



## A study of smoke formation from wood combustion



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### ABSTRACT

Aerosol time of flight mass spectrometry (ATOFMS) was used to analyse the particles emitted during the flaming and smouldering phases of the combustion of samples of hard and soft woods. Eugenol and furfural were also burned and using results from previous work of the authors, they have been shown to be useful proxies for initial wood combustion products. The ratios of elementary carbon to total carbon in the particles were similar for both the woods and for eugenol. The ATOFMS spectra of most of the particles were consistent with the presence of soot precursor constituents along with oxygen containing fragments. Most particle diameters were less than 2.5  $\mu\text{m}$ , with the greatest concentration of <0.12  $\mu\text{m}$ .

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### 1. Introduction

Solid biomass is a renewable fuel that is burned globally and particularly in developing countries. This use declined during the era of fossil fuels but the need for a low carbon energy source has resulted in a revival in its use. The difficulty is that in certain circumstances e.g., in small domestic stoves particularly of the type used in developing countries, biomass can form smoke which is both a health hazard [1] and an environmental problem through its influence on climate change [2]. The health hazards arise from the small particles (<2.5  $\mu\text{m}$ ) present in the smoke which are accompanied by toxic aromatic hydrocarbons such as phenols as well as polyaromatic hydrocarbons and related compounds which are carcinogenic [1]. The climate change problems arise from the same group of pollutants but on a global scale. This is because the carbon particles termed black carbon (BC) together with the organic compounds (OC) are climate forcing agents approximately being responsible for 25% of the total climate change [2]. Black carbon warms the Earth by absorbing heat in the atmosphere and by reducing albedo, the ability to reflect sunlight, when deposited on snow and ice. OC have a negative effect so the balance of the BC/OC influence is very important [2]. In addition to the anthropogenic combustion of biomass, wild fires are also another major source of smoke.

The general mechanism of biomass combustion has been extensively studied over a number of years [3–10], but recently much attention has been directed to the emission of fine particles, that is below 2.5  $\mu\text{m}$ . In previous work, we considered that the cellulose and lignin components can be treated separately in relation to their emissions [4, 5]. Cellulose decomposes largely to CO and H<sub>2</sub> together with other small molecules, whilst lignin decomposes to more complex aromatic products. Using proxy compounds for wood combustion (eugenol and furfural) we previously investigated [11] the mechanism of smoke formation and concluded that the cellulose compounds can form smoke via hydrogen abstraction/carbon addition (HACA), and that the lignin products form smoke through an aromatic species mechanism. In this paper, we report an investigation using aerosol time-of-flight mass spectrometry (ATOFMS, TSI 3800-100) of the size and composition of particles emitted during the combustion of real wood: softwood (pine and spruce) and hardwood (short-rotation coppice willow). Comparisons are made between results obtained for the wood samples and those for the proxies, and between those from two modes of combustion, flaming and smouldering conditions. An additional factor is the release of potassium from wood combustion [6,12,13] which can have a significant influence on the nature of the soot emitted from wood flames. In consequence this is important in determining the ratio of elementary to total carbon (EC/TC) ratio for the particular biomass.

For comparative purposes, additional information on smoke formation from the combustion of eugenol and furfural is presented here.

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We have previously shown that smoke from eugenol can be attributed to the lignin components of biomass [11] and is a major contributor to smoke formation. Furfural is produced largely by the cellulose and has been shown to produce less soot.

## 2. Experimental

Samples of wood chips were burned on a 100 mm diameter stainless steel mesh (5 mm × 5 mm hole) supported 50 mm high by a stand in a vertical 130 mm diameter quartz tube. The role of this tube which was 300 mm high was to contain and steady the flame. A flow of clean combustion air was introduced uniformly through holes at the bottom of the quartz tube at a flow rate of approximately 14 L min<sup>-1</sup>. The combustion products were sampled directly by a glass funnel located over the top of the quartz tube and passed to the ATOFMS inlet by a short (500 mm) Teflon tube. The general arrangement is shown in Fig. 1.

Samples of a softwood (pine/spruce mix) and hardwood (short-rotation coppice willow) chips were used. The former contained 800 ppm potassium and 0.3 wt.% ash and the hardwood contained 4000 ppm potassium and 4 wt.% ash. 5 g samples of chips (about 1 cm long and 0.5 cm diameter) were burned on the wire mesh. The wood was ignited with a butane torch for approximately 25 s and when fully ignited the combustion products were sampled. Separate sets of runs were carried out with the wood either flaming or smouldering conditions. The air flow was kept constant so that combustion takes place with excess air available, overall the ratio of excess air to that of the combustion products was a factor of three. However, the air entrained into the flame zone would be greater during the flaming stage compared with the smouldering phase because of the more rapid combustion.

The ATOFMS (Model 3800-100 from TSI Inc.) provides information on the aerodynamic size and chemical composition of particles in the size range of 100–3000 nm in diameter. Particles smaller than 100 nm can be sampled and analysed (mass spectra can be obtained) with this set-up, but with very low efficiency since the transmission of the aerodynamic lens decreases abruptly for these sizes, and they are too

small to be detected by the sizing laser that triggers the ablation laser. Particles are sized by passing between two laser beams; they are then desorbed and ionised by a Nd:YAG laser. An electric field is applied to the ions, separating them by charge and causing them to pass into two separate mass spectrometers. For each data set about 20 runs were undertaken.

For the experiment with biomass proxies, a diffusion flame supported on a wick burner was used as before [11] to generate particles of soot for comparison purposes. In this case, particle sizes were determined by diluting sampled flame gases and analysing using an electrical mobility instrument (DMS 500, Cambustion Ltd., Cambridge). The range that could be studied by this instrument was 5 to 2500 nm. Samples were collected directly from the flame using a glass probe connected to a Teflon tube. They were then introduced to the DMS via a heated sample line. A dilution factor of 5:1 was achieved using a supply of pure compressed air.

## 3. Experimental results

### 3.1. Composition of particles

Typical positive and negative ion mass spectra of particles from both combustion phases, flaming and smouldering, of both woods are shown in Fig. 2 and representative peaks are listed in Table 1.

In general, there is greater similarity between the spectra of the same combustion phase from different types of woods than between spectra of different phases of the same wood. This arises from the fact that the combustion in the flaming stage is dominated by the combustion of volatile species whilst the smouldering phase is dominated by the combustion of the wood char. There are few peaks with  $m/z$  greater than 100 because the combustion process is greatly diluted by excess air therefore diminishing the amount of organic species produced. In addition fragmentation occurs, some of which is attributed, according to Ferge et al. [14] to the effect of potassium which skews the spectra. Potassium is present in the woods and is released in approximately

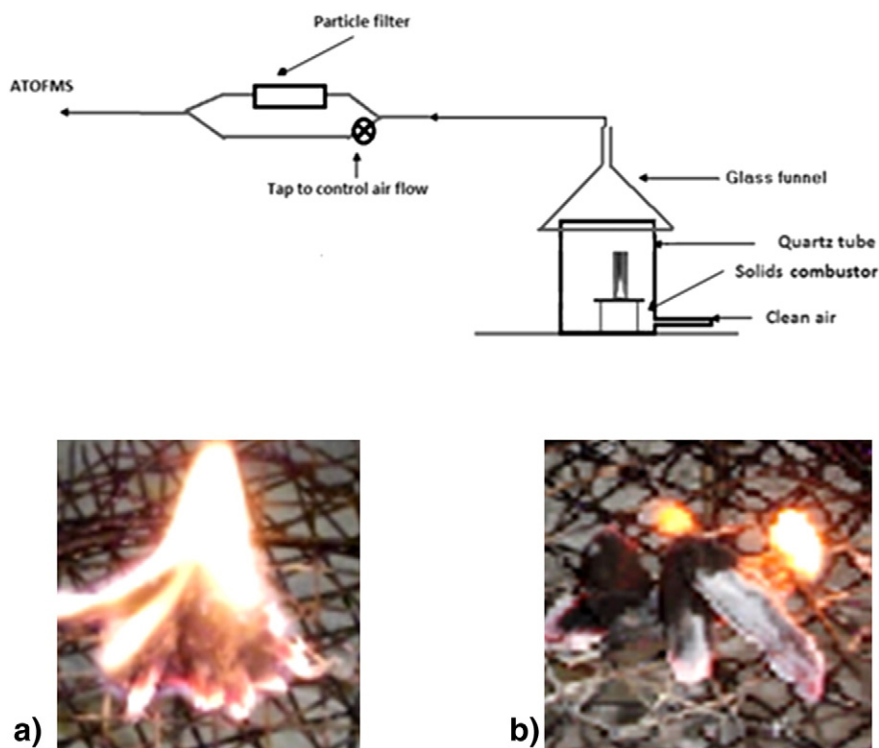


Fig. 1. Schematic of the experimental setup and (a) flaming combustion phase, (b) end of flaming stage/start of smouldering combustion.

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