Applied Mathematics, Modeling and Computer Simulation
C.-H. Chen et al. (Eds.)

doi:10.3233/ATDE221085

Simulation Analysis of Radio Frequency Heated Tobacco Based on COMSOL Multiphysics

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Abstract. With the further expansion and implementation of similar smoking bans around the world, research on heat-not-burn tobacco is considered to be one of the most important research areas for the transformation and upgrading of tobacco companies. At present, the working principles of the heat-not-burn tobacco heating equipment currently on the market or under research are mainly categorizeded into three types: carbon heating type, resistance heating type, and induction heating type. High-cost issue. Radiofrequency heating is a method of wireless energy transmission, which has the advantages of fast heating speed, high efficiency, non-contact, and so on, and has a wide application prospect in tobacco heating. However, the research and application of radiofrequency heating for tobacco heating is very limited at present. Therefore, it is significant to conduct related research on radiofrequency heating-not-burn tobacco. Based on the finite element simulation software COMSOL Multiphysics, this paper starts with the three-dimensional simulation model of bipolar plate RF heating tobacco and describes the simulation settings in detail. The solid heat transfer module simulates the heating results of the tobacco matrix from the transient and steady-state aspects, analyzes the simulation results, and obtains the temperature rise law of the tobacco matrix under different conditions, which provides a basis for subsequent equipment development. theoretical basis.

Keywords. Comsol Multiphysics, Multiphysics Analysis, Thermal Analysis, Rf-Heating; Heat-Not-Burn Tabacco.

1. Introduction

Since the implementation of the WHO Framework Convention on Tobacco Control in 2003, the use of smoking bans in public places has gradually expanded. To reverse the unfavorable situation of declining sales of traditional tobacco products and achieve sustainable development of the industry, major tobacco companies have increased their research and development efforts on new tobacco products. New tobacco products mainly refer to electronic cigarettes, heat-not-burn tobacco products. Common features of which are no burning, nicotine delivery, and basically no tar[1].

In this situation, the study of heat-not-burn tobacco products has been regarded as a major issue by many tobacco companies related to the long-term development of enterprises. From the perspective of patent layout, among the giant multinational tobacco

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companies, in addition to Reynolds Tobacco and American Smokeless Tobacco, the three major tobacco companies, such as Philip Morris Tobacco, British American Tobacco, and Japan Tobacco, many multinational tobacco giant, have attached more importance in patent layout of HNB tobacco products[2]. Among the related research on heat-not-burn tobacco products, Heating mechanisms innovation and corresponding equipment development are most noteworthy. The world's first heat-not-burn product is IQOS launched by Philips Morris in the United States. At present, the IQOS series of smoking sets have been updated to the fourth generation. The heating mechanism of the heating equipment includes the previous resistance heating and the new series iluma prime launched in 2020. The representative electromagnetic induction heating, Philip Morris International has made significant achievements in the heating method of smoking equipment and the structure of the pod, forming a system production model and technical barriers so that its market share can be steadily improved and guaranteed. The heating mechanism of products launched by domestic tobacco manufacturers in China, such as Sichuan China Tobacco's Kuanzhai Kungfu, Yunnan China Tobacco's VIPN, Guangdong China Tobacco's ING, Hubei China Tobacco's MOK, and Heilongjiang China Tobacco's KOKEN are all resistance heating mechanisms. However there is still a big gap with the international leading products. The improvement of the heating mechanism of the heat-not-burn tobacco product heating equipment has always been the focus of its research and development[3], because the heating mechanism of the heating equipment will directly affect the structure of the equipment and thus affect the user's smoking experience, and heating mechanism Innovation is also the most effective way for domestic manufacturers to break through the patent blockade of large foreign tobacco groups[4], so it is necessary to study the mechanism of radiofrequency heating of heat-not-burn tobacco products.

In terms of radiofrequency heating simulation, Gao Xiaohan et al[5] from Northeast Forestry University simulated the change law of tissue diathermy depth of pork fat tissue under different power radiation of radio frequency antenna, and analyzed the distribution of biological temperature field during radiofrequency ablation; Ge Zihan of Nanjing University of Science and Technology[6] obtained the heating trend of commonly used RF power devices in the frequency domain based on transmission line theory and multi-physics simulation software; Zhang Jianming of Shandong University et al[7] combined electromagnetic theory and heat transfer Combined established a mathematical model of the coupling field of soy food during RF heating and freezing; Zhou Hongxue et al[8] of Northwest A&F University used numerical simulation software to simulate the influence of various parameters on the final heating effect of rice during RF heating . However, there are few studies on the use of RF heating in the field of HNB tobacco products, and the temperature rise of tobacco products under different electric field strengths and dielectric loss properties remains to be studied. Therefore, the influencing factors of RF heating of HNB tobacco products need to be explored urgently.

The experiment intends to design a corresponding RF heating equipment model based on the actual size of the current HNB tobacco products, considering its dielectric loss properties and other physical parameters, and use COMSOL Multiphysics to analyze the spatial electric field gradient of HNB products under RF conditions. After solving the problem, combined with the solid heat transfer solution module, the corresponding temperature field change trend was obtained, and the influence of the dielectric loss characteristics of the material and the electric field strength between the plates on the overall temperature rise of the tobacco matrix was compared and analyzed, to grasp the heat-not-burn tobacco. The product RF heating temperature rise law and other key influencing factors provide a basis for the development of subsequent equipment.

2. Construction and Geometrical Dimensions of Specimens

2.1. Establishment of the Physical Model

This simulation selects the operating frequency of 27.12MHz parallel plate RF heating system for research. A radio frequency heating system generally includes a power amplifier module, an impedance matching module, a signal source module, and an output device. In this example, the output device is a radio frequency device composed of a pair of parallel radiofrequency electrodes. Since this simulation focuses on the temperature rise of heat-not-burn tobacco products, the model is simplified as follows: ① The model only retains the output device and the tobacco substrate in the RF heating system; ② The default voltage distribution on the wall of the electrode plate is uniform, and the same. The connecting part between the axis and the pole plate; ③ the tobacco matrix only retains the part in the heating area of the pole plate. The simplified model is shown in figure 1. The tobacco part is set as a cylinder with a diameter of 8mm and a height of 20mm according to the actual size of the HNB cigarette. The size of the pole plate is set as a cuboid of 22mm*10mm*1mm. The distance between the center point of the pole plate and the axis of the tobacco base is 5.5mm. The plates are distributed symmetrically. In addition to the polar plate and the tobacco base, there is also a 20mm*20mm*30mm cuboid air domain that can wrap all the objects to be simulated.

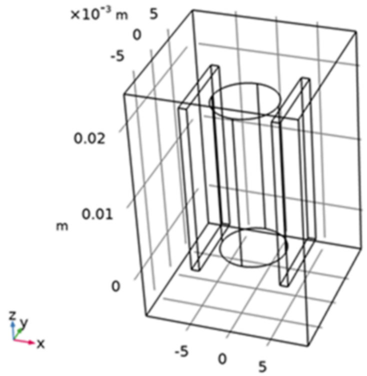


Figure 1. Construction and geometrical dimensions of specimens

2.2. Simulation Method and Meshing

The RF heating problem is a multi-physics coupling problem, which includes the bidirectional coupling of the electromagnetic field and the temperature field. The heated object is irradiated by RF to generate electromagnetic losses due to its dielectric properties so that the object that generates heat acts as a heat source to generate a temperature field in the electromagnetic field[9],the temperature change usually leads to the change of the dielectric properties of the object, and this change will, in turn,affect the electromagnetic field distribution and electromagnetic loss during the RF heating process, thereby affecting the temperature distribution of the heated object. Using COMSOL Multiphysics to solve the temperature rise process of HNB tobacco products under radiofrequency heating. The electric field wave equation is first solved to obtain the electromagnetic field distribution in the RF heating region and the electromagnetic losses in the tobacco matrix. The electromagnetic loss generated in the obtained electromagnetic field is directly coupled to the temperature field in the form of a heat source. Then, the temperature change curve and the spatial electric field distribution map are obtained from the post-processing module and the results are analyzed.

Considering that the calculation of the 3D simulation model is time-consuming, to shorten the simulation time, the grid division should be as regular and neat as possible under the premise of conforming to the characteristics of the model and simulation, which can speed up the convergence speed of the simulation and save memory reduce the calculation time. According to the above meshing principles, this paper uses the free tetrahedral meshing method in the unstructured mesh mode to achieve meshing. Depending on the focus of the research area, the size of the mesh will also be different[10]. In general, a more detailed mesh should be applied to the key research area as much as possible. In this simulation, it refers to the tobacco matrix, and the rest, such as Plates and air domains, the mesh should be simplified appropriately to improve simulation speed. In this paper, the mesh size of the tobacco matrix is extremely refined and the mesh size is customized. The mesh size of the air domain is customized and refined. The polar plate uses a predefined free tetrahedral mesh, with an average cell mass of 0.5946. The meshing is shown in figure 2.

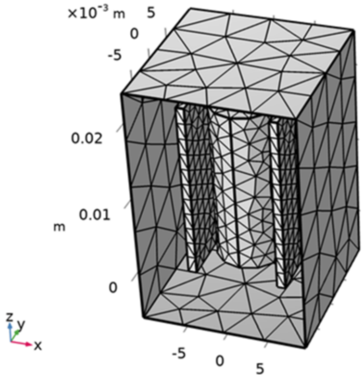


Figure 2. Geometrical dimensions of elements

2.3. Physics Governing Equations

A quasi-static approximation of the RF electric field is a valid assumption because the electromagnetic wave wavelength (approximately 11 meters)is much larger than the spatial dimensions of the RF heating zone[11]. The wavelength of a wave in a non-magnetic homogeneous dielectric material can be expressed as

$$\lambda_m = \lambda \Big/ \sqrt{\varepsilon_m'} \tag{1}$$

In the above equation: $\varepsilon_m{}'$——the dielectric constant of the material (real part). λ——the wavelength of the wave in the air.

Because of the low dielectric constant of the tobacco matrix material, a quasi-static RF electric field can be assumed inside the tobacco matrix.

The quasi-static electric field of the RF heating region can be obtained by solving the Laplace equation:

$$\nabla(\sigma + j2\pi f\varepsilon_0\varepsilon_m)\nabla V = 0 \tag{2}$$

In the above equation:J=$\sqrt{-1}$, V——voltage between the plates (V). ε_0——Vacuum dielectric constant (8.86× 10^{-12} F m^{-1}). σ ——the conductivity of the material (S·m^{-1}). ε_m——the relative permittivity of the material. ε_m=$\varepsilon_m{}'$- j*$\varepsilon_m{}''$. $\varepsilon_m{}''$——loss coefficient of material.

When the tobacco substrate is heated in the RF heating zone, the RF power density obtained by the tobacco substrate is Q(Wm^{-3}):

$$\mathrm{Q} = 2\pi \mathrm{f}\varepsilon_0\varepsilon_m{}''|E|^2 \tag{3}$$

$|E|$ ——Electric field modulus (Vm^{-1})

The radio frequency power density on the tobacco substrate is used as a heat source, and the following is the coupling equation of the quasi-static electromagnetic field and Fourier heat transfer:

$$\frac{\partial T}{\partial t} = \nabla\alpha\nabla T + \frac{Q}{\rho C_p} \tag{4}$$

In the above equation:T——material internal temperature(°C).t——heating time(s). ρ——Material density (kg·m^{-3}). α——material thermal diffusivity (m·s^{-2}). C_p——Material specific heat capacity (J · kg^{-1} · $°C^{-1}$).

According to the actual situation when the user smokes HNB tobacco products, the heat exchange form of the tobacco matrix is convection heat exchange, and its heat flux is:

$$q_0 = h(T_{ext} - T) \tag{5}$$

In the above equation: q_0——Heat flux.h——Convective heat transfer coefficient. T_{ext}——external temperature (293.15K).

2.4. Boundary Conditions and Simulation Parameters

In the actual working process, the voltage on the surface of the electrode plate of the RF heating output device changes, but Gong Chuting proposed in the article that the voltage on the electrode plate only changes by 7%[12], so a uniform electric field input is used on the surface of the left electrode plate and the right plate is grounded.

In this simulation, all the outer edges of the air domain where the heating device is located are scattering boundaries, and there is no incident wave. The expression equation is:

$$n \times (\nabla \times (\boldsymbol{E})) - jkn \times (E \times n) = 0 \tag{6}$$

Convective heat transfer coefficient h=15(W$m^{-1}k^{-1}$)

The parameters of the tobacco matrix material are shown in table 1.

Table 1. Tobacco Matrix Material Parameters

parameter	symbol	unit	value
density	ρ	kg/m³	1000
Thermal Conductivity	k_a	W/(m·K)	238
Relative permittivity (real part)	$\varepsilon_m{}'$	1	2.1
heat capacity	C_p	J/(kg·K)	2520
relative permeability	μ_r	1	1
loss tangent, loss angle	delta	rad	0.001*(T/300[K])

The Main simulation parameters are shown in table 2.

Table 2. Main simulation parameters

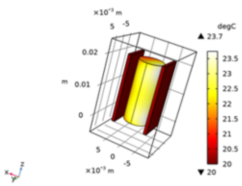
parameter	symbol	unit	value
Electric field strength	E_0	N/C	500000
Heat transfer coefficient	h	W/(m²·K)	238
External temperature	T_{ext}	K	293.15
Absolute pressure	P_A	Pa	1
frequency	f_0	MHz	27.12
Electromagnetic wavelength	I_{da0}	m	11.054

3. Test Results and Discussions

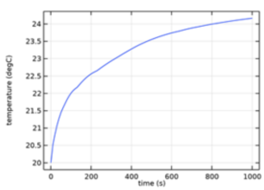
3.1. Transient Simulation Results and Analysis

The frequency of radiofrequency heating is usually 13.56MHz or 27.12MHz, and when it is used in the field of food heating, the voltage of the upper plate is usually between 2000V and 5000V. The frequency domain-transient solver was used to analyze the temperature rise of the tobacco substrate under these frequencies and the upper plate voltage respectively.

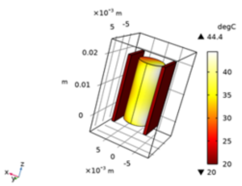
When the frequency is 13.56MHz the electric field strength between the plates is 200KV/m and 500KV/m respectively, the temperature rise of the tobacco matrix is shown in figure 3.



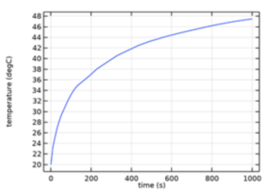
a) 13.56MHz, 200KV/m temperature distribution



b) 13.56MHz, 200KV/m, heating time 600s temperature rise curve



c) 13.56MHz, 500KV/m temperature distribution



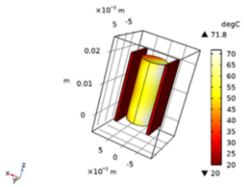
d) 213.56MHz, 500KV/m, heating time 600s temperature rise curve

Figure 3. Temperature rise diagram of tobacco substrate at 13.56MHz frequency

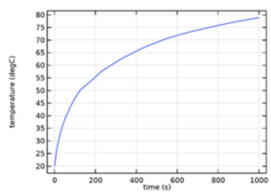
It can be seen from a) and c) that when the tobacco substrate is heated by radio frequency, the temperature of the outer edge will be slightly higher than that of the interior, and the temperature distribution on the tobacco substrate is basically uniform. The temperature of the plate does not change substantially during the heating process.

Comparing b) and d), it can be found that under the same heating frequency and heating time, the maximum temperature of the tobacco matrix when the electric field strength between the plates is 200KV/m is 24°C lower than that when the electric field strength between the plates is 500KV/m. However, the temperature rise trend of the tobacco matrix in the two cases is the same. The temperature in the first half increases rapidly. With the increase of the temperature of the tobacco matrix, the convective heat transfer with the outside world gradually intensifies, so that the temperature rise rate gradually decreases. The temperature tends to stabilize.

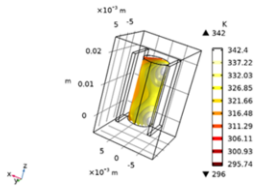
Figure 4 shows the temperature rise when the heating frequency is 27.12MHz and the electric field strength between the plates is 500KV/m.



e) 27.12MHz, 500KV/m temperature distribution



f) 27.12MHz, 500KV/m, heating time 600s temperature rise curve



g) 27.12MHz, 500KV/m, heating time 600s Isotherm diagram

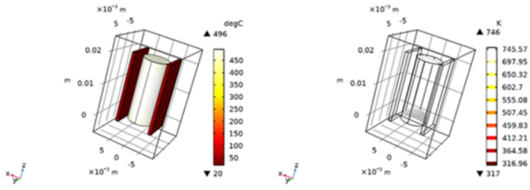
Figure 4. Temperature rise diagram of tobacco substrate at 27.12MHz frequency

Referring to formula (3), when the heating frequency becomes larger, the radiofrequency energy density Q obtained by the tobacco matrix will also increase linearly. It can be seen from f) and b) that when the heating frequency is 13.56MHz and 27.12MHz, the tobacco matrix will increase. The maximum temperatures of, respectively, are 46.5 °C and 71.8 °C.

It can be seen intuitively from figure 4 that there is a certain degree of energy accumulation at the edges of the top and bottom of the tobacco matrix, which causes the temperature at the edges to be higher than those at other positions, but as a whole, the isothermal surface.It is still uniformly distributed inside the tobacco matrix, and the main isothermal surface is continuous and runs through longitudinally, which is consistent with the heating requirements of the tobacco matrix.

3.2. Steady-State Simulation Results and Analysis

Given the use temperature of HNB tobacco is usually between 250 °C and 350 °C, after the influence of the electric field strength between the plates and the radio frequency heating frequency on the healing process of the tobacco matrix is obtained, it is still necessary to determine the final steady-state of the tobacco matrix. To verify the feasibility of radiofrequency heating technology in the field of heating non-burning tobacco.



d1) 27.12MHz, 500KV/m steady state temperature distribution

d2) 27.12MHz, 500KV/m, steady state isotherm diagram

Figure 5. Steady-state temperature rise diagram of tobacco substrate at 27.12MHz

Referring to figure 5, when the overall temperature of the tobacco substrate reaches a steady-state under radio frequency heating, the maximum temperature on it is 496°C, which can meet the temperature requirements for HNB tobacco use. It can be found from the figure that the temperature on the middle section of the tobacco substrate is in a steady-state.The distribution is very uniform. The temperature at the edges of both ends is slightly higher than the temperature in the middle section. The temperature distribution trend is consistent with the healing process, but the overall temperature distribution is more uniform.

4. Conclusion

Based on the results and discussions presented above, the conclusions are obtained as below:

(1) The frequency of radiofrequency heating and the electric field strength between the plates will significantly affect the temperature rise of the tobacco substrate, and the influence of the electric field strength between the plates is more obvious. Therefore, to ensure that there is no breakdown between the plates, the appropriately increase the plate voltage to increase the temperature rise rate of the tobacco substrate.

(2) During the heating process, the temperature at the edge of the tobacco matrix will be higher than the center temperature, and with the increase of the RF heating frequency and the voltage between the plates, this temperature difference will gradually increase, which may cause the edge temperature during the heating process. Beyond the use temperature range of heat-not-burn tobacco, the temperature distribution can be made more uniform by changing the shape of the tobacco matrix.

(3) At a heating frequency of 27.12MHz and an electric field strength between the plates of 500KV/m, the maximum temperature on the tobacco substrate can reach 496°C in a steady-state and the temperature distribution is uniform. Therefore, it is feasible to apply RF heating to the field of HNB tobacco.

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