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Research article

Design of the experimental rig for retrieving kinetic data of char particles

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ABSTRACT

A new concept for evaluating chemical kinetics data of combustion of coal char particle is proposed. The experimental rig based on the measurement of mass loss of the char particle during the combustion process has been designed and built. The char particles are dropped into a laminar carrier gas stream flowing in a narrow horizontal channel. Temperature and gas composition inside the channel are fully controlled and correspond to those encountered in industrial furnaces and boilers. The idea of the measuring method is to trace the falling particle in the carrier gas, retrieve the mass reduction rate from the curvature of the recorded trajectory of the particle, and measure its diameter. An original technique of determining the diameter using a medium resolution camera has been developed. The kinetic constants are evaluated using an original inverse technique.

1. Introduction

Coal-fired power plants currently fuel 40% of global electricity production and, in some countries e.g. in Poland the portion of energy produced from coal exceeds 90% [1]. Highly efficient and clean coal combustion process requires proper design and operation of the combustion chamber of the boilers. To meet the present and future efficiency and pollution limits, new combustion chambers are optimized while the existing chambers undergo appropriate modifications. The tool used for both processes is the Computational Fluid Dynamics (CFD). To produce reliable results, CFD at its present state of development, requires reliable experimental data. In the case of coal combustion, critical information concerns chemical kinetics. Due to the complex chemical composition of coal, these data cannot be obtained from molecular simulations, thus experiments remain the only way to retrieve kinetic models. The process is costly and time consuming. Examples of such CFD simulations for both fluidized and pulverized coal combustion are available in the literature. Some representatives examples of such an approach can be found in literature [2–6].

Combustion of a coal particle is composed of three elementary phenomena: drying, devolatilization and char combustion. Depending on the particle size, these three processes can occur simultaneously (large particle) or sequentially (small particle). The work deals with the longest stage of these elementary processes, namely the char combustion, which can take up to few seconds. Char oxidation is controlled by two phenomena, diffusion and kinetics. At high temperatures, diffusion control is limiting, whereas at low temperatures it is kinetics that controls the rate of char oxidation. The picture of the process is even more complex, as the chemical reactions can take place on the particle surface or/and within the particle pores.

The primary parameter to be determined in experiments whose aim is to retrieve the kinetics of coal combustion is the temporal variation of the burnout rate (mass loss) of the particle. However, to find the necessary data entering the kinetic equation, the changes in time of several other parameters should be known. This set of data comprises particle shape and temperature as well as the composition and temperature of the surrounding gas. The final kinetics equation is given by formulae containing several coefficients [7,8], whose values are evaluated by fitting the experimental data to measured values. 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. Mentioned physical parameters are often used as the input parameters for numerical modeling of industrial Pulverized Coal (PC) and Circulating Fluidized Bed (CFB) boilers using Computational Fluid Dynamics (CFD) methods. To accurately predict combustion process of coal, the kinetics data plays crucial role and has to be precisely defined. In computational codes combustion is modeled

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by employing mathematical models with number of coefficients which are obtained by fitting mathematical model to experimental data. The most popular methods to acquire experimental data are Drop Tube Furnaces (DTF) [9–12] and Thermogravimetric analysis (TGA) [13–16].

Over the years, the DTF achieved status of the experimental technique which can be applied for determining both combustion rates of volatile matter and char in various operating conditions. The heating rates, which achieve up to 10,000 K/s are similar to those expected within the real pulverized boilers. The measurement strategy requires that the coal particles are injected to the reactor at the upper zone which next are carried by the gases. To ensure isothermal conditions the external walls of the DTF are covered by electrical heaters. Depending on the position of the collector the residence time of the particles can change which ensure different combustion rates of the particles. The composition of the oxidizing atmosphere is controlled by a set of flow meters. Collected material at the bottom of the DTF in the next stage is analyzed using TGA to determine the remaining fraction of combustible matter in particles. This method provides accurate data, nevertheless the running of experiments is very expensive and required experienced operating stuff. Some application of the DTF for investigation pyrolysis process of coal and wood biomass can be found in [17], whereas in work [18] the useability of DTF for retrieving kinetic correlation for coal under high temperature.

The TGA method allows tracking the changes of the sample weight as the function of time and temperature [19,20]. It can be applied also for other materials like biomass, wastes, and swage sludge rather then only for coal. 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 of coal which is proven by the American Society for Testing and Materials (ASTM) [21]. Huge advantages of the TGA over the DTF is that the measurement process is relatively simple and cheap. However, huge disadvantages of the TGE is the low values of heating rate (1 K/s). In real pulverized coal combustion process the particles heating rates are much faster than those achieved in the TGA. The very rapid heating of coal particles may affect many physical processes and in consequence influences on predicted kinetics. That is the main reason why the kinetic data received from TGA experiments cannot be directly used while simulating pulverized coal boilers. Nevertheless, the kinetic data retrieved in chemically controlled regime [22] using TGA can be farther scaled to kinetic/diffusion or diffusion range [23]. Nevertheless, to use this concept the particle temperature, and oxygen fraction in vicinity to the particle has to be known, which in nature is difficult.

To mitigate the difficulties and restrictions of both mentioned methods, a new and unique experimental test-rig that can be used to measure the particle mass lost during combustion under different oxidizing atmospheres is proposed in this study. To combine advantages of both mentioned measurement methods (DTF and TGA), a new and unique experimental rig and particle tracking software have been proposed in this study. Experimental rig provides possibility to observe particle ignition, exact combustion time, instantaneous two-dimensional particle sphericity, and changes of particle diameter during combustion process. The particle tracking system collects particle trajectories which are then used by inverse analysis to determine the rate of burned char. Combining the tracking application with inverse code gives possibility to retrieve char kinetic data almost online which is extremely fast in contrary to other methods. Kinetic data in the next step can be relatively easily used as the input to sub-model for heterogeneous reactions of solid particles in a CFD code.

2. Designing of the experimental rig

The first step in the designing of the experimental rig was the formulation of the measurement methodology and concept of the test-rig. In the following stage Computational Fluid Dynamics (CFD) has been used to aid the detailed design of the experimental rig before its construction and assembly. Finally, the development of the numerical model was performed to retrieve the kinetic data out of the recorded particles trajectories.

2.1. Methodology

The main idea of the measuring procedure is illustrated in Fig. 1. The char particle is dropped vertically into a laminar gas stream flowing in a narrow horizontal channel. The composition of the gas is typically a controlled mixture of O_2/CO_2 or O_2/N_2, other options can readily be used. For a given composition and temperature of the gas, the velocity of free fall of the particle can be determined. Similarly, the horizontal velocity of the carrier gas can be measured or evaluated. The vertical component of the particle velocity and the horizontal component of the gas velocity component, should have similar magnitudes. The trajectory of the particle in an inert atmosphere (no combustion) would then be a straight line of an inclination close to 45° if the particle falling velocity was equal to that of the carrier gas velocity. Appropriate gas velocity for given coal type and flow condition (gas temperature and composition) is adjusted before measurement are running. In practice it is difficult to find the exact velocity in which the inclination angle will be equal to 45°. However, the developed algorithm for retrieving coal particle mass lost rate is non-sensitive on the particle inclination angle which means that the gas velocity is taken into account by the mathematical formulation of the inverse algorithm. For combusting particles, the chemical reaction consumes carbon causing mass loss. This in turn reduces the free fall velocity leading to a deviation of

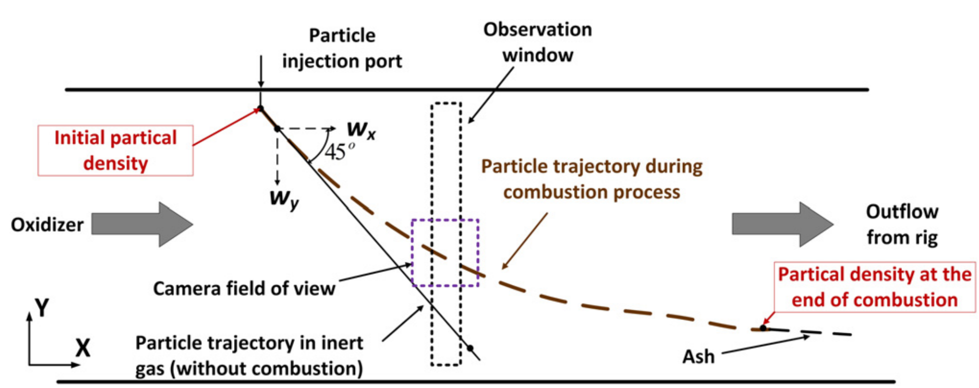

Fig. 1. Concept of the measurement procedure.