kuffel et al. 2000). In recent years, usage of high voltage electrical pulses in mineral processing field has been developed. A more efficient technique for rock breaking by high voltage pulses is called electrical disintegration, in which the energy of high voltage pulses is transferred to the rock by electrodes directly contacting the surface of the rock immersed in water. This differs from electrohydraulic disintegration, in which the energy is transferred through the surrounding water in the form of a shock wave impact (Andres 1995). History of research in this field is mainly related to the works done by Andres (1989, 1995, 1996, 2010) and Andres et al. (1999, 2001). His first systematic comparative liberation tests were performed on a sample of apatite–nepheline ore from Kola Peninsula at the Institute of Rare Elements of the Russian Academy of Science in Moscow in 1971. The experimental results indicated higher percentage of the liberated minerals and lower fine particles in electrical comminution in comparison with mechanical comminution (Andres 2010). While some reports demonstrated the effectiveness of mineral liberation by high voltage pulses (Anon 1986; Lastra et al. 2003; Ito et al. 2009; Dal Martello et al. 2012; Dodbiba et al. 2012), some of them demonstrated better mineral recovery or higher concentrate grade as a result of the better mineral liberation. It is expected that if the recovery/grade performance improves the cost of energy, the technology would be economical. However, the application of the high voltage pulse technology to the mineral industry is rather slow because the benefits are not demonstrated sufficiently to justify the perceived risks. One major concern has been the amount of energy consumption used in the electrical breakage process itself. Andres et al. (2001) reported that the consumption of energy per unit volume of the tested ores used for mineral liberation was on average 2–3 times higher than in conventional mechanical comminution. Usov and Tsukerman (2006) pointed out that there is a possibility to use the electrical pulse method of destruction for reduction of energy consumption but this possibility is limited. Combined application of electrical pulse destruction, electrical discharge weakening and traditional mechanical methods of destruction may give an option of reducing energy consumption for mineral processing. The most comprehensive investigation was performed on electrical comminution in the past five years with the aim of energy consumption optimization at the Julius Kruttschnitt Mineral Research Center (JKMRC) (Wang et al. 2011, 2012a, 2012b, 2012c). The research at the JKMRC was conducted in two major areas using high voltage pulses, that is particle pre-weakening and mineral liberation, both focused on improving energy efficiency. The studies showed that the ores treated by high voltage electrical pulses with low specific energy input (a few kWh/Mg) developed cracks and microcracks in the rock, and became weaker than untreated particles. Comparison of Bond work indices showed that the electrical treatment can reduce the energy consumption in downstream grinding processes by up to 24%. Moreover, the research conducted at the JKMRC showed that higher mineral liberation can be achieved using the electrical comminution (Wang et al. 2011).

Numerical simulation is a new approach that can help predict the behavior of systems related to their performance. After simulating the system, its performance is considered in response to changes in different parameters. The importance of simulation becomes evident when changing the parameters is difficult or impossible in virtual or laboratory conditions. Wang et al. (2012a, 2012b) performed numerical simulation of electrical field distribution using a commercial software package, COULOMB 3D, for various six ore-related properties to assist in identifying the major factors affecting electrical comminution performance and elucidating the reasons for the observed trends in the experimental results. They showed that the electrical comminution depends strongly on ore properties. Particles having coarse grained minerals of interest, large feed particle size, conductive minerals embedded within gangues and angular particle shape may enhance the electrical comminution performance. High electrical field intensity is found to occur along the boundaries of two mineral phases with large difference in their permittivity and conductivity. The existence of conductive minerals on the particle surface distorts the field distribution of the entire particle, changing the breakdown path and pattern, in turn, impacting the breakage and liberation results (Wang et al. 2012c).

In this paper, a high voltage electrical pulses crusher (HVEPC) was simulated by a commercial software, COMSOL Multiphysics®. Electricity principles suggest that the locations of breakdown or the paths of streamer are strongly related to the location of high intensity field (Andres 1995; Wang et al. 2012a). The simulated electrical field intensity was therefore used as an indicator of preferential breakdown because the higher value indicated the easier breakdown and inferring better liberation. The effect of such parameters as mineralogical composition, feed particle size and shape, and distance of the HV electrode from ore surface on electrical field distribution/intensity were investigated in detail.

Materials and methods

Materials

The sample used in this study was obtained from the Esfordi iron-phosphate mining complex located in Bafgh, Iran. The particle size distribution of this sample showed that 80% of particles were smaller than 15.5 mm, 17.6% finer than 150 μm, and 8.5% finer than 37 μm. The X-ray diffraction (XRD) and electron probe micro-analyzer (EPMA) analyses results showed that the sample mainly consisted of magnetite, apatite, and quartz with the grade of 30.5%, 15.74%, and 14.27%, respectively.

High voltage electrical pulse crusher (HVEPC)

The electrical treatment of the ores was conducted with HVEPC (high voltage electrical pulse crusher) based on a single stage impulse generator that has been developed at the Iran Mineral Processing Research Center (IMPRC). The 3D schematic diagram of circuits for single-stage impulse generators is shown in Fig.1. The capacitor C is slowly charged from a DC source (HV transformer and diods) until the spark gap breaks down. This spark gap acts as a voltage-limiting and voltage-sensitive switch, which ignition time (time to voltage breakdown) is very short. The control table of the system was equipped with a periodic shutdown system. Thus, by adjusting the frequency of pulse discharge, the required period of time could be easily determined, and then the number of pulses could be obtained.

The crushing chamber consisted of a rod-shaped electrode made of copper. The voltage between the generator and ground electrode made of an iron plate was measured by a probe connected to an oscilloscope. The ground electrode consisted of circular apertures to pass the crushed particles and prevent over-crushing (control sieve). The sample was immersed into water in the chamber between the two electrodes and then a high-voltage pulse was directly discharged to disintegrate the sample.

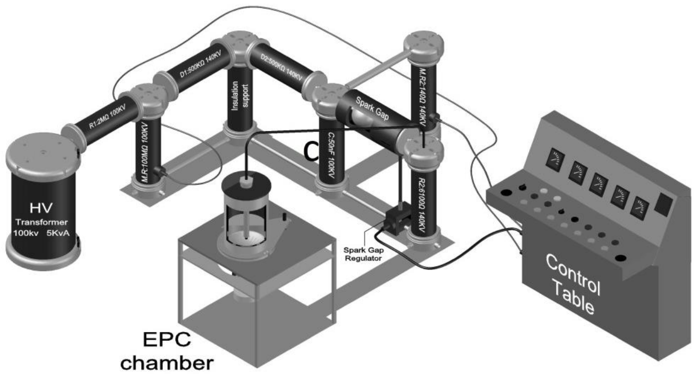


Fig. 1. 3D schematic diagram of high voltage electrical pulses crusher (HVEPC); C: capacitor

Experimental tests

One of the most critical design criteria for mineral processing plants is the choice of the particle size to which the comminution step must reduce the host rock (grind size) to ensure an economic level of liberation. The classical method of measuring the composition of rocks or broken particles is by manual mineral identification, fractionation, and counting under a binocular microscope. In order to investigate of degree of liberated minerals, representative samples of the HVEPC, laboratory jaw crusher and cone crusher products were taken for quantitative mineralogical analysis using the ZEISS Axioplan 2 polarizing optical microscope (reflected and transmitted light). In both methods, thin-smooth and smooth sections were prepared from fractionated samples in sizes of +1-2 mm, +0.7-1 mm, +0.5-0.7 mm, +0.3-0.5 mm, +0.15-0.3 mm, and +0.075-0.15 mm. In each fraction the particles composed of liberated mineral and locked minerals were counted and the ratio of liberated particles and the total number of particles was presented as percentage. Based on the valuable minerals present in the Esfordi iron-phosphate ore, the studies were conducted on apatite and magnetite. Graphical results of these studies are shown in Figs 2 and 3.

As clearly seen from Figs 2 and 3, the ratio of liberated particles to total particles was higher for electrical breakage than for mechanical one for both apatite and magnetite in all fractions. The differences of these results are related to the mechanism of the breakage methods. Furthermore, numerical simulations of electrical field distributions were applied in order to elucidate and confirm the experimental results.

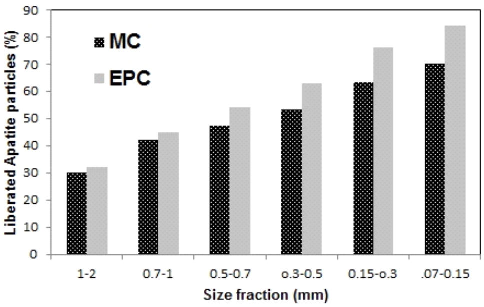


Fig. 2. Comparison of liberated particles of apatite comminuted by mechanical crushing (MC) and electrical pulses crushing (EPC)

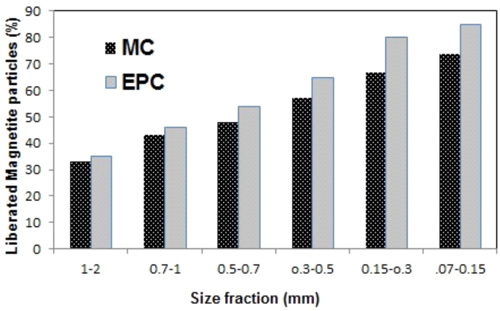


Fig. 3. Comparison of liberated particles of magnetite comminuted by mechanical crushing (MC) and electrical pulses crushing (EPC)

Finite element method simulation

In order to elucidate and confirm the experimental results, numerical simulation of electrical field distributions were performed. The COMSOL Multiphysics® software (its early version is called FEMLAB) was used for this aim. COMSOL Multiphysics® is a simulation software package for various physics and engineering applications, and consists of several add-on products among which the AC/DC Module add-ons were used in this paper. This software is based on the finite element method (FEM), a numerical technique in mathematics for calculating approximate solutions of partial differential equations (PDEs) with known boundary conditions (Reddy 2005). In this paper, major PDEs that define electromagnetic phenomena are Maxwell's equations which could be numerically solved relatively, quickly, and accurately using the software.

The complete set of Maxwell's equations is (Huray 2010):

$$\nabla \times H = J + \frac{\partial D}{\partial t} \tag{1}$$

$$\nabla \cdot B = 0 \tag{2}$$

$$\nabla \times E = -\frac{\partial B}{\partial t} \tag{3}$$

$$\nabla \cdot D = \rho \tag{4}$$

where H is the magnetic field intensity, J current density, D electrical flux density, B magnetic flux density, t time, E electrical field intensity, and ρ is the electrical charge density. There is interdependency between all variables in the equations and therefore, a unique solution. For stationary or quasi-stationary electromagnetic field distribution cases, the displacement current density term, $\frac{\partial D}{\partial t}$, is neglected, which gives the equations as below (Huray 2010):

$$\nabla \times H = J\ . \tag{5}$$

Since the divergence of the curl of any vector field in three dimensions is equal to zero, the following equation is obtained:

$$\nabla \cdot J = \nabla \cdot (\nabla \times H) = 0\ . \tag{6}$$

The macroscopic material properties are defined by the constitutive relations:

$$D = \varepsilon E \tag{7}$$

$$B = \mu H = \mu_r \mu_o H \tag{8}$$

$$J = \sigma E \tag{9}$$

where ε is the permittivity, μ is the magnetic permittivity, μ_r is the relative permittivity, μ_o is the permittivity in free space, and σ is the electrical conductivity.

FEM divides the geometry under study into many small tetrahedral parts, named finite elements, and solves the approximated PDEs for all of these simpler sub-domains. Such subdividing simplifies the inclusion of properties for dissimilar materials and facilitates the modeling of complex geometries. The main steps in setting up the simulations are mentioned below.

Building the geometry

The simulation model consists of four main objects: iron-phosphate ore, high-voltage electrode, zero-voltage electrode, and a spherical domain filled with water. In order to investigate the effects of several parameters that might affect the results, the ore morphology and size as well as the material and the electrodes distance should be flexible. The basic shape of the iron-phosphate ore was assumed to be elliptical (due to initial particle shapes before HV treatment, see Fig. 4) and other shapes obtained by subtraction of cubic shapes from this one as shown in Fig. 5.

Fig. 4. Initial iron-phosphate ore particles shape

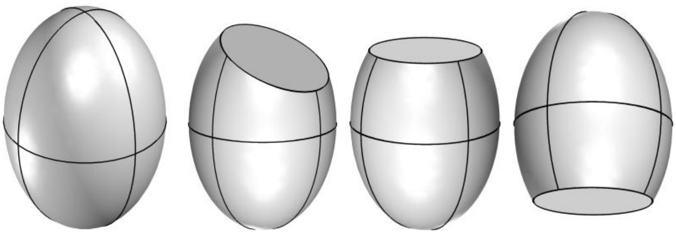
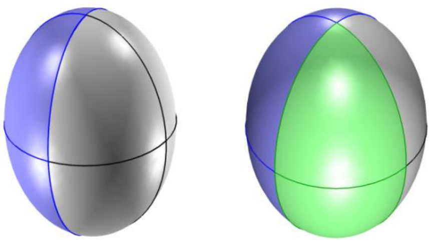


Fig. 5. Four shapes of iron-phosphate ore used in simulation models

Four diameters: 3.35 mm, 6.35 mm, 12.5 mm and 19 mm were used for basic elliptical ores to define four different sizes. In order to verify the effects of material, three different configurations and four compositions were defined. As shown in Fig. 6(a), the ore consisted of two equal parts. Therefore, these three compositions were conceivable: 50% magnetite-50% apatite, 50% magnetite-50% quartz, 50% apatite-50% quartz.



(a) (b)

Fig. 6. Composition of minerals forming iron-phosphate ore (a) when ore consists of two equal parts (b) when ore consists of three parts (final composition)

The ore was made up of 50% magnetite, 25% quartz, 25% apatite (this composition was assumed to be the final composition due to Esfordi iron-phosphate ore mineralogy) as shown in Fig. 6(b).

Four electrodes distances: to match ore diameters, with a gap equals half of the elliptical radius between high-voltage electrode and ore, with a gap equals the radius, and with a gap equals the diameter, were used. Figure 7 shows a typical model of simulation geometry where iron-phosphate ore consists of 50% magnetite-25% quartz-25% apatite and electrode distance matches the diameter of elliptic.

Assigning materials

The main material property used in the simulations was the electrical permittivity. COMSOL Multiphysics® has a noticeable material database with required properties and users can assign materials to each object, instead of directly assigning the physical properties. However, it is possible to define and change the properties of materials or requirements that might not be provided in the library. Table 1 presents material properties used in simulations.

Table 1. Electrical permittivity of compounds used in simulations (Telford et al. 1990)

Material	Electrical permittivity
Water	80.36
Quartz	4.20
Magnetite	81.00
Apatite	7.40

Defining boundary conditions

The voltages of electrodes are the boundary values entered in the software. In the simulations the peak value of voltage pulses were assumed to be 100 kV.

Meshing the geometry

Solving with FEM requires meshing the geometry. By using free tetrahedral option in Mesh entity of defined models, an appropriate mesh will be fitted to the geometry. Figure 8 shows the typical geometry defined in pervious parts with an appropriate mesh.

Solving the model

By using default options of the COMSOL solver, simulation was run, and the results were computed. The arrow colors and sizes as well as surface colors represent the electrical field intensity. The flux always flew from high potential toward low potential. The magnitude of the flux was presented on a color scale from red (high intensity) to blue (low intensity). The distance between the flux represented the concentration of charges such that shorter the distance is, the higher the concentration of charges is.

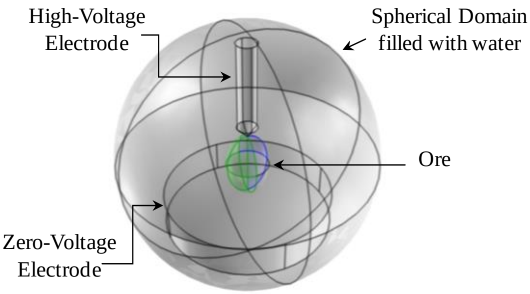


Fig. 7. Typical model of simulation geometry with iron-phosphate ore consists of three parts

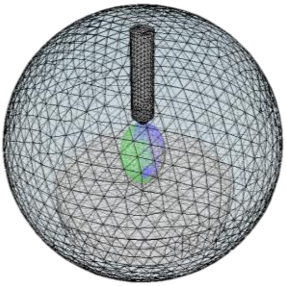


Fig. 8. Meshed typical geometry defined in section (a)

Results and discussion

Effect of minerals composition

The numerical simulation results for particles with different mineralogical compositions are shown in Fig. 9.

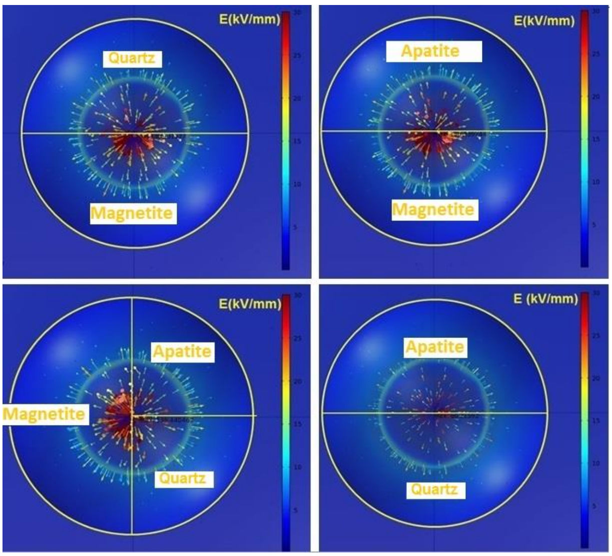


Fig. 9. Numerical simulation of the effect of mineral composition on electrical field intensity and distribution (top view)

In Fig. 9 the particle size is considered to be constant and equal to 12.5 mm. Three particles are considered to have dual composition and the final particle ternary composition. In the binary compound, one fraction contains magnetite, towards which the field intensity is steadily inclined which is due to higher permittivity of magnetite in comparison to the other two compounds. It is also noticeable in the case of the ternary compound. In the binary compounds of apatite and quartz, no clear difference is seen in the field intensity distribution due to proximity of the permittivity values of the two compounds. Another important point visible in all four cases of Fig. 9 is that the focus of field intensity shifted to the boundary of components. This confirms the prominent feature of crushing by electrical pulses in which crushing occurs at the contact surface of minerals. In other words, the electrical crushing is selective and not accidental, unlike the mechanical crushing.

Effect of particle shape

As already mentioned before, four general forms were considered according to the particles shape of Esfordi iron-phosphate ore. The numerical simulation results of these four particle shapes are shown in Fig. 10 (front view). For better comparison, the distance between the HV and zero electrodes in all cases was assumed to be 12.5 mm.

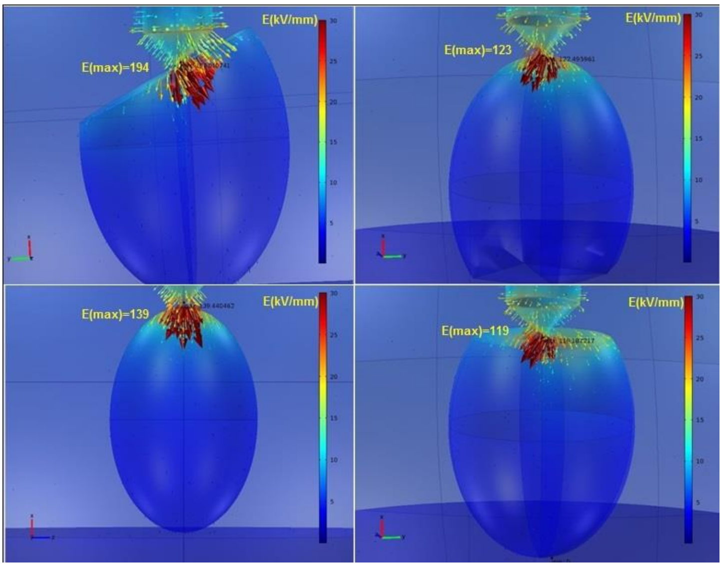


Fig. 10. Numerical simulation of the effect of particle shape on electrical field intensity and distribution (front view)

The results showed that the intensity of the electrical field decreased from full elliptical, incomplete elliptical (diagonal), partial elliptical (from bottom), and truncated elliptical (from above) forms, respectively. This is due to the angle between the HV electrode and contact surface of the material. Wang et al. (2012a) showed that sharpness of the material contact surface increases the intensity of the electrical field. Thus, for incomplete elliptical form (diagonal), contact with surface of the material and mineral is sharper than for other forms, and thus the intensity of the electrical field is maximum. The higher field intensity for the complete ellipse relative to truncated elliptical form (from below) is due to the scale up of the former. The scale up caused the elliptic surface to be smoother for the partial elliptical form (from bottom), relative to complete elliptical one, and thus the field intensity decreased. Minimum field intensity is seen for truncated elliptical form (from above), which has a completely smooth surface.

Effect of feed size

To observe the effect of particle size, four particle sizes of 19, 12.5, 6.35, and 3.35 mm were considered. The numerical simulation results of these four particle sizes are shown in Fig. 11 (front view). As can be seen from Fig. 11, the smaller the particle size the greater intensity of the electrical field. The reason for this behavior is related to the distance between two electrodes. The field intensity increases with the decreasing distance between the electrodes. In fact, particle size is one of the most important parameters in the electrical breakage as mentioned by Wang et al. (2012a). The maximum values of field intensity versus particle size (distance between two electrodes) are shown in Fig. 12. The maximum electrical field intensity decreases with particle size almost exponentially and the equation shown in Fig. 12 can be adequately used to define the relationship between maximum intensity and particle size.

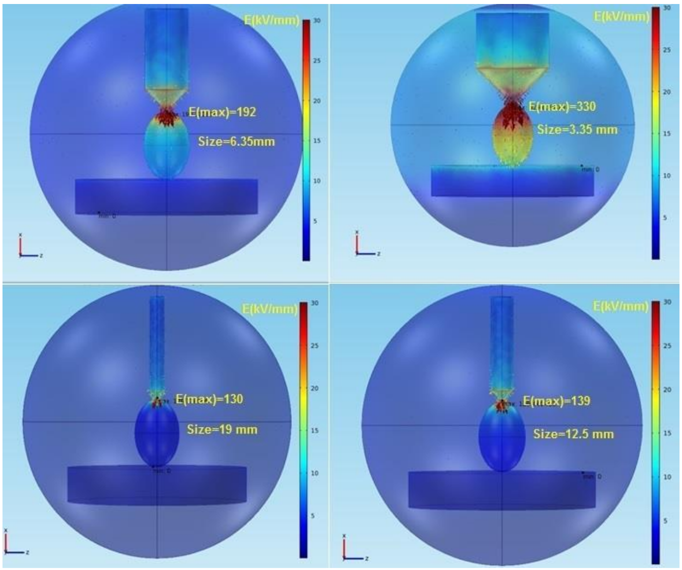


Fig. 11. Numerical simulation of the effect of feed size on electrical field intensity and distribution (front view)

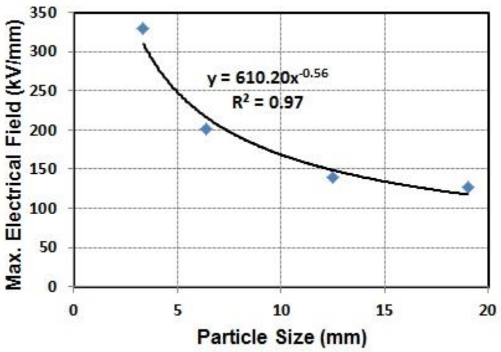


Fig. 12. Relationship between particle size (mm) and maximum electrical field intensity (kV/mm) in HVEPC

Effect of HV electrode distance

The effect of distance between the HV electrode and particle surface is shown (top view) in Fig. 13. In this case the particle size is 12.5 mm and mineralogical compositions are considered constant. Four cases: a quarter of diameter (0.25·D), half of diameter (0.5·D), and the whole diameter are considered for the distance between the HV electrode and particle. Comparison of the results shows that increasing of the distance of HV electrode from the particle surface resulted in a decreased effect of mineralogical composition on electrical field distribution. In other words, the increased distance decreases the length, color, and distribution of field intensity vectors, and for a higher distance, the intensity distribution becomes equal in all directions. Increasing the HV electrode distance from the surface of ore particles causes the effect of water around the electrode to be higher than the effect of minerals

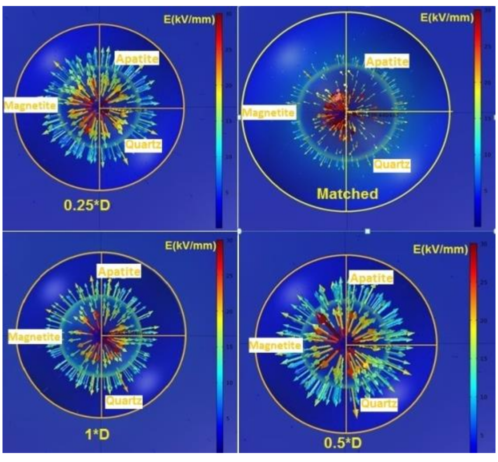


Fig. 13. Numerical simulation of the effect of HV electrode distance from particle surface on electrical field intensity and distribution (top view) (D: largest diameter of elliptical)

which means that the electrical discharge occurs in water instead of the particle. According to previous studies (Andres 1995, Andres et al. 2001), when the electrical discharge occurs in water, it is known as electrohydraulic disintegration. Thus, the increasing the distance of HV electrode from the particle surface increases the probability of electrohydraulic disintegration to occur instead of electrical disintegration.

Conclusions

Numerical simulation results involving iron-phosphate ore showed that the electrical field intensity distribution was highly dependent on electrical properties of the constituent minerals. For the iron-phosphate ore, magnetite, apatite, and quartz were considered in the experiments as the major minerals. Due to the higher permittivity of magnetite, the field intensity was higher for this mineral than for others. In addition, concentration of field intensity in the ternary compound showed that the intensity focus was on the boundary of mineral, which was also an indication of the selectivity feature of electrical crushing.

Electrical field intensity was proportional to the distance between the electrodes. Increasing the electrode distance, while the other factors were constant, would decrease the intensity of electrical field.

The angle of material contact surface with HV electrode was an important factor in the intensity of electrical field. Sharper contact angle induced higher intensity of the electrical field.

Increasing the distance between the HV electrode and material contact surface caused the intensity of the electrical field to decrease and change its distribution. In other words, the electrical disintegration in the material was converted to electrohydraulic disintegration by using the surrounding water environment.

Acknowledgments

The authors would like to acknowledge both Iran Mineral Processing Research Center (IMPRC) and Esfordi iron-phosphate complex for their effective cooperation and substantial input into the research essential for this paper.

References

ANDRES U., 1989, *Parameters of disintegration of rock by electrical pulses*, Powder Technology, 58, 265-269.

ANDRES U., 1995, *Electrical disintegration of rock*, Mineral Processing and Extractive Metallurgy Review, 14, 87-110.

ANDRES U., 1996. *Dielectric separation of minerals,* Journal of Electrostatics, 37, 227-248.

ANDRES U., 2010. *Development and prospects of mineral liberation by electrical pulses,* International Journal of Mineral Processing, 97, 31-38.

ANDRES U., JIRESTIG J., TIMOSHKIN I., 1999. *Liberation of minerals by high voltage electrical pulses*, Powder Technology, 104, 37-49.

ANDRES U., TIMOSHKIN I., SOLOVIEV M., 2001. *Liberation of valuable inclusions in ores and slags by electrical pulses*, Powder Technology, 114, 40-50.

ANON 1986. *New ideas in minerals processing*, World Mining Equipment, 10, 4-19.

CABRI L.J., 2008. *New technology for process mineralogy: Electric Pulse Disaggregation (EPD)*, CNT Mineral Consulting Inc. Ottawa, Canada, http://www.cnt-mc.com.

CABRI L.J., RUDASHEVSKY N.S., RUDASHEVSKY V.N. AND GORKOVETZV.YA., 2008. *Study of native gold from the Luopensulo deposit (Kostomuksha area, Karelia, Russia) using a combination of Electric Pulse Disaggregation (EPD) and Hydroseparation (HS)*, Minerals Engineering, 21, 463-470.

DAL MARTELLO E., BERNARDIS S., LARSEN R.B., TRANELL G., DI SABATINO M., ARNBERG L., 2012. *Electrical fragmentation as a novel rout for the refinement of quartz raw materials for trace mineral impurities*, Powder Technology, 224, 209-216.

DODBIBA G., NAGAI H., WANG L. P., OKAYA K., FUJITA T., 2012. *Leaching of indium from obsolete liquid crystal displays: comparing grinding with electrical disintegration in context of LCA*, Waste Management, 32(10), 1937-1944.

HURAY P. G., 2010. *Maxwell's Equations*, John Wiley & Sons, Inc., Hoboken, New Jersey.

ITOM., OWADA S., NISHIMURA T., OTA T., 2009. *Experimental study of coal liberation: electrical disintegration versus roll- crusher comminution*, International Journal of Mineral Processing, 92, 7-14.

KUFFEL E., ZAENGL W.S., KUFFEL J., 2000. *High Voltage Engineering Fundamentals*, Second edition published by Butterworth-Heinemann, 539.

LASTRA R., CABRI L., WEIBLEN P., 2003. *Comparative Liberation study by image analysis of Merensky Reef samples comminuted by electric- pulse disaggregation and by conventional crusher*, Proceeding of XXII International Mineral Processing Congress, Cape Town, South Africa,1, 251-260.

REDDY J.N., *An Introduction to the Finite Element Method*, 2005. Third Edition, McGraw-Hill Science/Engineering/Math.

TELFORD W.M., GELDART L.P., SHERIFF R.E., 1990. *Applied Geophysics*, second edition, Cambridge University Press, 291.

USOV A.F., TSUKERMAN V.A., 2006. *Electric pulse processes for processing of mineral raw materials: Energy aspect*. In: Proceedings of the XXIII International Mineral Processing Congress, Istanbul, Turkey, 2084-2088.

WANG E., SHI F., MANLAPIG E., 2011. *Pre-weakening of mineral ores by high voltage pulses*, Minerals Engineering, 24, 455-462.

WANG E., SHI F., MANLAPIG E., 2012A. *Factors affecting electrical comminution performance*, Minerals Engineering, 34, 48-54.

WANG E., SHI F., MANLAPIG E., 2012B. *Experimental and numerical studies of selective fragmentation of mineral ores in electrical comminution*, International Journal of Mineral Processing, 112-113, 30-36.

WANG E., SHI F., MANLAPIG E., 2012C. *Mineral liberation by high voltage pulses and conventional comminution with same specific energy levels*, Minerals Engineering, 27-28, 28-36.