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Full Length Article

Devolatilization of millimeter-sized biomass particles at high temperatures and heating rates. Part 1: Experimental methods and results

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ABSTRACT

In the framework of a general research on biomass combustion, this paper presents and discusses the experimental techniques developed to analyze the heating, drying and devolatilization of biomass particles of few millimeters, a size range scarcely studied in the past. Individual particles were suspended in a stream of hot gases generated by a Flat Flame Burner, with controlled temperature and composition. The evolution of their morphology was monitored by time-lapse photography; additionally, an estimate of the instantaneous volatile release rate was derived from the picture series based on the size of the volatile shell flame. The temperature inside the particles (3–15 mm in diameter) was measured with pairs of fine wire thermocouples located at the particle's center and near its surface. The systematic error associated to this technique (deviations up to 300 K in relation to the actual particle temperature), due to the intense heat transfer along the metal wires, was evaluated experimentally and modeled; the agreement found in the comparison allowed for establishing a procedure to correct those signals and thus adequately evaluate the thermal gradients within the particles. A subsequent comparison of the experimental results (evolution of size, shape, internal temperature and temperature gradients, volatile release rate in a variety of conditions) with simulations performed with models which alternatively consider or neglect internal gradients is presented in a separate paper [21].

1. Introduction

During the last decades the use of biomass as a fuel has been increasing due to its considerable environmental and economic advantages as a potential energy source [1,2] and at present, energy from biomass accounts for a relevant fraction of all primary energy in most of the industrialized countries (e.g. up to 9.7% in the USA, representing 50% of the total renewable energy used [3] and roughly 8% and 64%, respectively, in Europe [4]). When compared with traditional fossil fuels, such as coal, biofuels have, in general, lower fixed carbon and ash contents than coal, but higher volatile contents; for these reasons, and also because of the reactivity of the biomass char, biomass is usually burnt in sizes considerably bigger than those typical of pulverized coal in the same combustion facilities. Thus, the models for the drying, pyrolysis and combustion of biomass must reflect these differences, and specific experiments are needed to validate them. Depending on the conditions (ambient temperature, heating rate, size and type of the particles, kinetics of the reactions), two main situations regarding the magnitude of energy fluxes inside the particles can be distinguished: in some cases, the intraparticle energy transfer is so fast that the temperature profile is nearly uniform and the different processes occur sequentially; this is usually known as the thermally-thin (particle) regime. In the so-called thermally-thick regime, on the contrary, important intraparticle temperature gradients are observed and several sub-processes may occur simultaneously, although in different parts of the particle.

The various biomass modeling studies appearing in the literature present different versions or enrich the model suggested by Bamford et al. [5] which differ in the complexity level applied to the treatment of each stage and process occurring along the particle conversion history (e.g. moisture evaporation [6], kinetic mechanisms [7], physico-chemical properties [8], structural changes [9]). However, comparatively, there are few detailed experimental studies and those available in the open literature do not cover the whole range of applications of practical interest, being mostly focused on the 'limit' cases of the aforementioned thermal regimes. Most of them involve particles from few millimeters to several centimeters (millimeter-to-centimeter sized particles) in moderate thermal conditions typical of slow pyrolysis (low temperatures and/or heating rates, as in thermogravimetric analyzers) which are far from those of industrial pulverized-fuel systems and severely limit the

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Abbreviations: BC, boundary condition; FFB, flat flame burner

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Nomenclature

AR	aspect ratio of the particle
c_p	specific heat ($\mathrm{J\,kg^{-1}\,K^{-1}}$)
D_p	particle diameter (m)
L_c	contact length between the thermocouple and the particle (m)
L_{ext}	length of the external ends of the thermocouple (m)
Nu	Nusselt number
O_2	oxygen
Pr	Prandtl number
r	radial coordinate (m)
R	radius (m)
Re	Reynolds number
t	time (s)
T	temperature (K)
ΔT	deviation of the thermocouple temperature measurement (K)
v	velocity ($\mathrm{m\,s^{-1}}$)
z	axial coordinate (m)

Greek Symbols

ε	emmisivity
λ	thermal conductivity ($\mathrm{W\,m^{-1}\,K^{-1}}$)
ϕ	equivalence ratio (fuel-oxidant ratio)
σ	Stefan-Boltzmann constant ($5.98\cdot10^{-8}\,\mathrm{W\,m^{-2}\,K^{-4}}$)
ρ	density ($\mathrm{kg\,m^{-3}}$)

Subscripts

a	air
dev	devolatilization
exp	experiment
g	free gas stream
h	hole of the particle where the thermocouple is inserted
p	particle
s	solid
th	thermocouple

reliability of the kinetics derived from the experiments [10–13]. There are also some studies with tests at high temperatures and heating rates characteristic of pulverized-coal boilers but the particle sizes used range from hundreds of microns to a very few millimeters [14–19]. However, the intermediate range involving at the same time particles of several millimeters at severe conditions, which is of practical interest for pulverized-fuel applications, has been less explored. To the authors' knowledge, only the work of Lu et al. [20] combined both factors. In their investigation, two models for biomass devolatilization were developed under the assumption of thermally-thin or -thick regime, and their results were validated with different experiments. They concluded that the experimental trends for particles above few millimeters were only correctly reproduced when intraparticle temperature gradients were considered.

This paper presents part of a research globally aimed at assessing the relevance of the above-mentioned thermal gradients on the simulation of the combustion of particles with sizes of variable size (3–15 mm) in conditions typical of pulverized co-firing facilities. For that general purpose, a complete set of experiments in those conditions have been performed and the different processes studied have been also modeled under the assumption of thermally-thick and -thin particle regimes. The comparison between the experimental results and the simulations are presented in a separate article [21]. Here, the experimental facility and the methods developed to monitor the evolution of the particle and its volatiles by means of intrusive and non-intrusive techniques are described. In particular, the monitoring of the temperature at different radial positions inside the particle and the quantification of the internal gradients along its devolatilization play a central role in this work; however, the use of thermocouples for reliable time-resolved measurements is far from straightforward mainly because of potentially non-negligible deviations between the temperature of the sensor and that of the particle at a given radial position (in the absence of the thermocouple), due to the high thermal conductivity of the thermocouple wires. Although this artifact has been observed in some previous works, in which different approaches to minimize it were suggested ([22] for coal, [20] for biomass), to the authors' knowledge it has not been systematically analyzed. After an analysis of the effect of different factors influencing the above-mentioned deviations, a method has been developed to calculate the deviations and then correct the corresponding temperature curves. This procedure has been validated with data from two well-controlled setups.

2. Description and characterization of the combustion facility

The experiments were conducted in a Flat Flame Burner (FFB), which allows precisely setting the combustion conditions as well as full optical access to the burning particles; a schematic view of the main components of the LIFTEC's FFB is displayed in Fig. 1-left. The burner

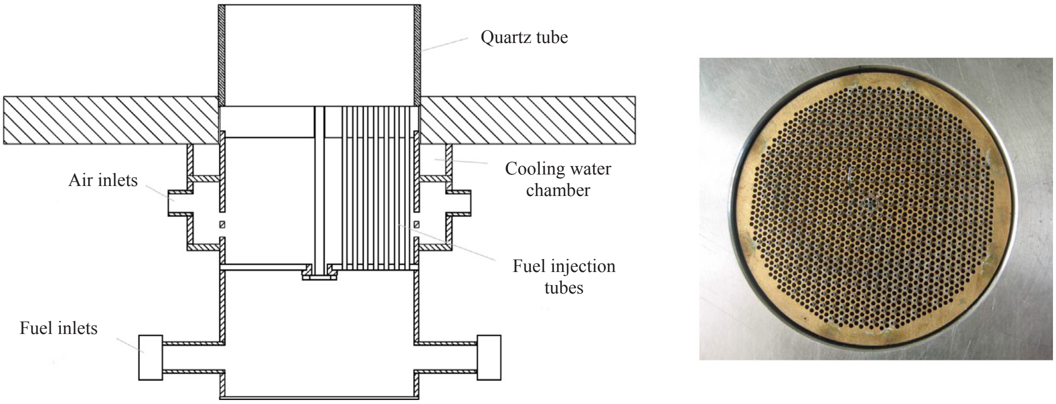

Fig. 1. Schematic view (left) and upper plate (right) of the Flat Flame Burner (FFB).