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Gas-phase pressure and flow velocity fields inside a burning cigarette during a puff

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ABSTRACT

Heat and mass transfer inside a burning cigarette directly influence the level and chemical composition of its mainstream and sidestream emissions. During a 2-s 35 mL model puffing regime, different thermophysical processes occur inside the burning coal as a result of forced air flow, including rapid temperature rise up to 900 °C and a series of pyrolytic or oxidative reactions leading to the formation of smoke aerosol. Accurate measurements of transient thermophysical parameters such as temperature, pressure and gas velocity are thus an essential step towards understanding the smoke formation. In this study, we have developed micro-sensors that can be accurately inserted at specific locations into a 3R4F research reference cigarette, and used to follow these sensitive and highly dynamic responses as a result of the puffing burn. Both temperature and pressure responses were systematically measured, and in combination with a computational method based on Darcy's Law, we obtained the gas flow velocity of the burning cigarette puffed under a standard machine-smoking protocol. These quantitative data provide unparalleled insights into the complex thermochemical processes responsible for smoke formation inside a burning cigarette.

1. Introduction

The main physicochemical processes responsible for smoke formation inside a burning cigarette were systematically investigated in the 1970s [1–3] and have been reviewed a number of times in recent years [4,5]. There is a need to update this knowledge because modern cigarettes have evolved considerably since these early studies, both through adoption of new materials (e.g., expanded tobacco), and incorporation of new design features (e.g., lower ignition propensity) as a result of regulation [1,2,6]. The main driver behind many of the complex thermophysical and thermochemical processes inside a burning cigarette remains the same, i.e., a puff, either taken by a laboratory smoking machine under model conditions, or by a human smoker under real-world conditions. As a result of a puff being taken, the burning tip of a lit cigarette experiences rapid air influx, which leads to the occurrence of a range of gas-phase and solid-phase processes that have been the subject of extensive research [7,8].

For the above reasons, we have recently developed a micro-array thermocouple technique which measures the gas-phase temperatures inside a burning cigarette during a puff [9–11], one of the most important parameters governing combustion behaviour. The measurements allowed us to model the transient temperature distribution by an empirical distribution equation [9,11], which reflected more closely the real effects of forced convective flow through the burning coal of a packed rod of cut tobacco. The gas-phase temperature is linked to the internal gas viscosity and pressure field within the tobacco rod, and is therefore a key factor controlling heat and mass transfer within a lit cigarette. Detailed knowledge on these processes are essential to understand the complex smoke formation processes [12,13]. To fully characterise the thermophysics of a burning cigarette, it is necessary to examine the gas flow and pressure fields during both smouldering and puffing burn cycles. These thermophysical processes are not uncommon in, for example, some industrial biomass conversion and combustion processes, however, to measure these parameters accurately in a cigarette, on a sub-millimetre scale with 0.1 s of time resolution, presents unique experimental challenges.

In this study, we performed both experimental measurements on internal temperature and pressure values, and deployed computational treatments to derive internal gas flow velocity distributions during a typical bell-shaped 2-s puff of 35 mL volume. Quantitative and systematic measurements of this nature in a burning cigarette have not previously been reported in the

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literature to our knowledge. This work forms a part of the broader research effort to map the main thermophysical parameters inside contemporary burning cigarettes smoked under a range of regulatory relevant smoking conditions [9–11].

2. Experimental

2.1. Computational approach to calculate flow velocity

Under a puff, the gas flow direction inside a burning cigarette is assumed to be perpendicular to the pressure contours and is in the direction of lower pressure areas of the cigarette [14]. Quantitatively, the volumetric flow rate (Q, cm^3 s^{-1}) and pressure differential (ΔP, Pa) across a given length (L, cm) can be further assumed to obey Darcy's Law for Newtonian (viscous) flow:

$$Q = -\frac{1}{\varepsilon} A \frac{\Delta P}{L} \tag{1}$$

In which, A is the area through which the gas flows (cm^2), ε is the impedance of the tobacco rod at the ambient temperature (Pa, s cm^{-2}).

The impedance of a porous body to gas flow (u, cm s^{-1}) is directly proportional to the viscosity (μ, Pa s) of the gas flowing through the body, and the proportionality factor is termed as permeability, k, its unit is Darcy or millidarcy (md) which is a measure of a porous media (i.e., tobacco rod) ability to transmit a fluid, such as a heated aerosol stream:

$$u = -\frac{k}{\mu} \nabla P \tag{2}$$

$$u = \frac{Q}{A} \tag{3}$$

$$\frac{1}{\varepsilon} = \frac{k}{\mu}, \ \mu = k\varepsilon \tag{4}$$

It is often further assumed that the structure of the tobacco rod does not change significantly with temperature—this is not entirely accurate, as the burning tip experiences a range of temperatures and hence the tobacco particles within are subject to a range of thermal degradation conditions. The extent of structural change is however small, especially for the bulk of the burning tip where the burning temperature is below ca. 500 °C [11] hence ε is a function of μ only.

For a horizontally positioned tobacco rod where the flow proceeds within its interior, the flow may be assumed to be rotationally symmetrical during a puff.

Hence for a given cross section of the tobacco rod (with its lighting end on the left, and flow proceeding to the right), the gas flow velocity vector in the axial direction, is represented by u_z (cm s^{-1}) at temperature T (K),

$$u_z = -\frac{k}{\mu} \frac{\partial P}{\partial z} \tag{5}$$

At any location within a cross section, the velocity can be further described by

$$u_r = -\frac{k}{\mu} \frac{\partial P}{\partial r} \tag{6}$$

$$u_\theta = -\frac{1}{r} \frac{k}{\mu} \frac{\partial P}{\partial \theta} = 0 \tag{7}$$

In which the direction of r, θ and z are shown in the Fig. 1.

For a given gas, its viscosity (μ) is an inherent property, which increases significantly with temperature and less so with pressure.

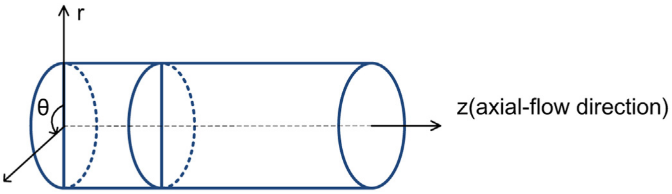

Fig. 1. A schematic of tobacco rod and its axial definition.

When $T < 2000$ K, the viscosity of a gas can be calculated by the Sutherland Law:

$$\mu = \mu_0 \left(T/T_0\right)^{3/2} \left(\frac{T+B}{T_0+B}\right) \tag{8}$$

In which T_0, μ_0 are reference temperature and corresponding viscosity (for example, at an ambient condition). B is a constant depending on the variety of gases within the mixture: $B = 110.4$ K for air. For a burning cigarette, the temperature (T) field during a puff has been determined previously [11]; with the pressure field determined experimentally from this study, the gas flow velocity field can thus be calculated.

2.2. Experimental procedures for pressure measurement

Experimentally, pressure measurements at a specific location within the burning coal were conducted by inserting up to 6 fine quartz sample probes (0.25 mm inner diameter and 1.4 μm wall thickness) at specified locations. The pressure sensors have a pressure range between −2048 and + 2048 Pa (±5%) and the pressure was sampled with an analogue-to-digital converter (24 bit) with up to 24 Hz sample rate (Anhui Precision Optical Instrument, China). The insertion for both thermocouples and pressure sensors followed the same procedure as that used for inserting thermocouples for temperature measurements [9–11]. The positioning was based on a software-controlled x–y sample stage and has an accuracy of 0.1 mm. The location readings started at 23 mm from the lighting end of the cigarette, schematically shown as the grids in Fig. 2. The horizontal distance between the grids was 3 mm apart. For the axial insertion on a cross section, 9 equally spaced grids were made at 0.97 mm apart. Due to axial symmetry of the tobacco rod, only half of the positions were measured. The data sampling rate was 10 Hz at each location for both the pressure and temperature measurements. Note that the positions used to measure pressure covered a similar coal surface area as those used in measuring gas-phase temperature [11], with a number of overlapping positions as the reference temperature points; this allows the calculations as defined by Eqs. (1)–(8) to be conducted.

To estimate an unmeasured pressure value within the pressure field a cubic spline interpolation was numerically performed, which is based on Taylor expansion:

$$\begin{gathered} \frac{\partial P(x)}{\partial x} = \frac{P(x+h) - P(x-h)}{2h} - \frac{h^2}{6} P'''(x) + O(h^3); \\ \frac{\partial P(x)}{\partial x} \approx \frac{P(x+h) - P(x-h)}{2h}; \\ x = r, z; \end{gathered} \tag{9}$$

In which $h = 0.14$, which is the minimum step after the interpolation, $O(h^3)$ is the truncation error. Cubic spline interpolation was also used to interpolate flow velocity between experimental data points along a direction. In this way, 2-D velocity distribution maps were constructed to visualise the transient flow caused by a puff.