Study on heat transfer process of a heat not burn tobacco product flow field

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Abstract. A new-style cigarette works by a battery-powered device heating cut-tobacco to generate an aerosol. This product heats the tobacco at low temperature and produces less harmful and potentially harmful constituents (HPHCs). In this paper, a heat not burn tobacco product has been designed, and the heat transfer process in the cigarette has been studied based on a porous medium theory. Both of viscous resistance and inertia force effect on pressure gradient have been considered using Darcy-Forchheimer model. After numerical simulation the process of gas traversing the cut-tobacco medium, the temperature field distribution has been acquired in the new-style cigarette. The result shows the heating system of the heat not burn tobacco product satisfies the demand of temperature control. The aerosol of the new style cigarette can reduce the yield of tobacco combustion produces.

1. Introduction

A few hundred million people choose to smoke despite warnings from the International Agency for Research on Cancer (IARC) [1] that adverse health effects may arise from smoking, such as human cancer [2,3]. With the continuous advancement of the anti-smoking movement, the Chinese government has been tightening its restrictions on smoking, especially in public places. It is necessary to produce a new style cigarette with less damage to satisfy the smoker. Some smokers are unwilling to sacrifice flavour for reduce tar. Therefore, this has prompted a continuing effort to develop alternative cigarette designs.

Conventional cigarette (c-cigarette) smoking, also known as tobacco smoking producing HPHCs such as carbon monoxide, carbon dioxide, hydrogen, particulate matter, nicotine and tar etc. has been causing multifarious problems and arousing concerns. Substantial evidence tended to substantiate that c-cigarette smoking is the primary etiological factor responsible for the progressing of bronchiolitis-interstitial lung disease (RB-ILD), desquamative interstitial pneumonia (DIP) and adult pulmonary Langerhans’ cell histiocytosis (PLCH) [4,5]. For purpose of replacing c-cigarettes as well as minimizing the toxic effect the new style cigarettes such as heat not burn tobacco, electronic cigarette have brought out[6,7]. The traditional cigarettes produce an enormous amount of harmful substances at high temperatures of 350 °C to 600 °C. While the heat not burn tobacco and E-cigarettes are battery-powered devices which heat tobacco or vaporize a liquid solution into aerosol under condition of 250–550 °C. Such products have less nicotine and other combustion products [8]. Not like traditional cigarettes, the new products heat the tobacco or liquid at under 550 °C, result in only 5% of the substances and 14% of the cytotoxicity produced by traditional cigarettes [9]. Compared with other
novel cigarettes, their flavour can better satisfy consumers’ needs and provide them with an authentic tobacco taste. Additionally, due to the condition of heating of liquid of e-cigarette in which chemical reactions could result in the formation of new compounds, chemical composition of aerosol could be different from the composition contained in liquid [10,11]. Uchiyama et al. [12] demonstrated that 70% of examined e-cigarette brands contained or generated carbonyl compounds such as formaldehyde, acetaldehyde, acrolein, crotonaldehyde and methylglyoxal. Therefore, the heat not burn tobacco product attracts people’s attention recently. The heat not burn tobacco products have the following advantages: (1) they are less harmful than traditional cigarettes because they avoid combustion and, therefore, drastically reduce the production of tar and other harmful substances; (2) to a certain extent, they resolve the conflicts between smoking and the ban on smoking in public because they do not produce second-hand smoke, which damages the environment and other people’s health; and (3) since they contain tobacco, they can adapt to and satisfy the consumers’ physical needs, which is the most outstanding feature of the international tobacco industry in recent years [13,14]. However, as novel cigarette in the market work by heating and atomizing the liquid or gel inside a cartridge at under 200 °C, the cut tobacco or tobacco extract cannot release the chemicals into the air at this temperature. Therefore, these products do not taste as good as traditional ones. To reach a suitable temperature for heating, studies should be conducted on the structure and heat transfer process of the invention. In 2014, Philip Morris International Inc. launched IQOS, a heat-not-burn tobacco product that uses electronics to heat specially designed tobacco units to release a nicotine-containing vapour [15]. In comparison, the new cigarette technology in China is still in its infancy. The Zhengzhou Tobacco Research Institute has made progress in studying the feasibility of research and the development of new style cigarettes in terms of heat source, heating parameters, and other factors [16]; however, since the research has been performed for only a short period of time, a lack of depth or final products as well as a low degree of industrialization has be emerged.

The difficulty in designing heat not burn tobacco products lies in controlling the suitable temperature field for the tobacco to release its chemicals at certain temperatures. Therefore, in this study, the structure of a heat not burn tobacco product has been designed, and the numerical simulation has been used to optimised for the product parameters by examining their temperature field. The heat transfer process in a porous media of cut-tobacco has been analysed. This approach will improve the products, then reduce the air pollution from smoking.

2. The structural of heat not burn tobacco product

Figure 1 illustrates the structure of the heat not burn tobacco product, which is made up of five parts: an inner shell, a heating wire, a filter mouthpiece, an outer shell, and a temperature control device. The inner shell stores tobacco units in the form of shreds, granules, or fragments. Eight pores of 1-mm diameter are evenly distributed across the bottom of the shell to ensure air permeability during

![Figure 1. Schematic of a new-style cigarette](image)

Inhalation. The heating wires are kept at a temperature of around 400, as studies show that cracking at below 500 produces fewer harmful substances [17]. The temperature is regulated by the temperature control device with an error of +2. The outer shell functions as a heat preserver, while the filter
mouthpiece reduces the concentration of tar and nicotine in the smoke and cools down the smoke before inhalation.

Figure 2 illustrates the flow of air during inhalation. Air enters the inner shell through the pores on the outer shell. Then, the heating needle transfers heat to the cut tobacco in the inner shell which gives off substances such as alcohols, aldehydes, and ketones as the temperature rises. These substances are mixed with air which enters the cavity through the filter mouthpiece during inhalation.

![Figure 2. Schematic of fluid flow in a new-style cigarette](image)

![Figure 3. The geometric model](image)

3. Physical model and mesh generation
The cylinder shown in Figure 3 is the geometric model of the flow field of a new-style cigarette. The center contains heating wires; between the wires and the interior wall of the chamber is cut-tobacco. The cylinder has a radius of 45 mm, a wall thickness of 5 mm, a length of 240 mm and a wick of 8 mm diameter. As the space between the interior wall and the wick is filled with cut-tobacco, air passes through from one side and takes away the heat of the wick in a laminar flow. During simulation, the following assumptions were made: 1) the porous medium was even and isotropic, 2) the porosity, specific heat capacity, density, and heat transfer coefficient were constant, and 3) natural convection and radiation were ignored.

The equations for the flow and heat transfer control of the above model are as following equations [18, 19]:

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0 \tag{1}
\]

\[
\frac{\partial}{\partial t} (\rho \mathbf{v}) + \mathbf{v} \cdot \nabla (\rho \mathbf{v}) = -\nabla p + \nu \nabla^2 \mathbf{v} + \rho \mathbf{g} + \mathbf{F} \tag{2}
\]

\[
\sigma \frac{\partial T}{\partial t} + \mathbf{v} \cdot \nabla T = \nabla (\alpha \nabla T) \tag{3}
\]

In the equations, \(\mathbf{v}\), \(p\), and \(T\) denote the average velocity, pressure, and temperature of the fluid, respectively. \(\rho\) is the fluid density, \(\nu\) is the kinematic viscosity, \(\mathbf{g}\) is the gravity acceleration, \(\sigma\) is the
heat capacity of the solid matrix and fluid in the porous medium, α is the thermal diffusivity, and F is the source term in the momentum equation of the porous medium. According to J. Pascal and H. Pascal [20, 21], for a flow at low Reynolds numbers, the pressure gradient is mainly to overcome the viscous resistance. Darcy’s law is applicable. When the velocity accelerates to a certain level, the fluid inertia increases, therefore, the pressure gradient must overcome not only the viscous resistance but also the inertia; the higher the velocity, the stronger the inertia. The correlation between the pressure gradient and velocity can be expressed by the Darcy–Forchheimer law. Since the materials are isotropic, the source term can be simplified as following [22]:

\[ F = -\left( \frac{\mu}{\alpha} v + C_2 \frac{1}{2} \rho |v|^2 \right) \]  

(4)

In this equation, \( \mu \) is the kinematic viscosity of air and \( \alpha \) is the permeability. C2 is the inertia coefficient, which means the pressure dropper unit length in the flow direction.

The governing equations were discretized by the finite volume method and solved with an unsteady implicit scheme, while the semi-implicit method for pressure-linked equations (SIMPLE) algorithm was used for pressure-velocity coupling. The temperature of the wick was set at 673.15 K according to the condition of heat –not burn product, and the permeability of the cut tobacco was 0.249 m/d acquired by experiment. As the wall of the cylinder is made of stainless steel, it had a heat transfer coefficient of 15 W/m²K; it was solid and 1 mm thick. The initial temperature and velocity of the air flowing into the model were 295.15 K and 17.5 ml/s, respectively. The physical parameters of cut tobacco in the wick were as follow: the density \( \rho_m = 288.98 \text{ kg/m}^3 \), the specific heat capacity \( C = 794.1252 \text{ J/kg·K} \), and the heat transfer coefficient \( \lambda = 0.08186 \text{ W/m·K} \). Based on the geometric and physical model, the hybrid grids of both the structured and unstructured portions were used for the mesh refinement of the central wick. The total number of meshes was 280,800.

4. Computation results and discussion

4.1. The temperature distribution in a new-style cigarette

Figure 4 displays the transient temperature distribution along the x-axis of the cigarette after 6.5 s of heat transfer. During computation, the volumetric air flow rate was fixed at the standard level of 17.5 ml/s. As shown in Figure 4a, heat from the central heating wires spreads through the cut tobacco and air; during inhalation, heat diffuses faster at the upper part of the cigarette because the air flows upwards and brings the heat with it. At the same time, air enters at a low temperature (295.15 K) and takes away the heat of the surrounding medium as it rises. The closer to the entrance, the more slowly the temperature rises, and the lower the thermal diffusivity. Hence, before the heat is transferred to the wall, the isotherm of the cut tobacco exhibits a V shape. Figure 4b shows the temperature distribution along the x-axis after 5 s of heating. It is evident that the distribution of the temperature field is radially symmetrical. As time passes, heat continues to diffuse from the centre to the surroundings. The comparison reveals that airflow drastically increases heat transfer and leads to a faster increase in the temperature of the cut tobacco; there is a huge difference in the temperature field without or without airflow.

![Figure 4. The temperature distribution of a cigarette at t=6.5s along x axis](image-url)
After 20 s of heating, the heat at the top diffuses to the interior wall, the temperature of which then increases significantly. It passes through the wall and spreads to the exterior. Figure 5a shows the temperature distribution along the x-axis after 55 s of heating. With increasing duration, the temperature of the wall rises gradually, first at the air exit and eventually at the entrance; there is also an increasing heat transfer to the exterior. Figure 5b shows the temperature distribution along the x-axis after 55 s of heating. At this point, the temperature of the wall exceeds the fixed ambient temperature, but the temperature field distribution is still axially symmetrical.

Figures 6 demonstrate the temperature distribution along a vertical axis 0.5 mm from the exterior Wall when heating a new-style cigarettes. As shown in the figure, for this cigarette, the initial temperature of the shell equals the ambient temperature. As time passes, heat from the central wick spreads outwards and the internal temperature of the cut tobacco increases. The temperature increases while the rate of increase is on the decline with increasing of the heating time. The result clarifies that the temperature in the inner shell surface is less than 70°C after 80 seconds heating and suction. It is satisfied the safety requirement of the product.

4.2. Chemical constituent in aerosol of a new-style cigarette
The chemical analyses have been performed on smoke generated with the standard FTC methods. The measurement shows the tar yield from the new-style cigarette being 3mg compared to 11mg from the traditional cigarette. The nicotine release from the new cigarette are 0.2mg which is a quarter of the reference traditional cigarette. The results mean the less HPHCs products of heat not burn cigarette

5. Conclusion
This study designed a structure of a new type of e-cigarette and analyzed its process of heating and internal airflow. The Darcy–Forchheimer model of porous media was used to examine the issues of convective heat transfer inside the cigarette chamber of cut tobacco. The temperature field distribution
in the inner shell of the new style cigarette has been studied considering the suction process. The aerosol of this cigarette has been measured using FTC method. The research results show that: (1) the new style cigarette can acquired the temperature condition of heat but not burn tobacco; (2) the temperature of inner cut tobacco changing with suction process and heating time, finally tends to be steady; (3) the new style cigarette in this paper can reduce the yield of tobacco combustion produces and resulted in a reduction of harmful activity in smokers.

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