Fuel 134 (2014) 53–62

Contents lists available at ScienceDirect

Fuel

journal homepage: www.elsevier.com/locate/fuel

Char burning kinetics from imaging pyrometry: Particle shape effects

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HIGHLIGHTS

- The effect of particle shapes on pulverized fuel particles was analyzed.
- Theoretical considerations were tested and applied on experimental data.
- The particle shape was found to have an effect on the burning rate of fuel particles.
- Current models should be adapted for non-spherical particles.

ARTICLE INFO

Article history:
Received 13 March 2014
Received in revised form 20 May 2014
Accepted 20 May 2014
Available online 2 June 2014

Keywords:
Char combustion
Biomass
Burning rate
Pyrometry

ABSTRACT

Biomass combustion becomes increasingly important in nowadays energy production. One of the major differences between biomass and coal is the particle shape. Therefore the effect of particle shape variations was calculated to determine the effect of spheroidal or cylindrical particle shapes when determining char burning kinetics of pulverized fuel particles from pyrometric measurements. A model frequently used for char kinetics determination was adapted to spheroidal and cylindrical particles under typical combustion conditions. The impact of the particle shape on the energy balance, which is needed for the determination of kinetics parameters, was calculated for typical particle sizes and length to diameter ratios. As the calculations show, the influence of particle shape effects is not negligible for the determination of biomass char burning parameters by pyrometric measurements. The application of the adapted model on measured data shows, that particle shape effects can be resolved by pyrometric techniques. The results presented indicate that a sound analysis of the particle burning rate should include a three-dimensional particle shape measurement.

1. Introduction

Due to the demand for carbon-neutral fuels, the amount of biomass replacing coal in pulverized fuel boilers is increasing [1]. In pulverized fuel (pf) combustion, the combustion of char (fixed carbon) is the time-determining step. Design of pf-boilers, which is usually supported by CFD-simulations, requires an exact prediction of the char burning rate, both for the determination of spatial heat release and for sufficient burn out.

At least three competing techniques to determine char burning kinetics are known in literature. TGA experiments have been performed on a variety of fuels (coals, raw and torrefied biomass) under air-fired and oxy-fuel conditions [2–4]. In TGA experiments, the temperature is usually kept low enough to assure chemically controlled (Zone-I) combustion conditions, but at low heating rates which are not typical for pf-combustion. Typical heating rates are easily achieved in drop tube reactors (DTR) or entrained flow reactors (EFR), which have been applied to study the combustion and gasification rates of coal and biomass char under air-fired and oxy-fuel conditions [2,5]. In DTRs the fuel particles follow a linear trajectory at a nearly constant velocity, which simplifies the determination of residence times. A common technique to determine the reaction kinetics parameters is sampling of solid combustion residues. These samples are then used to measure the degree of conversion by the so-called ash tracer method [6].

1.1. Optical determination of burning rates: state of the art

Another method to determine the apparent reaction kinetics of char particles in DTRs is two-color pyrometry. This method is based on measuring temperature and diameter of a single burning char particle under well-defined conditions. From these experimental data, the energy balance around the particle is calculated.

Several research groups have deployed ratio pyrometers in two or three-color versions to determine char burning rates. At Sandia

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http://dx.doi.org/10.1016/j.fuel.2014.05.049
0016-2361/

Nomenclature

A_o	pre-exponential factor (mol/(m^2 s))	$\dot{q}_{conv}$	convective heat flux R (W/m^2)
A	area (m^2)	$\dot{q}_{inert}$	heat flux into the non-reacting particle (W/m^2)
A_{cyl}	cylinder surface (m^2)	$\dot{q}_i$	heat flux (W/m^2)
A_s	outer surface area (m^2)	$\dot{q}_{rad}$	radiative heat flux (W/m^2)
c_p	heat capacity of char (J/(kg K))	$\dot{q}_{react}$	surface-specific heat of reaction (W/m^2)
d	minor particles' axis (ellipsoid), diameter (cylinder)	Q_i	energy of type i (J)
d_A	surface diameter (μm)	R	molar gas constant (J/(mol K))
d_{char}	characteristic diameter (μm)	s_{px}	pixel size (μm)
d_p	particle diameter (μm)	t	time (s)
d_{sphere}	diameter of particle with equal projection area (μm)	T_f	film temperature (K)
d_V	volume diameter (μm)	T_g	gas temperature (K)
E_a	activation energy (J/mol)	T_p	particle temperature (K)
h	heat transfer coefficient (W/(m^2 K))	T_w	wall temperature (K)
ΔH	heat of reaction (J/mol)	v_p	particle velocity (m/s)
L	largest dimension of particle (m)	V_{cyl}	cylinder volume (m^3)
n	reaction order (–)	V_p	particle volume (m^3)
n_{px}	number of pixels	x	variable (–)
Nu	Nusselt number (–)	z	distance to fuel inlet (EFR) (m)
$p_{O_2,s}$	O_2-pressure at a particles' surface (Pa)	α	heat transfer coefficient (W/(m^2 K))
q	burning rate (mol/(m^2 s))	ε	emissivity (–)
q_{cyl}	burning rate assuming cylindrical particle (mol/(m^2 s))	λ	thermal conductivity (W/(m K))
q_{ell}	burning rate assuming elliptical particle (mol/(m^2 s))	ρ_p	char density (kg/m^3)
q_{sphere}	burning rate assuming spherical particles (mol/(m^2 s))	σ	Stefan–Boltzmann constant ($5.67 * 10^{-8}$ (W/(m^2 K^4)))

National Laboratories, two-color pyrometry of burning char particles in an EFR has been carried out for a long period. From the late 1970s on, coal and biomass chars have been investigated for their burning behaviour [7–13]. This system is based on a coded aperture for particle size detection. As the particle size is deduced from intensities measured by photo multipliers (PMT), the particle shape is assumed to be spherical. Another system based on size measurement by a coded aperture has been developed by Cope et al. [14], also using PMTs to measure the intensity of burning coal char particles. Other groups developed systems using fibre optics to guide particle radiation to PMTs, e.g. Spliethoff et al. [15] and Joutsenoja et al. [16,17], both using pyrometric data from single burning particles to determine char burning rates. All pyrometers mentioned so far have in common to measure in radial direction perpendicular to the coal streak in an EFR or DTR. Therefore only a momentary of each particle passing the pyrometers field of view is detected. Typically, a number of particles sufficient for reliable statistics are collected at a specified distance to the solid fuel inlet, and several measurements at different distances (residence times) are required to cover the burning history of a fuel sample. Another approach has been chosen in the work of Levendis and his group. The pyrometer system, described in detail in [18], measures along the axis of the EFR, which allows to measure the complete trajectory of a single particle. Thus, beneath the determination of particle temperatures [19], the burning time can be measured directly [20,21]. Particle burning rates have been derived from these measurements [20], and literature data has been tested to fit the measured burning times and particle temperatures of different coal samples with good agreement [21].

A system based on intensified (I)CCD cameras has been used to measure particle temperature and size by two-color pyrometry by Hackert et al. [22]. As the ICCD imaging technique provides spatially resolved 2d-images of burning particles with a resolution of 10 μm or less, particles of typical size for pf-firing (d_p = 50–100 μm) can be resolved spatially. The pyrometer system has been used for further investigation of coal and biomass chars, an example on particle temperature measurement of coal chars in oxyfuel atmospheres is given in [23].

While coal particles in pf-applications are typically compact and nearly spherical, even for those particles shape effects have been considered in literature [24]. Biomass particles originating from woody and herbaceous fuels show severe deviations from the spherical shape [25–27]. As will be described in the following, the particle shape has to be considered when deriving char burning kinetics from pyrometric measurements, as the energy balance, which is the key element of burning rate calculations, is affected by the particle shape. As the fibrous structure of biomass particles leads to particle shapes which can be assumed to be cylindrical or ellipsoidal, both shapes are tested in theory and on exemplary measurements.

2. Char burning kinetics from pyrometry

2.1. Energy balance around burning particles

The key element of burning rate determination by pyrometry is the energy flow balance at the outer surface of a particle:

$$\dot{q}_{react} = \dot{q}_{rad} + \dot{q}_{conv} + \dot{q}_{inert}\left[\frac{J}{m^2 s}\right]. \quad (1)$$

As shown in Eq. (1), the energy produced by reaction is balanced by the radiative heat transfer between the particle and its surrounding, the convective heat transfer between particle and gas phase and the temperature change of the inert particle (the non-reacting char and ash). In the following, the participating energy fluxes are calculated for particles of spherical, prolate ellipsoidal and cylindrical shape (Fig. 1).

In general it is assumed, that the surface temperature is constant and the heat and mass transfer are homogeneous, so that the surface dependency of $\dot{q}_i = dQ_i/(dt * dA)$ can be expressed by setting $dA = A_s$, where A_s denotes the particles outer surface. Under the given assumptions, the expressions for the reaction energy and the radiative heat transfer are shape-independent, as shown in Table 1. The reaction part of the heat flux is calculated from the surface reaction rate q and the heat of reaction ΔH:

$$\dot{q}_{react} = q\Delta H. \quad (2)$$