Numerical calculations of human-body capacitance in mining tunnel environment

Linfeng Yang*, Hu Liu, Lin Xing, Haizhen Ren, Jingchang Zhang
Zhongyuan University of Technology, Zhengzhou, China
E-mail: laodizhu@yahoo.com.cn

Abstract. The Electrostatic Discharge (ESD) is the main cause of some disasters in the mining environments. The ESD depends mainly on the capacitance and resistance of human-body and the capacitance is very sensitive to the environments. In this paper, the figure capacitance of human-body in mining tunnel environment was studied with numerical simulation. It was found that the human-body capacitance in mining tunnel environment depended mainly on the human figure and the shape of the tunnel, only slightly related to the position. The results implied the ESD model was significant in the mining environments; moreover, the human-body capacitance in mining tunnel environment was also approximately linear to the figure size and its value was around 250 pF, which was coincident with Human Body Model (HBM). The figure capacitance was dependent on the constituent of coal layer as well, the typical value of capacitance was 20% larger than that at free space, which meant the mining tunnel was an electrostatic sensitive environment.

1. Introduction
One of the most common causes of electrostatic accidents is the direct transfer of electrostatic charge through a significant series resistor from the human body or from a charged material to the electrostatic discharge sensitive (ESDS) device. Human-body can be regarded as a mobile conductor, when one touches or is near a charged object or even just walks across a floor in dry air, electrostatic charge will accumulate on the body and the electrostatic voltage can be high to thousands even ten thousands volts. As the local electric field strength is higher than disruptive field intensity threshold, the air dielectric medium will be broken down and instantaneous discharge takes place and gives out electric spark, which possibly results in device damage or electrostatic accident in the environment of inflammable and explosive gases or particulate matter such as gasoline or mash gases.

The mineral environment is a place where the electrostatic accidents are easy and frequent to happen and result in great casualties: firstly, the rapid body movement during working process can generate electrostatic charges on the body; secondly, a relative dry room is formed around the body inside the thick working clothes; thirdly, the mineral tunnel is abundant of firedamp (methane) gases. It is significant to eliminate the potential safety hazard and prevent electrostatic losses.

* To whom any correspondence should be addressed.
2. Model and formulism

Most of static electricity protection standards are based on human-body electrostatic phenomena because human-body electrostatic is the main and frequent cause of electrostatic accidents [1-3]. To eliminate the potential safety hazards, we need to study the human-body discharging process mechanism and to setup human-body discharging models in different environments. The model used to simulate this event is the Human Body Model (HBM). The HBM testing model represents the discharge from the fingertip of a standing individual delivered to the device. It is simulated by a 100 pF capacitor discharged through a switching component and a 1.5 kΩ series resistor into the component. This model, which was derived from the nineteenth century, was developed for investigating explosions of gas mixtures in mines. A typical Human Body Model circuit is presented in figure 1.

![Figure 1. A typical human-body electrostatic discharging model.](image1)

A discharging similar to the HBM event also can occur from a charged conductive object [4, 5], such as a metallic tool, the model circuit can be seen in figure 2. The model is called machine model (MM), as a result of investigating worst-case scenarios of the HBM, the Machine Model simulates a more rapid and severe electrostatic discharge from a charged machine, fixture, or tool. The MM test circuit charges a 200 pF capacitor to a certain voltage and then discharges this capacitor directly into the device being tested through a 500 nH inductor with no series resistor.

![Figure 2. Typical machine model circuit.](image2)

To establish the human-body electrostatic discharging model in coal mineral tunnel environment we need to determine the parameters of human-body resister and figure capacitance in tunnel environment. The resister is easy to measure and is independent of the special environment, but the human figure capacitance is much more complicated. The human-body capacitance is dependent not only on the figure of human-body and the relative position in the mineral tunnel, but also is sensitive to the shape of the coal mineral tunnel and the dielectric constant $\varepsilon$ of the coal layer. So it is a hard task to calculate the human-body figure capacitance precisely.

The simplest way to compute the human body capacitance is to consider the human-body in coal mineral tunnel as a hollow coaxial cylindrical conductors system, by using electrostatic charge image method of a dielectric cylindrical wire. We can replace the mineral tunnel environment equivalence to a parallel cylindrical wire (cylindrical wire electric image of human-body), then calculate the capacitance of the two parallel wires system. But this kind of treatment has three shortcomings: First, the section shape of most coal mineral tunnels are not circle but rectangle instead; second, the human-body is finite, we can’t treat it as a point or a infinite long wire; last, the human-body always is not parallel to the axis of the tunnel.

To calculate the human body figure capacitance in coal mineral environment more accurately, we developed a multi-fold electrical images method in this paper, we treat the section shape of mineral tunnels as rectangle with width $W$ and height $L$, treat the human-body as a cylinder shape with human height $h$ and human waist circumference (radius $r$) standing on ground parallel to side tunnel walls; treat the coal layers as four infinite dielectric matter (dielectric constant $\varepsilon$) with plane surfaces enclose the human-body, by using the electric image method to every one of the four mirror surfaces, four
first-order image human-body will be formed symmetry to the mirror surfaces. Apply the new formed “image human-body” to the four mirror surfaces, every new formed image human-body will then form four higher-order human-body images, and so forth, a plain “woods” of human-body images generated with different orders. The effects of the mineral tunnel environment can be equivalent to a human-body electric images woods conductor system. For the $N$ conductors system, we can obtain the equation groups as follows:

$$
\begin{align*}
V_1 &= P_{11}q_1 + P_{12}q_2 + P_{13}q_3 + \cdots + P_{1N}q_N \\
V_2 &= P_{21}q_1 + P_{22}q_2 + P_{23}q_3 + \cdots + P_{2N}q_N \\
&\vdots \\
V_N &= P_{N1}q_1 + P_{N2}q_2 + P_{N3}q_3 + \cdots + P_{NN}q_N
\end{align*}
$$

Where $p_{ij}$ is the potential coefficient, we can also express $q_i$ with $C_{ij}$ and $V_i$, we can also express $q_i$ with $C_{ii}$ and $V_i$ as follows:

$$
\begin{align*}
q_i &= C_{i1}V_1 + C_{i2}(V_2 - V_1) + C_{i3}(V_3 - V_2) + \cdots + C_{iN}(V_N - V_1) \\
q_i &= C_{i1}(V_1 - V_i) + C_{i2}(V_2 - V_i) + C_{i3}(V_3 - V_i) + \cdots + C_{iN}(V_N - V_i) \\
q_i &= C_{i1}(V_i - V_1) + C_{i2}(V_i - V_2) + C_{i3}(V_i - V_3) + \cdots + C_{iN}(V_i - V_N)
\end{align*}
$$

Where $C_{ij}$ is the capacitance coefficients and $C_{ii}$ ($i\neq j$) is inducing coefficient.

3. Results and discussions

The calculation of human-body figure capacitance can be equivalent to calculate the human-body capacitance of human-body in electric images woods conductor system as illustrated in previous section. To calculate the figure capacitance, we assume that the human-body carries electrostatic charge $q$ Coulomb, the $n$th-order electric image then has image charge as follows:

$$
q_n = \left(\frac{\varepsilon - \varepsilon_0}{\varepsilon}\right)^n q
$$

Where $\varepsilon$ is the dielectric constant of coal layer and $\varepsilon_0$ is the dielectric constant in air.

Figure 3. Human-body capacitance versus human height.

Figure 4. Human-body capacitance versus human position in tunnel.
By calculating the total electrostatic potential of human-body in electric images woods, we can get the human-body figure capacitance in mineral environment. We first calculated the figure capacitance variation with human-body height; the result can be seen in figure 3. The human-body capacitance in mineral environment is also approximately linear to the man height, and the value, around 250 pF, is coincident well to HBM by Kirk [3, 4]. The relationship of human-body capacitance and the position in the tunnel is investigated as seen in figure 4, where d represents the distance between the human-body and the side wall of the tunnel, we can see from the figures that the human-body capacitance is mainly dependent on the human figure and the shape of the tunnel, and it is only slightly related to the position, which means the ESD model is significant in mineral environment.

The human-body capacitance is dependent on the shape of the tunnel. To study how the human-body capacitance change with the tunnel shape, we have calculated the human-body capacitance at different tunnel lengths with the section area keeping constant, the calculated result is seen in figure 5, it is clear that as the tunnel length rises, the human-body capacitance decreases, that is to say, the wider the tunnel, the smaller the figure capacitance. At last, we investigated the figure capacitance variation to the coal dielectric constant $\varepsilon$, the calculated result can be seen in figure 6.

![Figure 5. Human-body capacitance versus tunnel length.](image1)

![Figure 6. Human-body capacitance versus dielectric constant of the coal layer.](image2)

It is very interesting that the human-body capacitance is dependent on the constituent of coal layer as well, which is a peculiar property of human-body capacitance in coal mineral environment. As the dielectric constant $\varepsilon$ approaching zero, the effect of tunnel environment can be neglected, as dielectric constant is nearly infinite, the effect is also small since the contribution of the equal image charge with opposite sign compensate mutually. The maximum peak around $\varepsilon_r = 7$ ($\varepsilon_r = 6.3$ for dry coal layer) explains why the electrostatic accidents occurred frequently in the coal mine environment.

4. Conclusions

The numerical modelling results indicate that the human-body capacitance mainly depends on the human figure and the shape of the tunnel, and it is approximately linear to the human-body figure size, and it is only slightly related to the position. So the human-body figure capacitance is a feature quantity of human-body and miner tunnel shape, which means the ESD model is significant in mineral environment. The human-body capacitance in all tunnels is related to the dielectric constant $\varepsilon$ of the layer and becomes the largest in the coal mineral environment. Therefore, the coal mineral tunnel becomes the potential electrostatic disaster environment.
Acknowledgments
This work was supported by the Natural Science Foundation of China under Grant No. 51077134 and 50977093

References
[1] Avery L R 1987 *Electr. Overstress Electrost. Discharge Symp. Proc. (Orlando)* (NY, Rome: US/ESD Assn) p 186
[2] Steven H V 2009 *ESD: Failure Mechanisms and Models* (New York: Wiley–Interscience)
[3] Renninger R G 1991 *Electr. Overstress Electrost. Discharge Symp. Proc. (Las Vegas)* (Griffiss: US/AFB Reliability Analysis Cent) p 127
[4] Verhaege K, Russ C, Robinson-Hahn D, Farris M, Scanlon J, Lin D, Velti J and Groeseneken G 1996 *Overstress Electrost. Discharge Symp. Proc. (Orlando)* (NY, Rome: US/ESD Assn) p 40
[5] Wada T 1995 *Electr. Overstress Electrost. Discharge Symp. Proc. (Phoenix)* (NY, Rome: US/ESD Assn) p 186