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Relationship between wettabilities and chemical compositions of candle soots

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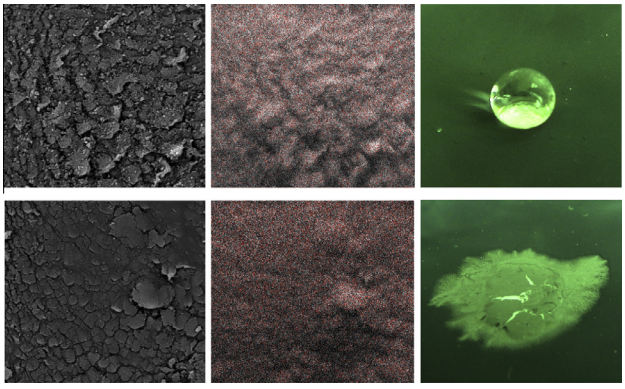
HIGHLIGHTS

- Wettabilities of soot particles formed in different regions of the candle flame are different.
- The flame tip soot particles are small and loose, and contain ash and little organics.
- The flame tip soot particles are hydrophilic and oleophilic.
- The inner flame soot particles, which are dominated by organics, are large and compact.
- The inner flame soot particles are superhydrophobic and superoleophilic.

GRAPHICAL ABSTRACT



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ABSTRACT

The soot particles formed in the inner flame region and the flame tip of a paraffin candle were collected, and their morphologies and chemical compositions have been studied. The wettabilities of the soot particles were also investigated through dispersing the soot particles in water, trichloromethane or glycerin, and dropping these solvents on the surface of the soot particles. The results show that the inner flame soot particles are superhydrophobic and superoleophilic, because they are relatively large particles and aggregated, and are mostly composed of organics. The flame tip emits ultrafine particles, which mainly consist of elemental carbon and ash, and the flame tip soot particles are loose aggregates. So the flame tip soot particles are hydrophilic and oleophilic.

1. Introduction

Candle soot is the black smoke coming from the controlled burning of a candle. Candle soot particles are tiny particles of solid, unburned carbon produced through the incomplete combustion of candles. Candle soots have recently drawn research interest due to their excellent properties, and the soot nanoparticles have shown promise for different applications. For example, Vollmer et al. used candle soot as a template for a transparent robust superamphiphobic coating [1], and Kumar and Bohidar reported that non-functionalized nanoparticles from candle soot have the potential to be used as green fluorescence probes [2]. Khanam et al. presented a simple and novel synthesis route to produce hydroxyl functionalized fluorescent carbon nanoparticles derived from candle soot

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using organic base and surfactant [3]. Unfortunately, soot from candles can also be toxic. Previous studies have shown that the carbonaceous (soot) particulate itself seems to affect human health [4–8].

A candle flame has three distinct regions. The innermost zone, directly above the wick, contains wax vapor that has just been vaporized [9]. The temperature of dark brown/red inner part of the flame is 800 °C. The middle zone, the yellow portion of the flame is an oxygen depleted zone, where partial oxidation has occurred, but insufficient oxygen exists to burn all of the vapors present. The temperature in this region is hotter than the innermost zone, but cooler than the outer zone. The outer zone is the area where the flame is the hottest and the oxidation process is complete, and the temperature of blue/white outer edge of the flame is 1400 °C. The steam is made in the blue part of a candle flame, where the wax burns cleanly with lots of oxygen.

Many studies [10–14] have reported that particle number, particle surface area, and PM fraction emitted by candle combustion were associated with burning mode, ventilation and surface interactions. Pagels et al. studied the physical and chemical properties of particle emissions from candle burning in indoor air, and found that the particle size was related with the candle burning mode [14]. Particles emitted during smouldering upon extinction are dominated by organic matter. It has been reported that black carbon is hydrophobic [15]. However, we found that the wettabilities of the soot particles formed in different regions of the candle flame are different. In this study, the relationship between the wettabilities and the chemical compositions of the soot particles produced through the incomplete combustion of candles was investigated.

2. Experimental

2.1. Materials

Candle wax used in this study were purchased from open shop in Guangzhou, China and used without further treatment.

2.2. Preparation and wettability test of candle soot

Ceramics slide (4 cm × 6 cm) were used as a substrate, and the surface of a ceramics slide was held above the inner flame region or the flame tip of a paraffin candle in an experimental room air without ventilation. Deposition of a soot layer turns the ceramics black after 3 min, and it was used directly to test its wettability through dropping water, trichloromethane or glycerin on its surface. In addition, soot particles were also collected after a soot layer deposited on the ceramics for 4 min. The wettabilities of soot particles were also investigated through dispersing soot particles in water or organic solvents. The soot particles collected were used directly without any treatment.

2.3. Characterization

The X-ray diffraction (XRD) patterns, which were obtained with a MSAL XD-2 diffractometer (λ = 0.15406 nm), were used to determine the crystalline phases. The Fourier transform infrared (FT-IR) spectroscopy was performed with a spectrophotometer (Nicolet 510P). The thermogravimetry–differential thermal analysis (TGA) measurements were carried out on a thermogravimetry/differential thermal analyzer (DTG-60, Shimadzu, Japan) in air condition at a scan rate of 10 °C min^{-1} in the range from room temperature to 900 °C to obtain information on the combustion properties of the soot particles. The morphologies of samples were recorded using a FEI-Tecnai 12 transmission electron microscopy (TEM) and a Hitachi S3400-N scanning electron microscope (SEM). The energy dispersive X-ray spectroscopy (EDX) and the energy dispersive spectroscopy (EDS) measurements of samples were recorded with a Hitachi S3400-N scanning electron microscope. The Brunauer–Emmett–Teller (BET) specific surface area of the samples was determined by nitrogen adsorption–desorption isotherm measurements at 77 K on a nitrogen adsorption apparatus (Micromeritics N5).

3. Results and discussion

3.1. XRD analysis

Fig. 1 shows XRD patterns of the soot particles formed in the inner flame region and the flame tip, and XRD patterns reveal that both these samples have the same phase composition. The carbonaceous flame soot particles obtained were used directly. The Bragg diffraction peaks at about 24° and 42° are the main peaks obtained in the XRD analysis, and these two peaks correspond to hexagonal graphite lattice of carbon nanotubes [6,16]. The intense, broad peak at about 24° is also the characteristic of amorphous nature of material [17,18]. This suggests that there is an indication of large amounts of amorphous carbon material and a small quantity of carbon nanotubes present in both soot particles.

3.2. FT-IR analysis

FT–IR spectra of the soot particles formed in the inner flame region and the flame tip are shown in Fig. 2. The strong, broad band at about 3430 cm^{-1} is due to the stretching vibration of surface hydroxyl group, which is attributed to the adsorbed water, and the band at about 1622 cm^{-1} is attributed to the H_2O bending mode [19]. The band at 2916 cm^{-1} is attributed to the C–H asymmetric stretching vibration of the CH_2, while the bands at 2953 and 2852 cm^{-1} are assigned to the symmetric and asymmetric vibrations of the CH_3 moiety. The bands at 1456 and 1401 cm^{-1} are assigned to the H–C–H symmetric and asymmetric bending of the CH_3, respectively, and the band at 1254 cm^{-1} is attributed the shoulder peak of the methylene groups [20]. For the flame tip soot particles (see Fig. 2a), the bands observed at 1089 and 1043 cm^{-1} probably are due to carboxy groups (C–O) stretching of oxidized carbons [21,22]. For the soot particles formed in the inner flame region (see Fig. 2b), the stronger bands at 2953 and 2852 cm^{-1} reveal that more organics released due to the slightly oxidized wax molecules under the low fraction of oxygen in the inner flame region.

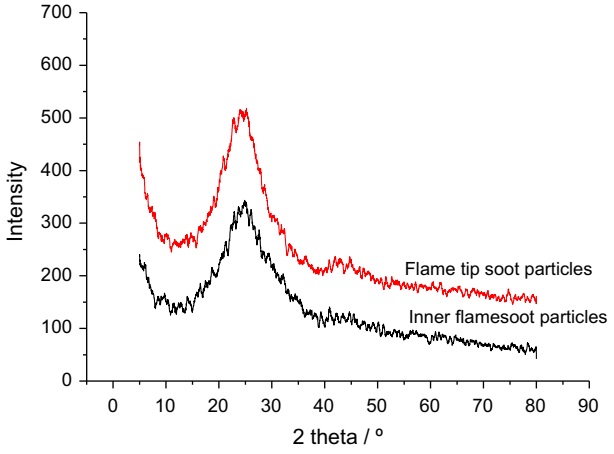

Fig. 1. XRD patterns of the inner flame soot particles and the flame tip soot particles.