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Evaluation of the combustion behaviour and ash characteristics of biomass waste derived fuels, pine and coal in a drop tube furnace

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HIGHLIGHTS

- Combustion of five biomass fuels and coal were investigated in a drop tube furnace (DTF).
- Biomass fuels yield burnout values comparable to those of coal.
- Residence time of the particles in the DTF is strongly affected by the particle size.
- Sauter mean or mass median diameters are not appropriate to represent the biomass particle sizes in models.
- Refuse derived fuels, rice husk and straw may promote slag formation.

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ABSTRACT

Currently there is an increasing interest on a new generation of low cost biomass fuels derived from human activities like wood and forestry residues, crop residues and refuse derived fuels (RDF) produced from municipal or industrial solid waste. The main objective of this study is to evaluate the combustion behaviour and ash characteristics of a number of these renewable fuels, namely rice husk, straw, coffee husk and RDF derived from municipal waste. For comparisons purposes, the study also includes a bituminous coal and pine branches. The study was carried out in a drop tube furnace (DTF), where data was obtained for gas temperatures, particle burnout, and carbon, hydrogen and nitrogen release along the reactor for the six solid fuels. The analysis of the experimental data included the use of both a one dimensional (1D) model and the Fluent. The results reveal that biomass fuels yield particle burnout values comparable to those of coal due to a number of factors that have opposite effects, mainly their higher volatile matter, which increases the burnout, and their higher moisture content and larger particle size, which decreases it. According to the 1D model, the residence time of the particles in the DTF is strongly affected by the particle size, but the number of size fractions considered has little influence on the calculated burnout. Moreover, the use of the Sauter mean or mass median diameters is not appropriated to represent the biomass particle sizes in model calculations. Predicted burnout with the 1D model is similar to those predicted by the Fluent. The ash composition of the fuels revealed that RDF might have some corrosion and slagging potential, while the use of rice husk and straw could induce slagging through the formation of low melting temperature ashes.

1. Introduction

Coal is the most used solid fuel for electricity production worldwide. As it is the most abundant fossil solid fuel in the world, it is economically more attractive than any other fuels. However, its use is facing challenges arising mainly from the environmental impact it causes and power production industry is now shifting towards new approaches. As discussed elsewhere [1], the main drivers for this new paradigm are the need to reduce the emissions of greenhouse gases (mainly CO_2), particulate matter and other pollutants like NO_x and SO_x associated to coal combustion.

Possible approaches include technological solutions like oxy-fuel combustion, which allows for achieving a sequestration of CO_2 in gas streams from power plants. However, costs are still a significant barrier for its commercial application [2–4]. Meanwhile, partial substitution of coal by alternative fuels like biomass has gained relevance, as these are CO_2 neutral. Biomass solid fuels under use can be divided in two main groups: a first generation biomass fuels, consisting mainly of purpose-grown energy crops like woody or agricultural crops and a second generation biomass fuels composed of wastes arising from human activities like wood

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Nomenclature

A	external particle surface
A_C	pre-exponential factor of the char combustion
A_V	pre-exponential factor of the devolatilization
c_p	specific heat of the particle
c	physical constant in Eq. (12), $c = 2.5\times 10^{-12}$ kg/(m.s.Pa.K$^{0.75}$)
C_D	drag coefficient
d	thermocouple bead diameter
d_p	particle diameter
E_C	activation energy of the char combustion
E_V	activation energy of the devolatilization
f_h	fraction of heat absorbed
F_s	slagging index
g	acceleration of gravity
h	convective heat transfer coefficient
k	gas thermal conductivity
k_C	kinetic rate of char combustion
k_D	kinetic rate of diffusion
k_V	kinetic rate of devolatilization
m_p	particle mass
n	apparent reaction order
Nu	Nusselt number
p	CO/CO_2 molar ratio
$P_{O_2,s}$	oxygen pressure on the char particle surface
$P_{O_2,\infty}$	oxygen pressure in the combustion chamber
R	universal gas constant
Re	Reynolds number
t	time
T_p	particle temperature
T_{gas}	gas temperature
T_t	thermocouple temperature
T_{wall}	wall temperature
U_{gas}	gas velocity
U_p	particle velocity
V	time dependent volatiles yield
V^*	maximum volatiles yield

Greek symbols

β	release of C, H and N
ε	emissivity
ρ_{gas}	gas density
σ	Stefan–Boltzmann constant, $\sigma = 5.67 \times 10^{-8}$ J/(s m^2 K^4)
τ	particle relaxation time
ϕ	combustion factor
ψ	particle burnout
ω_{ik}	weight fraction of species i in the input solid fuel (i = H, C, N)
ω_{ix}	weight fraction of species i in the sampled char (i = H, C, N)
ω_k	ash weight fraction in the input solid fuel
ω_x	ash weight fraction in the sampled char
h_{fg}	vaporization enthalpy at 373.15 K
HV (char)	heating value of char
Q	Q-factor
$RMSD$	root-mean-square deviation
μ	gas viscosity

and forestry residues, crop residues and refuse derived fuels (RDF) produced from municipal or industrial solid waste [5,6]. The interest on the latter fuels is because they are energetically attractive as their raw materials need no input and they are available local and permanently at little or no cost.

To evaluate the possible application of these fuels to pulverized fuel boilers some work has been done at pilot-scale (e.g., [7–10]) and at laboratory-scale using drop tube furnaces (DTF) (e.g., [11–13]). A number of authors (e.g., [12,13]) have concluded that overall burnout in co-firing processes with coal can be enhanced using secondary fuels with low fuel ratio (fixed carbon/volatile matter). Moreover, there are already available a number of studies on biomass derived from agricultural wastes conducted in DTFs. For instance, Chen et al. [14] have studied agricultural residues typically found in Asian regions like bamboo, rice husk, and Madagascar almond and concluded that high burnout (>95%) is attainable with these materials. Other fuels such as coffee husk and straw have also been investigated, although using different techniques and conditions [15–17], revealing that for both biomass fuels devolatilisation is rather fast. As far as RDF is concerned, published work based also on different laboratory-scale methodologies discloses a similar behaviour to other biomass fuels [18–20].

Gaseous corrosion and ash fouling or slagging problems are of major importance when choosing alternative fuels. Despite the influence of combustion technologies that are used and process specificities like temperature and residence time, fuel composition generally allows for an initial assessment of the major aspects of concern. For example, it is known that chlorine is associated to gaseous and deposit induced corrosion in biomass-fired boilers. Ash-forming species present in mature fuels like coal are mainly minerals (Si, Al, Fe, Mn), while in recently formed fuels like biomass free ionic forms, precipitated salts and organic molecules are expected to be rich in alkali and alkali earth metals (K, Na, Ca, Mg) [21]. These ash-forming species can volatilise to form fly ash, whereas the ash components remaining in the parent particles can be found either in the so-called bottom ashes or in the coarse fly ash fraction. Alkali metals are generally released to a larger extent than the other mentioned species since this release occurs mainly at low boiler temperatures (<873 K) [22]. Problems arise once alkali metals react with silica to form alkali silicates that melt or soften at low temperatures causing slagging, or when the reaction of alkali with sulphur or chlorine to form alkali sulphates and chlorides occurs on the heat transfer surfaces leading to corrosion [23,24]. However literature states the importance of alkali earth metals for the extent and properties of alkali metals released forms. Alkali earth metals decrease the retention of alkali metals on silicates leading to the formation of less adhesive compounds [25,26]. An initial assessment on corrosion, fouling and slagging propensity is usually obtained from standard indexes that reflect the relative abundance of some of these elements, known for being in the origin of such phenomena. Experimental work on ash fouling and slagging potential is quite extensive, mainly for woody biomass, while for the second generation biomass fuels these studies include rice husk and straw [27–30], coffee husk [15] and RDF [7,31,32].

Despite the potential of the second generation biomass fuels, as discussed above, their use in industry is still in its infancy and deeper knowledge of their combustion characteristics is needed, at least for some combustion technologies such as for pulverized fuel boilers. In light of this, the main objective of the present study was to evaluate the combustion behaviour and ash characteristics of a number of these biomass fuels, namely rice husk, straw, coffee husk and RDF. For comparisons purposes, the study also included a United Kingdom bituminous coal and pine branches. The study was carried out in a DTF, where data was obtained for gas temperatures, particle burnout, and carbon, hydrogen and nitrogen release along the reactor for the six solid fuels. The analysis of the experimental data included the use of both a one dimensional (1D) model and the Fluent.