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The impact of fuel properties on the emissions from the combustion of biomass and other solid fuels in a fixed bed domestic stove

E.J.S. Mitchell [a], A.R. Lea-Langton [a], J.M. Jones [a], A. Williams [a,*], P. Layden [b], R. Johnson [b]

[a] Energy Research Institute, School of Chemical and Process Engineering, University of Leeds, Leeds LS29JT, UK,
[b] Arigna Fuels, Arigna, County Roscommon, Ireland

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ABSTRACT

Experimental results are presented on the emissions from a single combustion chamber stove burning wood, coal and processed fuels. This technique was used to permit comparisons to be made of the influence of different fuel types without it being influenced by the effects of secondary combustion. Measurements were made of CO, NO_x and fine particulates during the major phases of combustion, namely flaming and smouldering. Measurements of the particulates were made in two ways: firstly using a gravimetric total particulate measurement and secondly using a cyclone technique to give $PM_{2.5}$ and PM_{10} size fractions. Smoke emissions from the different fuels were very dependent on the phase of combustion especially for the total particulate results, where flaming phase emissions were much higher than in the smouldering phase. It was found that the particulate emission factors for the wood fuels were dependent on the volatile content whilst the coals followed a different pattern. NO_x was linearly dependent on the fuel-N content for all the fuel types, but the relationship for biomass is different from that for coal. CO emissions were very dependent on the combustion phase.

1. Introduction

A number of countries have introduced energy policies in order to reduce greenhouse gases. In the case of heating applications this has led to an increase in the use of wood burning stoves and boilers particularly in Europe, although coal burning appliances are still widely used in many parts of the world. The use of solid biofuels has been the fastest growing energy source in the UK in the last two decades and a similar situation applies across the EU. In many cases these appliances use a single combustion chamber originally designed for the combustion of coal and often the combustion process is poorly controlled. More recently stoves designed specifically for biomass fuels and employing better fuel preparation have reduced the extent of the emissions. Nevertheless there are still concerns about the health effects particularly from fine particles and NO_x [1–5] as well as from the influence of black carbon and organic compounds on climate change [6,7].

In the UK the Renewable Heat Incentive (RHI) [7] has been promoted for both domestic and commercial application which advocates the use of low carbon technologies including the use of biomass fuels. Similar schemes operate in many parts of Europe; in Ireland a combination of higher prices and policies such as the Greener Homes Scheme has resulted in a greater use of wood for domestic heating. The UK Clean Air Act and RHI [8] place emission limits on small appliances when tested to standard methods (BS PD 6434 and BS EN 303-5). A variety of emissions limits or test standards operate around the world. In the EU there is a proposal to bring in much tighter legislation by 2022 (Eco-design) for solid fuel local space heaters, with particulate emissions and NO_x varying according to fuel type. The emphasis on emissions is currently directed to both fine particulates and NO_x. Many of the particles produced are below 1 μm in diameter which are the most hazardous to health [1]. Wood burning is also associated with high emissions of organics such as polycyclic aromatic hydrocarbons (PAH) which are known to be mutagenic and carcinogenic [2–4]. Consequently a number of research programmes have looked in detail at the emissions from wood-fuelled appliances [3,9–18] and there is also interest in pre-processing the fuels to reduce emissions.

In this paper we have used a fixed grate stove with a single combustion chamber. This type of stove has the advantage of giving information on the emissions directly released from the primary combustion of the fuel enabling the effects of different fuel types to be studied. Thus we have studied a range of fuels, two woods, a torrefied fuel, a peat, a biomass/coal blend and two smokeless fuels. This design is still widely used in many countries for domestic heating. Measurements were made of the particulate and gaseous emissions during a single combustion cycle for a number of fuels used typically in the UK and Ireland in order to obtain insight into the effects of the different phases of combustion, flaming and smouldering, on pollutant formation. A flue gas sample dilution tunnel was

* Corresponding author.

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not used because of the diverse fuels studied and so information was obtained only on the primary products formed.

2. Experimental methods

2.1. Fuels used

A total of eight fuels were studied which are listed in Table 1. They consist of three groups; (1) two woods, these having similar moisture levels to avoid the complications resulting from too many variables, (2) a pre-treated biomass fuel and (3) coal or coal derived fuels, these being included for comparison purposes. Biomass fuels were shredded using a Retsch SM100 cutting mill to a size of <1 mm, and were then milled using a SPEX 6770 cryogenic grinder to achieve a very fine particle size required for analysis. The mineral fuels were milled using a Retsch PM100 ball mill. All samples were sieved to ensure a particle size of 90 μm or less. The wood logs were milled and analysed including the bark.

Proximate analysis on the coal and smokeless fuels was carried out according to BSO ISO 17246. For the biomass fuels, proximate analysis was carried out according to BS EN 14774-3 for moisture, BS EN 15148 for volatile matter and BS EN 14775 for ash. These are the same as for mineral fuels, but the moisture was determined in air rather than nitrogen, and the ashing temperature is 550 °C rather than 815 °C. The 50:50 blended fuel was tested both ways for comparison purposes. Ultimate analysis (CHNS) was carried out on a CE Instruments Flash EA1112. Gross calorific values (GCV) were determined on a weight % dry basis by bomb calorimetry using a Parr 6200 Calorimeter. Cl and P were determined via ion chromatography of the washings following bomb calorimetry. This method is in accordance with Method A of BS EN 15289:2011. The P and Ca values were determined by means of nitric acid digestion and ICP-MS, and K values were determined using atomic absorption spectroscopy (AAS) since it is more accurate than ICP-MS. The data obtained are given in Table 2. VM denotes volatile matter and FC the fixed carbon content.

2.2. Combustion experiments

A fixed bed stove (Waterford Stanley Oisin) was used which meets the current designs to use multiple fuels. The appliance is nominally rated as having a maximum non-boiler thermal output of 5.7 kW and an efficiency of 79% and in these experiments the unit was run at approximately full load. A diagram of the unit and the flue and sampling arrangements are shown in Fig. 1. The internal dimensions of the combustor are 250 × 270 × 190 mm (height × width × depth) with a deflector plate across the top section. The geometry of the combustion chamber was unchanged in all the experiments. There is a single primary air supply under the grate which is manually controlled via a damper. The dimensions of the grate which determines the distribution of the air flow as well as the movement of the fuel particles and ash in the burning bed are shown in Fig. 2. The stove was mounted on an electronic balance and the general arrangement of the test equipment was largely in accordance with BS EN 13240. Each run was started using the stove at room temperature to replicate a cold start.

Sampling was undertaken by means of ports in the flue positioned 1.43 m above the stove as shown in Fig. 1. The insulated flue had an internal diameter of 125 mm. The stove was directly underneath a laboratory extraction system which applied a continuous draught of 12 Pa as required for the nominal heat output test in BS EN 13240.

A weighed batch of fuel which was in the range of 2–3 kg was used for each run, with no re-loading being undertaken; this mass was chosen on the basis of BS13240 and the nominal heat output and efficiency. As far as possible the fuels were placed on the grate in a similar way each time with a uniform level bed layer. The sizes of the fuels are given in Table 1. All of the briquetted fuels were approximately the same size and logs of a similar size were selected but in this case there was a greater variation. There are some small deviations from the strict application of the standard method (such as the diameter of the flue) but in these experiments using a small stove the objective is to compare fuels using combustion of a single batch of fuel. The primary air flow was adjusted on the basis to give 100% excess air for the coal-based fuels and 150% for the biomass fuels as recommended by the manufacturer for this stove. Ignition was undertaken by means of a known mass of firelighters which were arranged in the same position on the grate for each experiment. The early part of the ignition phase is influenced by this process and these results are not included.

Flue gas samples were taken when ignition was complete and combustion established. Their composition was measured using a Testo 340 instrument for O_2, CO_2, CO, NO, NO_2, SO_2 as well as the flue gas temperature. The accuracy of the gas composition measurements was ±5%. Flue gas velocity and flow rate were measured using a Wöhler DC100 computer for pressure measurements and an S-type pitot tube, in accordance with BS EN ISO 16911-1.

The particulate content in the combustion gases was measured in two ways. In the first, PM_{10} and $PM_{2.5}$ were determined using a cyclone set (US EPA Method 201a and BS ISO 25597). Here a sampling probe consisting of cyclones, a pitot tube and a thermocouple is inserted directly into the flue. Flue gas is drawn through the sampling nozzle into the cyclone separators and then through a heated line into a set of impingers to collect water and other condensables, and then to a dry gas metre. The cyclones were mounted externally to the flue at a controlled temperature of 170 °C. As far as possible isokinetic sampling was used but with the low flow rate in the flue (<1.5 m s^{-1}) this was difficult and is not necessary for the relatively small particulate sizes [19]. Sampling was carried out for a period of typically 20 min for each fuel. The filters were stored at 5 °C prior to analysis.

In the second method, total particulate matter (PM_t) was determined using a gravimetric method which required 25 L of sampled gas passed through a Whatman GF/F glass microfibre (0.7 μm) filter paper, with a second one used as a backing filter paper. The gas was taken via a heated line at 120 °C and passed through the filter papers which were in a holder mounted on a furnace at 70 °C. The furnace arrangement permitted the gases to be cooled to this temperature and permitted the condensation

Table 1
Fuels types used in the study.

Fuel no.	Fuel type	Physical description
1	Domestic firewood (A)	Commercially available seasoned mixed hardwood. ~200 mm long; diam. ~70 mm
2	Domestic firewood (B)	Air dried hardwood (silver birch) logs, ~200 mm long; diam. ~70 mm
3	Torrefied wood briquettes	Torrefied spruce wood (bark-free). Briquettes approx. 70 mm diameter. From Andritz AG. Torrefaction temperature approx. 280–295 °C.
4	Peat briquettes	Briquettes of pressed peat. Length ~185 mm diam. ~70 mm
5	Bituminous coal	Premium grade bituminous coal (Poland) supplied in lumps ~100 mm
6	Biomass/coal blend	Briquetted blend of 50% olive stone/50% low sulphur petroleum coke, coal and anthracite. Approx. 80 mm diameter
7	Low smoke fuel	Cosyglo (supplied by Arigna Fuels). Anthracite based commercially available product, 84 × 65 × 35 mm briquettes.
8	Smokeless fuel	Ecobrite (supplied by Arigna Fuels). Anthracite based commercially available product, 50 × 50 × 30 mm briquettes.