Research Article

Influence of Mine Tunnel Wall Humidity on Electromagnetic Waves Propagation

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High moisture in mine tunnel can cause the change of the permittivity and conductivity of tunnel walls, therefore influence the characteristics of electromagnetic waves propagation. This paper analyzes the mechanism of humidity influencing the permittivity and conductivity and attenuation of electromagnetic waves propagation in the circular tunnel and rectangular tunnel. The study result shows that, in the interest frequency range, the change of permittivity caused by humidity has little effect on propagation attenuation, but the effect on the conductivity change cannot be ignored. When the humidity is greater than a certain value, the attenuation will be increased significantly.

1. Introduction

In China, underground mining is the uppermost form of coal mining. There are a lot of factors having a significant impact on mobile communications in mine tunnels, such as limited spaces, the corner and branch of tunnels, roughness and tilt of tunnel wall, mine dust in tunnels, and obstacles [1]. Mine dust is harmful to workman health. The most common dedusting method is prewetting. Absorbing the moisture, the electrical parameters of tunnel walls will change, thus affect the propagation of electromagnetic waves.

In recent decades, there were many research works on electromagnetic waves propagation in tunnels. Emslie et al. [2] deduced the approximate solution of propagation attenuation in rectangular tunnel of nonideal conductive wall and gave the attenuation expression for the horizontal polarization and vertical polarization in lower transverse electric mode. Sun [3] studied the influence of electrical parameters of tunnel walls on the propagation and proposed the concept of conductivity breakpoint, where the influence of conductivity is minor and can be ignored when the conductivity value is low, and the influence is significant when the conductivity value is bigger than the certain value. Zhao [4] and Wei [5–7] studied the influence of moisture, aerosol droplets, and wet tunnel walls on the electromagnetic waves propagation.

This paper mainly studies the humidity of tunnel walls influencing the permittivity and conductivity and affecting the propagation of electromagnetic waves.

2. Electromagnetic Waves Propagation Model in Tunnels

2.1. Circular Tunnel Model. The attenuation constants of the circular waveguide in different modes are given by [8]

$$\alpha_{0n} \approx 8.686 \frac{\chi_{1n}^2}{k_0^2 a^3} \begin{cases} \operatorname{Re} \left(\frac{1}{\sqrt{\epsilon'_r - 1}} \right) & \text{TE}_{0n} \text{ modes,} \\ \operatorname{Re} \left(\frac{\epsilon'_r}{\sqrt{\epsilon'_r - 1}} \right) & \text{TM}_{0n} \text{ modes,} \end{cases} \quad (1)$$

$$\alpha_{mn}^{\pm} \approx 8.686 \frac{\chi_{m \pm 1, n}^2}{k_0^2 a^3} \operatorname{Re} \left(\frac{\epsilon'_r + 1}{2\sqrt{\epsilon'_r - 1}} \right) \quad \text{EH}_{mn}^{\pm} \text{ modes,}$$

where α is attenuation in dB/m, mn is the order of modes, and χ_{1n} is the n th nonvanishing root of the first-order Bessel function; $\epsilon'_r = k_1^2/k_0^2$ is the relative complex permittivity of the surrounding rock, where $k_1 = \sqrt{\omega^2 \mu_1 \epsilon'_1}$, $k_0 = \sqrt{\omega^2 \mu_0 \epsilon_0}$, $\epsilon'_1 = \epsilon_1 - j\sigma_1/\omega$ is the relatively complex permittivity, ω is the radian frequency, ϵ_1 , μ_1 , and σ_1 are the permittivity, permeability, and conductivity of tunnel walls, respectively,

and ϵ_0 and μ_0 are the permittivity and permeability of the air; a is the radius of the circular tunnel; $\text{Re}(\cdot)$ is the real part of the complex variable.

2.2. Rectangular Tunnels Model. The attenuation constants of rectangular waveguide different modes are given by [2]

$$\begin{aligned}\alpha_{E_h(n_1, n_2)} &= 4.343\lambda^2 \left(\frac{n_1^2 \epsilon_1}{a^3 \sqrt{\epsilon_1 - 1}} + \frac{n_2^2}{b^3 \sqrt{\epsilon_2 - 1}} \right), \\ \alpha_{E_v(n_1, n_2)} &= 4.343\lambda^2 \left(\frac{n_1^2}{a^3 \sqrt{\epsilon_1 - 1}} + \frac{n_2^2 \epsilon_2}{b^3 \sqrt{\epsilon_2 - 1}} \right),\end{aligned}\quad (2)$$

where α is attenuation in dB/m, and (n_1, n_2) is the order of $E_h(n_1, n_2)$ and $E_v(n_1, n_2)$, a and b are the width and height of the rectangular tunnel, respectively, ϵ_1 is the relative permittivity of the two side wall, and ϵ_2 is the relative permittivity of tunnel top and bottom.

If the conductivity is considered, the relative permittivity in formula (2) is replaced by the relatively complex permittivity as follows

$$\begin{aligned}\alpha_{E_h(n_1, n_2)} &= 4.343\lambda^2 \text{Re} \left[\frac{n_1^2 \epsilon'_{r1}}{a^3 \sqrt{\epsilon'_{r1} - 1}} + \frac{n_2^2}{b^3 \sqrt{\epsilon'_{r2} - 1}} \right] - 4.343 \\ &\quad \times \frac{\lambda^3}{2\pi} \text{Im} \left[\frac{n_1^2 \epsilon'^2_{r1}}{a^4 (\epsilon'_{r1} - 1)} + \frac{n_2^2}{b^4 (\epsilon'_{r2} - 1)} \right], \\ \alpha_{E_v(n_1, n_2)} &= 4.343\lambda^2 \text{Re} \left[\frac{n_1^2}{a^3 \sqrt{\epsilon'_{r1} - 1}} + \frac{n_2^2 \epsilon'_{r2}}{b^3 \sqrt{\epsilon'_{r2} - 1}} \right] - 4.343 \\ &\quad \times \frac{\lambda^3}{2\pi} \text{Im} \left[\frac{n_1^2}{a^4 (\epsilon'_{r1} - 1)} + \frac{n_2^2 \epsilon'^2_{r2}}{b^4 (\epsilon'_{r2} - 1)} \right],\end{aligned}\quad (3)$$

where $\epsilon'_r = \epsilon_r - j\sigma/\omega\epsilon_0$.

3. Influence of Humidity on Permittivity

3.1. Permittivity and Humidity of Tunnel Wall. Rock permittivity is relative to water saturation, frequency, and lithology. Figure 1 showed the frequency dispersion characteristics of fine sandstone permittivity measured by Rock Physics Laboratory of China University of Petroleum from 1 kHz to 3 GHz [9], curve 1 for drying rock and curve 2 for 100% saturated rock.

As shown in Figure 1, when $f < 100$ MHz, the permittivity of saturated rock decreases with the frequency, while that of drying rock is almost the stable value of 4. The value of saturated rock is significantly higher than the latter. When $f > 100$ MHz, the permittivity of saturated rock is close to the stable value of 8 and the permittivity of drying rock to the value of 2.5.

3.2. Influence of Permittivity on Electromagnetic Waves Propagation. According to formula (1), propagation attenuation curves of circular tunnels in saturated rock and drying rock are drawn in Figure 2, for tunnel radius is 2.5 m, the conductivity of tunnel walls is 0.01 S/m, the permittivity of drying rock is 2.5, and the permittivity of saturated rock is 8.

FIGURE 1: Frequency dispersion characteristics of fine sandstone permittivity from 1 kHz to 3 GHz.

Obviously, propagation attenuation of saturated rock tunnel is higher than that of drying rock tunnel in TM_{01} mode and EH_{11} mode, but that is contrary in TE_{01} mode. However, the difference of propagation attenuation between both rock tunnels is small compared with the attenuation.

Similarly, propagation attenuation curves of rectangular tunnel of width 4 m and height 2.5 m are shown in Figure 3. It is seen that the difference between both rock tunnels is also small.

3.3. Summary. To sum up, the rock permittivity increases with the water saturation and decreases with the frequency, but tends to a stable value when $f > 100$ MHz. Whether in circular tunnels or rectangular tunnels, the difference of propagation attenuation between saturated rock tunnels and drying rock tunnels is small and negligible.

4. Influence of Humidity on Conductivity

4.1. Conductivity and Rock Moisture Content of Tunnel Wall. Generally, tunnel rock is composed of spherical particles and rock pores and the holes among particles fill with water. The rock moisture content w and the conductivity of rock pore water σ_w will impact on the wet rock conductivity σ as follows [10]:

$$\sigma = \sigma_w \cdot \frac{2w}{3 - w}, \quad (4)$$

where the range of σ_w is from 0.1 S/m to 1 S/m. Then, we can draw the curves of σ changing with w as shown in Figure 4.

It is seen that the rock conductivity increases with the rock moisture content, that is, humidity; moreover, the greater the conductivity of rock pore water is, the more apparent the increase trend of the rock conductivity is.

FIGURE 2: Propagation attenuation curves of circular tunnels in saturated rock and drying rock.

FIGURE 3: Propagation attenuation curves of rectangular tunnels in saturated rock and drying rock.

FIGURE 4: Rock conductivity versus rock moisture content.

4.2. Influence of Humidity on Electromagnetic Waves Propagation. According to formulae (1) and (4), attenuation curves of circular tunnel in different modes are shown in Figure 5, for tunnel radius is 2.5 m, the conductivity of rock pore water $\sigma_w = 0.1$ S/m, and $\sigma_w = 1$ S/m, respectively. In the same way, according to formulae (3) and (4), attenuation curves of rectangular tunnel of width 4 m and height 2.5 m are shown in Figure 6.

It can be seen in Figures 5 and 6 that, when the conductivity of rock pore water is 0.1 S/m, attenuation of different propagation modes has little change with the humidity of tunnel walls; when the conductivity of rock pore

— TE_{01}
 —•— TM_{01}
 EH_{11}

(a) $\sigma_w = 0.1 \text{ S/m}$

— TE_{01}
 —•— TM_{01}
 EH_{11}

(b) $\sigma_w = 1 \text{ S/m}$

FIGURE 5: Attenuation of circular tunnels versus humidity of tunnel walls.

water increases to 1 S/m, as the humidity value changes from 0.1 to 1, attenuation of TM_{01} and EH_{11} mode in circular tunnels increases from about 60 dB/km to 80 dB/km and attenuation of $E_h(1,1)$ mode in rectangular tunnels increases from 8 dB/km to 13 dB/km.

4.3. Summary. As mentioned in [3], the effect of tunnel wall conductivity on electromagnetic wave attenuation is large or small, determined by the conductivity breakpoint.

When the pore water conductivity is low, the conductivity of tunnel walls cannot reach the conductivity breakpoint regardless of the humidity of tunnel walls. So, the effect

— $E_h(1,1)$
 —•— $E_v(1,1)$

(a) $\sigma_w = 0.1 \text{ S/m}$

— $E_h(1,1)$
 —•— $E_v(1,1)$

(b) $\sigma_w = 1 \text{ S/m}$

FIGURE 6: Attenuation of rectangular tunnels versus humidity of tunnel walls.

of humidity on electromagnetic wave propagation is very small. When the pore water conductivity is great enough, the tunnel conductivity will increase markedly with humidity; once the conductivity is greater than the breakpoint, it will cause a great deal of attenuation of electromagnetic waves propagation.

5. Conclusions

Humidity of tunnel walls causes the change of the permittivity and conductivity, therefore influences the propagation of electromagnetic waves. In the circular tunnel of radius 2.5 m and rectangular tunnel of width 4 m and height 2.5 m, at the frequency range of mine mobile communications, the

effect of the permittivity on propagation caused by humidity is negligible, and the effect of the wall conductivity depends on the pore water conductivity. When the conductivity is low, the effect is small and negligible. However, when the conductivity is great enough, the humidity of tunnel walls will cause significant attenuation of electromagnetic waves propagation.

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