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Visualization system for the measurement of size and sphericity of char particles under combustion conditions

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ABSTRACT

Advanced visualization systems are used in many engineering applications where information about particle size and position plays critical roles. In practice, the manual detection and following of individual or groups of particles is not feasible; an automated computational method must be used. Devices and mathematical algorithms capable of tracking particles have been developed by many engineering groups. The applicability of available methods is limited to detecting and tracking particle size and position only under cold flow conditions being the main weakness of these methods. To mitigate this limitation, a unique experimental rig and detection algorithm used for calculating particle size and sphericity under combustion process are investigated in this study. The data collected by the proposed visualization system are used to gather kinetic data of combustion. Reliable kinetic data are critical for accurate simulations of coal combusted in the large industrial boilers used in the energy sector, and thus, they are a pre-requisite for computer aided boiler optimization.

1. Introduction

Within the energy sector, where fossil fuels are commonly used, there is a question on how the fuel conversion process can be improved in order to reduce cost while keeping the pollutant emission within admissible range. The answer for this question can be given by application of the complex numerical models based on the Computational Fluid Dynamics (CFD). An example of such application can be found in works [1,2] and [3,4] where the advanced numerical techniques were used for modeling combustion process in experimental rig and large scale pulverized coal (PC) boilers. A necessary condition to achieve simulation accurate results is the access to appropriate kinetic data for the burned fuel. These data can be obtained only experimentally using dedicated devices.

Combustion of a coal particle undergoes in several steps. When the solid particle is exposed to hot gases (i.e., combustion products), the particle mass can change due to three processes: moisture evaporation, devolatilization (i.e., pyrolysis) and char combustion [5]. Depending on the particle size, those three processes can occur sequentially (large particle) or simultaneously (small particle). Evaporation under industrial conditions takes place within the coal mills where coal or biomass is heated to the desired temperature by hot primary air or recirculated flue gases. This stage is required to avoid blocking of the primary pipe which supplies pulverized coal to the burners. Contact of the particle with gas phase temperature of above 300 °C volatile matter consisting of light gases, tar, and remaining water is released. This stage is strongly connected with heating rate, composition of the gas and pressure [6]. The characteristic feature of devolatilization is that the gases which diffuse to the particle surface can cause its swelling. Bituminous coals [7,8] undergo such process, lignite particles may fragment [9]. The last step of coal combustion is the char oxidation, which is the slowest step of the overall coal combustion process. The rate of coal combustion process is related to its composition and structure as well as the composition, pressure and temperature of the oxidizer. The coal burning rate in turn affects residence time of the particles in combustion chamber and therefore influences the overall heat transfer processes and efficiency of the combustion process. Char oxidation is controlled by two processes: diffusion and kinetics (chemical control) [10]. At high temperatures, the rate is controlled by diffusion, while at low temperatures, the rate is controlled by chemical kinetic. However, under certain conditions, chemical reactions can proceed simultaneously either on the particle surface (diffusion) or within the particle (kinetic). As char combustion rate directly influences on the amount of unburned carbon (UBC), which affect plant thermal efficiency, it is very important to use reliable submodels of combustion rate to be embedded in the overall model of the boiler.

To determine the kinetic data of a given type of coal, several parameters must be known, including particle dimension, shape, rate of the particle mass loss and particle surface temperature [11,12]. The last

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parameter is difficult to measure [13,14]. These parameters are often used as the input for CFD models of combustion processes of industrial Pulverized Coal (PC) and Circulating Fluidized Bed (CFB) boilers to predict concentration of NOx and CO, temperature and flow field throughout the boiler. Coal kinetics data are then used to calculate the temporal mass variation of particles using mathematical formulae containing many coefficients [11,15]. The values of the latter are obtained by fitting them with experimental data. The most popular methods to acquire experimental data are Drop Tube Furnaces (DTF) [16,17,18] and Thermogravimetric analysis (TGA) [19,10,20]. Over the years, the DT reactor becomes experimental technique of choice for determining both combustion rates of volatile matter and char in various operating conditions. The strength of this technique is the heating rates up to 10,000 K/s which are similar to those expected within the real pulverized boilers. Fig. 1 (left) illustrates the design of DTF. The general measurement idea is as follows. The coal particles are injected to the reactor at its upper part and they are carried by the gases through the reactor. To ensure isothermal conditions the temperature of the external walls of the DTF is controlled by electrical heaters. Depending on the position of the collector the residence time of the particles can change which ensures different combustion rates of the particles. The composition of the oxidant (flue gases) is controlled by the excess air used in the combustion process of the hydrocarbon fuel, typically methane. The set of experiments is always run for several temperatures, particle residence times, and oxidation atmospheres, collected by the sample collector and the solid separator is then analyzed using TGA to determine remaining fraction of combustible matter in particles. In the case of using DTF for measuring combustion rate of volatile matter, the measurement procedure is the same, except the oxidant that is replaced by an inert gas (nitrogen or helium) to prevent uncontrolled char ignition at high temperature. DTF provides accurate data, nevertheless the running of experiments is very expensive and requires experienced operating staff. Moreover, the collected samples need to be further analyzed using TGA to determine their UBC fraction.

The TGA allows to track the changes of the coal particles weight as the function of time and temperature [21,22]. It can be applied also for other materials like biomass, wastes, and sewage sludge. The scheme of TGA device is depicted in Fig. 1 (right). The sample of coal (typically 1 mg to 30 mg) is placed on the load cell in an enclosure with controlled oxidation atmosphere. The TGA can also be used for carrying out proximate analysis [23]. The advantage of TGA over DTF is relatively simple and cheap the measurement process. However, in real pulverized coal combustion process that occure within PC boilers the particles heating rate is much faster than 1 K/s which can be achieved in TGA. That is the main reason why the kinetic data received from TGA experiments cannot be directly used. Nevertheless, the kinetic data retrieved in chemically controlled regime **I** [15] using TGA at temperature range from 700 °C to 1050 °C can be further extended to kinetic/diffusion (**II**) and diffusion (**III**) zones using the kinetic/diffusion model [11,24]. To use this approach, the particle temperature, and oxygen fraction in the vicinity of the particle have to be known, which is in practice difficult to obtain.

Nowadays, many efforts are made to develop advanced vision system for characterization and analysis of the char combustion under various conditions. Vision systems give possibility to observe changing of the particle diameter, structure or propagation of ignition at relatively low cost [25]. Literature describes some application of vision system [26,27]. Both papers used a visualization system to trace a single particle under different atmospheres during combustion. In their studies, a visualization system was used to observe behaviour of the falling particles, where both the moment of ignition, and particle swelling or breakage processes were caught. Cloke et al. [28] applied the vision system for measuring particle porosity, size and wall thickness. In recent advanced studies [29,30] the Infrared Camera (IR) was used to record the particle temperature and changes of the particle size. The calculated intrinsic reaction rate constant for lignite coal based on the measured particle mass loss shows very good agreement with the experimental data measured using TGA device. Other application of the vision system for measuring

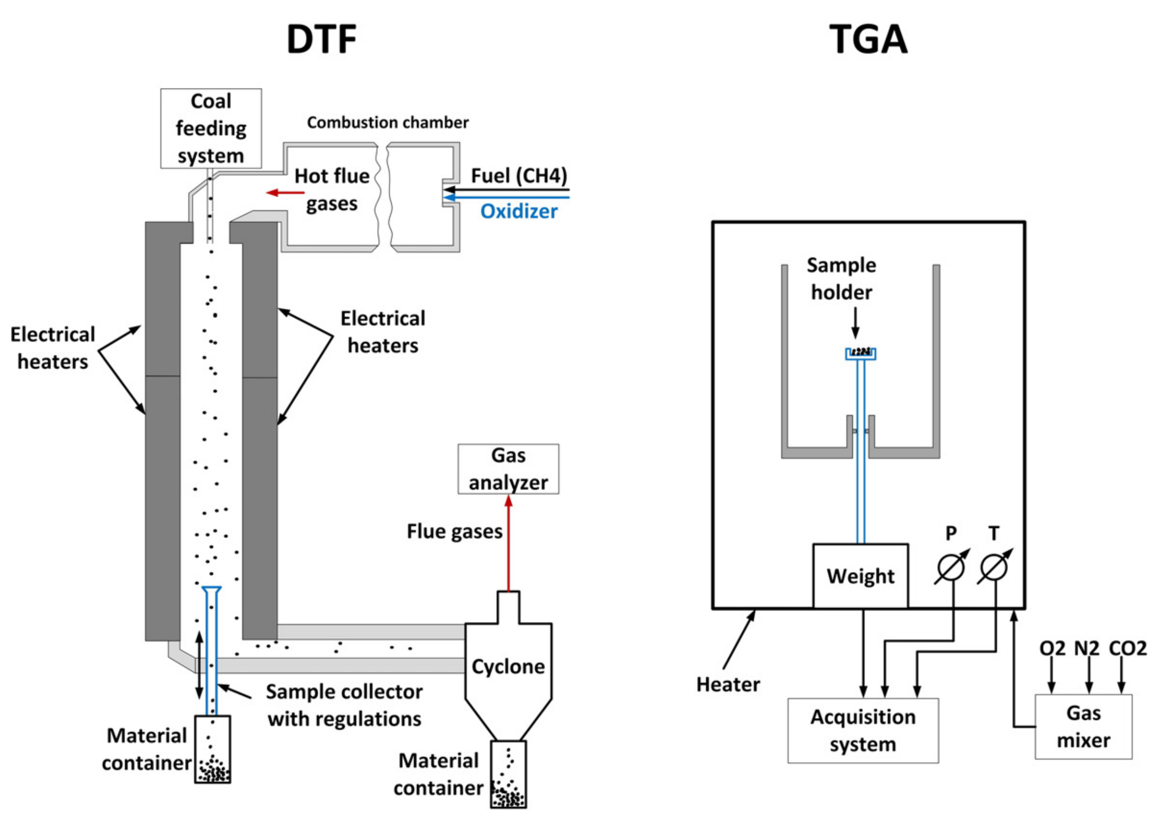

Fig. 1. Construction of the drop tube furnace (left) and thermogravimetric device (right).