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Analysis for relationship of transmembrane potential–pulsed electric field frequency

Li Jiahui, Wei Xinlao, Wang Yonghong, Liu Gongqiang*

College of Electrical & Electronic Engineering, Harbin University of Science and Technology, Harbin, China

ABSTRACT

The paper presents a model of a spherical cell. The transmembrane potential on cell membrane is obtained by solving the Laplace's equation. The frequency dependence of the transmembrane potential in pulsed electric fields is described. The value of transmembrane potential decreases as the frequency of external electric field increases. And there is a range of frequency for the value of transmembrane potential to decrease fast. It is shown that there is a strong relationship between the value of transmembrane potential and frequency components contained in the pulse. With more low-frequency components, the value of transmembrane potential is increasing and thus a better sterilization effect can be obtained. By comparing the frequency components contained in square wave pulse, exponentially decaying pulse, oscillatory pulse and their sterilization effect respectively, the analysis results about the relationship of transmembrane potential-frequency presented in this paper is validated.

Keywords: Bacteria; Electric field analysis; Transmembrane potential; Frequency components

1. Introduction

Pulsed electric field food processing is one of non-thermal food preservation methods. In this method, food is exposed to a pulsed electric field. Transmembrane potential is induced on the cell membrane of bacteria by the pulsed electric field applied. The value of the transmembrane potential increases as the external electric field intensity increases. When electric field intensity exceeds a critical value, cell membrane may breakdown. Consequently, the object of food sterilization is achieved (Xu and Wang, 2005). Comparing to the thermal food processing that is widely used, protein is not damaged, vitamins and volatile flavors are not loss and the sensory and nutritional properties remain.

Assuming that the geometric parameters of bacteria are not affected by frequency and intensity of pulsed electric field, the transmembrane potential depends on the frequency of the electric field and its value varied significantly. For the three types of pulsed electric field mostly used in food processing, the transmembrane potential on cell membrane of bacteria caused by frequency components contained in the pulses are different.

2. Theory

The spherical model of a bacterium is shown in Fig. 1 (Pavlin and Miklavcic, 2003). The inside radius and outside radius of the membrane are denoted by r_i and r_e respectively. The complex conductivity of cytoplasm, cell membrane and extracellular solution are denoted by σ_i^*, σ_{im}^* and σ_e^* respectively. Assuming the extracellular solution, cytoplasm and cell membrane are linear, isotropic, and homogeneous dielectric medium. The electric potential at any point is satisfies the Laplace's equation. The Laplace's equation can be expressed as Eq. (1) in spherical coordinate (Guru and Hiziroglu, 2004)

$$\nabla^2\phi = \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial\phi}{\partial r}\right) + \frac{1}{r^2\ \sin\theta}\frac{\partial}{\partial\theta}\left(\sin\theta\frac{\partial\phi}{\partial\theta}\right) + \frac{1}{r^2\ \sin\theta}\frac{\partial^2\phi}{\partial\varphi^2} = 0 \quad (1)$$

Taking the spherical center as the original point, there is symmetry about φ co-ordinate, that is, solutions depend on r and θ but not on φ. Then Eq. (1) reduces to

* *Corresponding author.*
E-mail address: weixinlao@hrbust.edu.cn (W. Xinlao).
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Nomenclature

r_e	outside radius
r_i	inside radius
Greek symbols	
ε_i	permittivity of cytoplasm
ε_{im}	permittivity of cell membrane
ε_e	permittivity of extracellular solution
σ	conductivity
σ_e^*	complex conductivity of extracellular solution
σ_i^*	complex conductivity of cytoplasm
σ_{im}^*	complex conductivity of cell membrane
ϕ	electric potential
ϕ_i	electric potential in cytoplasm
ϕ_{im}	electric potential in cell membrane
ϕ_e	electric potential in extracellular solution
$\Delta\phi_m$	transmembrane potential of cell membrane
ε	permittivity
σ_i	conductivity of cytoplasm
σ_{im}	conductivity of cell membrane
σ_e	conductivity of extracellular solution

$$\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial\phi}{\partial r}\right)+\frac{1}{r^2\sin\theta}\frac{\partial}{\partial\theta}\left(\sin\theta\frac{\partial\phi}{\partial\theta}\right)=0 \quad (2)$$

By solving for ϕ in a separable form $\phi(r,\theta)=\lambda(r)\Theta(\theta)$ (Sun and Liu, 2000), Eq. (2) becomes

$$\frac{1}{\lambda}\left(r^2\frac{\partial^2\lambda}{\partial r^2}+2r\frac{\partial\lambda}{\partial r}\right)=-\frac{1}{\Theta}\left(\frac{\partial^2\Theta}{\partial\theta^2}+\mathrm{ctg}\ \theta\frac{\partial\Theta}{\partial\theta}\right) \quad (3)$$

The left-hand side of Eq. (3) depends only on r, while the right-hand side depends only on θ. This can only occur when both sides are equal to a constant, denoted by α

$$\frac{1}{\lambda}\left(r^2\frac{\partial^2\lambda}{\partial r^2}+2r\frac{\partial\lambda}{\partial r}\right)=\alpha \quad (4)$$

$$\frac{1}{\Theta}\left(\frac{\partial^2\Theta}{\partial\theta^2}+\mathrm{ctg}\ \theta\frac{\partial\Theta}{\partial\theta}\right)=-\alpha \quad (5)$$

Let $\alpha=n(n+1)$. Eq. (4) then satisfies the Euler equation

$$r^2\frac{d^2\lambda}{d^2r}+2r\frac{d\lambda}{dr}-n(n+1)\lambda=0 \quad (6)$$

Eq. (6) has the solution

$$\lambda=a_1r^n+a_2r^{-(n+1)} \quad (7)$$

In terms of $\alpha=n(n+1)$, Eq. (5) takes the form of

$$\frac{d^2\Theta}{d\theta^2}+\mathrm{ctg}\ \theta\frac{d\Theta}{d\theta}+n(n+1)\Theta=0 \quad (8)$$

Substituting $x=\cos\theta$ and $\Theta=P(x)$ into Eq. (8), it can be written as

$$(1-x^2)\frac{d^2P}{dx^2}-2x\frac{dP}{dx}+n(n+1)P=0 \quad (9)$$

The solution of Eq. (9) is given by the Legendre polynomials $P_n(x)$.

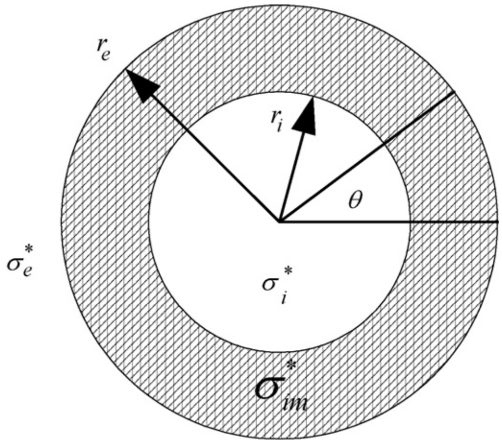

Fig. 1 – The spherical model for bacterium.

Therefore, the general potential solutions associated with the three media are

$$\phi_i=\sum_{n=0}^{\infty}[A_nr^n+B_nr^{-(n+1)}]P_n(\cos\ \theta),\quad 0<r\le r_i \quad (10)$$

$$\phi_{im}=\sum_{n=0}^{\infty}[C_nr^n+D_nr^{-(n+1)}]P_n(\cos\ \theta),\quad r_i<r\le r_e \quad (11)$$

$$\phi_e=\sum_{n=0}^{\infty}[E_nr^n+F_nr^{-(n+1)}]P_n(\cos\ \theta),\quad r>r_e \quad (12)$$

where A_n, B_n, C_n, D_n, E_n, F_n are constants to be determined; $P_n(\cos\theta)$ is Legendre Polynomials; n is any positive integer including 0.

The intracellular potential remains infinite as $r\to 0$

$$\phi_i=\sum_{n=0}^{\infty}A_nr^nP_n(\cos\ \theta) \quad (13)$$

The extracellular potential ϕ_e tends to applied electric field potential as $r\to\infty$

$$\phi_e=-E_0(t)r\ \cos\theta+\sum_{n=0}^{\infty}F_nr^{-(n+1)}P_n(\cos\ \theta) \quad (14)$$

The electric potential and the normal components of current densities at the interface between dielectrics are continuous under time-varying electric field (Vladimir et al., 2001). Therefore, the boundary conditions at each interface can be expressed as follows:

$$\begin{cases}\phi_i(r_i,\theta)=\phi_{im}(r_i,\theta)\\ \sigma_i^*\dfrac{\partial\phi_i}{\partial r}_{|r=r_i}=\sigma_{im}^*\dfrac{\partial\phi_{im}}{\partial r}_{|r=r_i}\end{cases} \quad (15)$$

$$\begin{cases}\phi_{im}(r_e,\theta)=\phi_e(r_e,\theta)\\ \sigma_{im}^*\dfrac{\partial\phi_{im}}{\partial r}_{|r=r_e}=\sigma_e^*\dfrac{\partial\phi_e}{\partial r}_{|r=r_e}\end{cases} \quad (16)$$