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Optical techniques for characterizing the biomass particle flow fluctuations in lab- and pilot-scale thermochemical systems

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ABSTRACT

The work demonstrates the performance of the optical extinction technique for real-time diagnostics of the fluctuations in biomass particle flows. The online measurements of fluctuations of density were used to determine the biomass particle mass flow fluctuations. Biomass flows were produced using laboratory biomass particle feeder (mass flux up to 10 g/min) and the hopper-screw feeding system of the pilot-scale entrained flow rector, mass flux up to 500 g/min, located at SP ETC in Piteå. The experiments showed that the time-averaged extinction appeared to be linearly related to the real particle mass flow. The relatively fast variations in biomass feeding rates measured using the extinction technique were confirmed by fast balance measurements (in laboratory feeder experiments) and by real-time tunable diode laser CO and H_2O concentrations measured in the reactor core of the entrained flow gasifier.

1. Introduction

Biomass is one of most promising alternatives to fossil fuels in the light of the effort to reduce greenhouse gas emissions as well as because of its renewable character. Thermochemical conversion (combustion, gasification, pyrolysis) is the most widespread method of the energy generation from biomass. A critical common challenge in the thermochemical conversion devices employing different types of the feeders is the uncontrolled perturbations in the feeding rate of biomass [1]. The fast perturbations of the biomass powder flow are often related to the fuel properties (density, moisture, content) and can negatively influence the stability, efficiency, and completeness of operational processes, increase the pollutant emissions. Accurate real-time measurements of the biomass powder mass flow can help to identify, monitor and control these perturbations/variations. Furthermore, the accurate online information on the biomass feeding rate is essential for laboratory scale studies pursuing the fundamental understanding of the biomass energy conversion processes. Conventional analytical instruments (such as balances) often fail to detect the variations with the desired temporal resolution.

The optical techniques have been successfully used for characterizing the laden particles flow and are capable of real-time measurements of the concentration, size distribution and velocity of the particles [2]. For example, Ichikura and Watanabe [3] measured the particle flow in a pipeline by an optical method; speed measurement was made by spatial filtering and mass concentration measurement by extinction. Herbert et al. [4] applied fiber optic reflection probes to measure local particle velocity and concentration in gas-solid flow. A novel multifunctional optical fiber probe was applied by Yen et al. [5] for direct local measurements of instantaneous solid flux in a circulating fluidized bed riser. Birzer et al. [6,7] conducted planar nephelometry of two phase jets to determine qualitative particle concentration measurements. Despite many advances in the field, the methods have been rarely applied in the biomass flows. Here we propose to use the laser extinction measurements for diagnostics of the density fluctuations in the pulverized biomass flows consisting of non-spherical particles with varying sizes. The measurements are performed in pilot and lab-scale equipment. The online measurements of fluctuations of density can be used to determine the biomass particle mass flow fluctuations. To evaluate the performance of the method, the extinction derived data are compared with balance measurements (lab experiments) and real-time in situ CO and H_2O TDLAS sensing in the reactor core of an entrained-flow biomass gasifier (pilot-scale experiments).

2. Experimental

Fig. 1 shows the schematic of the experimental set up used for study of the fluctuations in biomass particle flows. The intensity modulated radiation from a cw diode laser at 637 nm is directed through the studied volume. The modulation was performed using the box shape function at 50 kHz. The laser system consists of Thorlabs Benchtop Laser Diode/TEC Controller (ITC4001) and the laser head (Thorlabs LDM9LP laser diode mount and LP637-SF70 single mode fiber-pigtailed laser).

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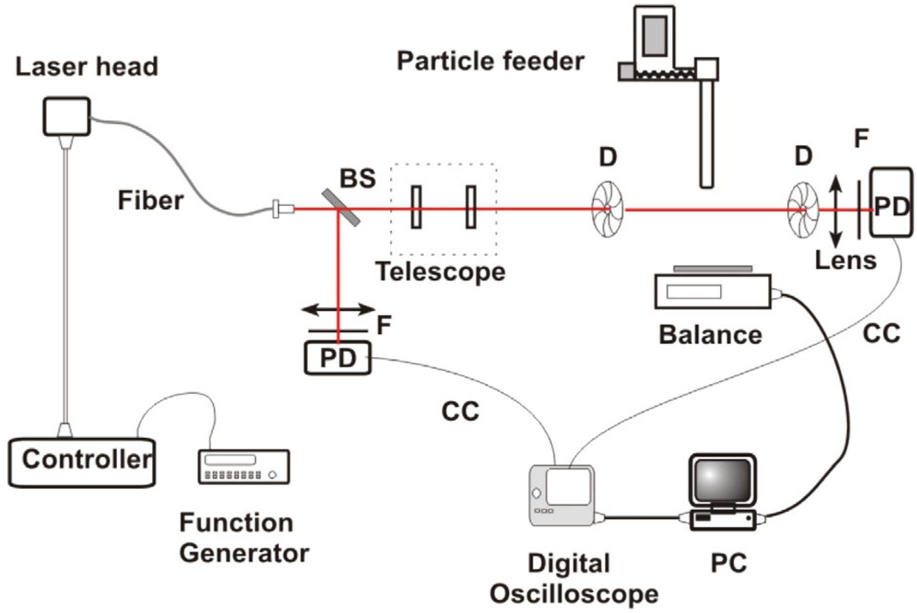

Fig. 1. Schematic of extinction experimental set up. Code: BS, beam splitter; D, diaphragm; F, filter; PD, photodetector; CC, coaxial cable; PC, personal computer.

Before crossing the biomass flow, the laser beam is split off to produce the reference signal and then expanded using the adjustable telescope, in such a way to insure that the volume taken by biomass particles exiting the feeder system during a short time interval, dt, is filled with the laser radiation. The radiation exiting the studied volume is directed using a number of optical elements to the IR detector. The intensities of the reference and sample beams are measured by New Focus 2033 large area photodiodes with internal amplifiers. The photodiode signals were digitized and processed by a PC.

Two feeders were used in the experiments. The first one is the laboratory-scaled particle feeder [8], Fig. 2a, mass flux up to 10 g/min, and the second is the hopper-screw feeding system (five screws) of the pilot-scale entrained flow rector (Fig. 2b) [9,10], mass flux up to 500 g/min, located at SP ETC in Piteå. In lab feeder experiments, biomass particles were fed at different rates using a particle feeder that dispensed particles by gravity through an injection tube. The constant flow rate of the carrier gas N_2 (Fig. 2a) was set to 1 l/min in all experiments. Feed rate was controlled by altering the velocity of a pusher block. Particles were agitated using a vibration motor and fed onto a balance (model PG1003-S/PH from Mettler Toledo, Switzerland) with a maximum capacity of 1010.0 g and a readability step of 0.001 g. The mass readings were logged with a time interval of 1 s. The extinction measurements were made at the exit of the particle injection tube (Fig. 2a).

The extinction measurements in the feeding system of the pilot-scale entrained flow rector were supplemented with TDLAS measurements made in the reactor core of the gasifier operating in combustion mode. TDLAS measurements of CO and H_2O are performed using the method reported in our previous work [10]. To enable extinction measurements of the biomass flow density, the quartz windows were installed to the biomass transport tube connecting the hopper and the top of the entrained flow reactor (Fig. 2b). The fuel feeding rate was controlled by the rotational speed of the five screws in the bottom of the fuel hopper. The constant flow rate of the carrier gas Air (Fig. 2b) was set to 210 l/min in all experiments.

Biomass particles were produced from wood pellets (Glommers Miljöenergi AB, Sweden) which in turn were produced from stemwood sawdust from Scottish pine and Norway spruce. Pellets were crushed in a hammer mill until all material has passed through a 0.75 mm mesh, the obtained particles was used in the pilot scale experiments. In the lab scale studies, the particles were further size separated by a series of sieves with mesh sizes of 1000, 500, 250, 125, 75, and 40 μm for 15 min at an amplitude of 1.5 mm using an analysette 3 vibratory sieve shaker (Fritsch, Germany). This produced size fractions of 40–75, 75–125, 125–250, 250–500, and 500–1000 μm.

3. Basic theory

For simplicity, we assume that the biomass particles are spheres of the same diameter. In this case, the extinction of a collimated laser beam through a cloud of particles can be written as

$$A(t) = -\ln\left(\frac{I(t)}{I_0}\right) = N(t)\frac{\sigma_p}{\sigma_L}Q_e, \tag{1}$$

where (I/I_0) is the transmittance, $N(t)$ is the number of particles in the studied volume, σ_p and σ_L are the particle and laser cross sections, Q_e is the light extinction efficiency factor (approximately 2 for large particles) [11]. For non-spherical particles, σ_p would represent a factor depending on a mean particle size and parameters of the size distribution function.

At any given moment a balance reports the total mass of the particles at the balance plate. Measurements are typically done at the constant time step Δt, therefore, the difference between consequent measurement points represents the mass, M, accumulated in the given time interval

$$M = \overline{n}(t) \cdot \overline{v} \cdot \Delta t \cdot \sigma_t \cdot m, \tag{2}$$

where $\overline{n}(t)$ and $\overline{v}(t)$ are the time-averaged density and velocity of the biomass particles, σ_t is the cross section of the feeder tube and m is the mass of biomass particle. The time-averaged density can be expressed via the time-averaged extinction of the laser beam, $\overline{A}(t) = \int^{\Delta t} A(t)dt \cdot \frac{1}{\Delta t}$, using Eq. (1)

$$\overline{n}(t) = \int^{\Delta t} \frac{N(t)}{D_t \cdot \sigma_L} dt \cdot \frac{1}{\Delta t} = \frac{\overline{A}(t)}{D_t \cdot \sigma_p Q_e}, \tag{3}$$

where D_t is the diameter of the feeder tube. Substituting Eq. (3) to Eq. (2) and rearranging the received expression, one can express the