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Gas phase potassium release from a single particle of biomass during high temperature combustion

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Abstract

A notable characteristic of solid biomass fuels as compared to coal is their significantly higher potassium content. Potassium influences ash deposition and corrosion mechanisms in furnaces and boilers, the effects of which may differ depending on phase transformations of potassium species in the gas phase and condensed phase. An understanding of how potassium is released from biomass fuels during the combustion process is therefore useful for plant designers and operators assessing means of avoiding or mitigating these potential problems. An experimental method is used to measure release patterns from single particles of biomass fuels using flame emission spectroscopy and a single-particle combustion rig. The experimental arrangement also allowed simultaneous thermal imaging of the combusting particle in order to determine the surface temperature. A model of the single particle combustion is presented. Using experimental data on devolatilisation and burnout times for different sized particles and the measured surface temperature profiles, the thermal and kinetic sub-models are verified. A model for potassium release is described and this is integrated to the single particle combustion model to allow prediction of the temporal patterns of release of gas-phase potassium. The modelled release patterns were compared with those observed. Good agreement between modelled and measured potassium release patterns was attained confirming that the proposed mechanisms affecting potassium release are valid.

Keywords: Biomass; Combustion; Single-particle; Modelling; Potassium

1. Introduction

Combustion of solid biomass fuels, as an alternative to coal in large-scale combustion plant, or in dedicated boilers, introduces various challenges to operators. In particular, certain biomass materials have ash compositions which introduce problems of fouling, slagging and corrosion issues. Biomass fuels contain variable proportions of potassium, a key plant nutrient, and this is one of the more significant components affecting ash behaviour. Potassium is associated with both the organic and inorganic fractions in the biomass [1]. Because of the importance of K-partitioning in combustion systems, various research teams

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have sought to measure and model its behavior [1–5]. Some is released during pyrolysis, possibly entrained in the volatiles, and some of the inorganic potassium evolves as KOH or KCl to the gas phase during combustion temperatures. This partitioning is followed by gas phase reactions and deposition of potassium aerosols in convective sections of the boiler, where corrosive deposits are formed. The potassium that remains in the solid phase impacts on ash behavior and influences both fouling and slagging in the furnace.

Modelling of combustion and predicting ash behavior is essential in boiler design and requires effective sub-models [6] specific to biomass. Woody and herbaceous biomass materials are anisotropic, non-homogeneous and there is a natural variation in physical and chemical characteristics even within samples from the same source. It is therefore important to recognise that any model must be of an idealised version of the actual material. In the case of modelling heat transfer, the particle shape is often idealised to quasi-spherical, even though in most cases biomass particles tend to be more quasi-cylindrical. This allows mathematical models to be simplified to one-dimensional systems such as described by Porteiro et al. [7] and Haseli et al. [8]. Others have adopted two-dimensional models to account for the effects of shape such as that described by Yang et al. [9].

Since the thermal conductivity of biomass is low in relation to particle sizes and heating rates in the relevant applications, accounting for internal heat transfer is an important consideration [10]. The effects of particle size and shape and the associated internal temperature gradients on thermal conversion have been investigated by Lu et al. [11] and illustrated with experimental data on relatively large particles (~11 mm diameter). Internal thermal gradients may be approximated using idealised analytical equations. However, to practically account for the intrinsic thermal effects of combustion reactions, numerical methods are necessary. One approach is to consider the particle as comprising of a series of concentric, discrete layers such that heat flow and mass transfer from the surface to the center and vice-versa can be accounted for. Such an approach has been adopted by Thunman et al. [12] and Porteiro et al. [7]. The approach to single particle combustion modelling described is also applicable to modelling the evolution of inorganic species during the combustion process.

Experimental studies on potassium release from biomass combustion have shown that evolution of potassium to the gas-phase is highly dependent on the particle temperature and higher proportions of potassium are released in the latter stages of the char combustion [2,13–15]. Previous modelling of potassium release during single particle combustion assumed a small fraction of the potassium (<15%) is released at the same rate as pyrolysis, and the volatile inorganic potassium was described by an evaporation model [2]. This paper extends our previous work in modelling the phase transformation of potassium species to the gas phase. The model is derived from, and validated by single particle combustion measurements [16,17]. In this extended model, the prediction of potassium release is closely linked to the prediction of temperature of the combusting particle and the concentration of potassium during the progressing stages of combustion. The model accounts for internal thermal effects and is used as a basis to predict gas-phase potassium release. The results of the model are compared to experimental data including the measured particle surface temperature and the observed potassium release.

Table 1
Composition of selected biomass fuels.

Content	Basis	Units	Pine	Willow
Moisture	a.r.	%wt	8.3	6.0
Ash	dry	%wt	2.0	2.0
Volatile	daf	%wt	82.5	83.6
Char	daf	%wt	17.5	16.4
GCV	dry	MJ kg^{-1}	18.6	19.8
Elemental				
C	daf	%wt	47.4	50.8
H	daf	%wt	5.3	6.0
O	daf	%wt	45.9	42.7
N	daf	%wt	1.3	0.4
K	dry	%wt	0.12	0.21

2. Experimental method

2.1. Biomass fuel samples, characterisation and preparation

Two woody biomass materials are investigated: pine and willow. The pine is representative of the typical "white wood" commonly used in many biomass furnaces. The willow is a UK short rotation coppice energy crop. The fuels were characterised using CEN standard procedures for determining composition as summarised in Table 1. While the speciation of potassium in the solid phase is uncertain, at the temperature of the flame (1800 K) the stable gas-phase species are KCl and KOH [18]. For both samples, chlorine measurements were at the limit of measurement errors (<0.05 %wt). For the purposes of modelling, it was estimated that potassium volatilised predominantly in the form of KOH with around 25% KCl. Individual samples of biomass (~0.5–4 mm in length) were prepared as regular cuboid-shaped particles and the volume, mass and density of each particle were recorded. A separate set of willow particles were prepared with known quantities of potassium by means of doping with a solution of potas-