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Parametric study on the particulate matter emissions during solid fuel combustion in a drop tube furnace

Sami Zellagui, Gwenaëlle Trouvé *, Cornelius Schönnenbeck, Nabila Zouaoui-Mahzoul, Jean-François Brilhac

Laboratoire Gestion des Risques et Environnement (LGRE, EA2334), Institut de Recherche Jean-Baptiste Donnet, Université de Haute-Alsace, 3bis rue Alfred Werner, 68093 Mulhouse Cedex, France

HIGHLIGHTS

- Study of combustion and oxy-combustion of coal and woody biomass in a drop tube furnace.
- Measurements of particulate matter.
- Determination of number size distribution of PM_1.
- Influence of parameters as temperature, residence time, atmosphere and nature of the coals.
- Combustion of mixture of coal and biomass.

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ABSTRACT

Investigations on particulate matter (PM) emissions from solid fuel combustion are important due to their negative impacts on human health and the environment. A full parametric study of the amount and size distribution of particle emissions from solid fuel combustion have been performed using a drop tube furnace (DTF). Different operating conditions have been experimented for coals or biomass, including combustion atmosphere (air or oxy-fuel conditions), particle residence time and temperature. First, the gas atmosphere has a significant effect on PM_1 emissions from coal combustion but not from biomass combustion. Second, when the particle residence time increases, the amount of PM_1 tends to increase with biomass combustion but to decrease with coal combustion. Third, increasing temperature during biomass combustion tends to increase ultrafine particle emissions such as $PM_{0.1}$. Fourth, the type of coal greatly affects the PM_1 emissions during combustion. Finally, coal co-burning with biomass optimizes the amount of PM_1 emitted when the biomass mass ratio is around 25% in the blend.

1. Introduction

Particulate matter (PM) is one of the major constituents of air pollution and it has received much attention in the last few years. These particles are sourced from natural phenomena (volcanic eruptions, wind erosion, forest fires, etc.) or from human activities (domestic heating, electricity production, fuel combustion, transport, etc.). Fine particles are mainly a mixture of solid and/or liquid particles suspended in the air. Recent data show that the exposure to fine particulate matter pollution contributed to 3.2 million of premature deaths in the world, mainly caused by cardiovascular diseases and lung cancer [1].

The combustion of solid fuels such as coal and biomass for heat and electricity generation is one of the principal contributors to PM emissions. Coal fired boilers are indeed widely used in power plants due to their low cost and to the abundance of this fuel despite the fact that coal combustion produces significant amounts of pollutants. Fine particles $PM_{2.5}$ (particles with size diameter below 2.5 μm), nitrogen oxides and carbon dioxide are of major concern because of their effect on climate change and human health. Concerning the biomass, the residential wood combustion mainly contributes to local air pollution with emissions of various gaseous compounds and particulate matter [2–5]. The evaluation of particles emission factors proved that the energy production in domestic devices is one of the major sources of atmospheric fine particle ($PM_{2.5}$) in many parts of the world and particularly in Europe [6,7].

In full scale thermal biomass and coal facilities, the impact of the primary particulate emissions as fly ashes is largely reduced

* Corresponding author.
E-mail addresses: sami.zellagui@uha.fr (S. Zellagui), gwenaelle.trouve@uha.fr (G. Trouvé), cornelius.schonnenbeck@uha.fr (C. Schönnenbeck), nabila.zouaoui-mahzoul@uha.fr (N. Zouaoui-Mahzoul), jean-francois.brilhac@uha.fr (J.-F. Brilhac).

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in mass due to various efficient flue gas technologies such as scrubbers, multi-cyclones, baghouse filters and electrostatic precipitators, thus more complying with environmental regulations. Nevertheless, these flue gas post treatment systems are not relevant for nanoparticles which represent more than 90% of total emitted particles in number. Another issue is the chemical composition of particles because some alkaline metals provoke fouling and corrosion on heated tubes of boilers. For example, KCl and NaCl are well-known to participate in deposit formation and high temperature corrosion processes of heated tubes during biomass combustion. The chloride lower ash melting temperatures contribute to increase both the ash growth and stickness [8].

Many studies have already been carried out to investigate the formation of PM emitted from both coal and biomass. In coal combustion, most of PM formation mechanisms are related to the mineral properties of coals [9] and to the ash/char fragmentation at high temperatures [10–12]. The mineral matter can be included or excluded in nature [13,14]. The included minerals are entrapped with the coal matrix and comprise finely dispersed minerals and organically-bound elements (e.g. Na, K, Ca, and Mg). However, the excluded minerals have a little association with carbon matrix [9]. The classical theories regarding the formation of PM involve two distinct pathways. In the first path, the excluded minerals are directly transformed in PM without experiencing vaporization, via the solid to particle pathway [15,16]. Nevertheless, in the second path, vaporized mineral species volatilize at high temperature and undergo different transformations such as homogeneous nucleation, coagulation and agglomeration. The mineral species are then converted into solid fine aerosols (<1 μm) by condensation when temperatures cool down, via the solid-vapor-particle pathway. For a better understanding of the mechanism of PM formation from coal firing, simplified schematics are presented in [9,17,18].

Considering the biomass combustion, the PM formation is also classified into two distinct pathways. The first one gathers the PM formed by the direct transformation of non-volatile inorganic elements (Ca, Si, Mg, etc.) on coarse ash particles (>1 μm). The second one concerns the PM formed by the transformation of inorganic vapors (KOH, KCl, ZnO, K_2CO_3, etc.) on fine ash particles (<1 μm) after undergoing different interactions such as nucleation, condensation, surface reactions, coagulation and agglomeration [19]. In addition, an incomplete combustion can lead to the formation of soot and organic material such as tars and volatile organic compounds. The mineral matter included in biomass has different characteristics and composition than that included in coal. Consequently the particles formed from the two solid fuels exhibits different characteristics [20,21].

The total amount of particulate matter emitted from coal and biomass combustions depend on various factors. Numerous studies already proved the influence of experimental conditions on the emissions of PM during coal and biomass combustion. Several parameters were investigated, including solid fuel type [15,22–25], residence time [26,27], reaction temperature [28,29] and coal combustion environment [30–32]. The impact of the operating conditions on the PM emissions was investigated in different combustion systems at a laboratory scale and using various PM measurement devices. To our knowledge, a complete parametric study using a single experimental device - especially a Drop Tube Furnace (DTF) - has not yet been performed.

The studies [9,33] focused on submicron ash formation from conventional air coal combustion in a DTF system. Other studies [34,35] investigated the impact of coal combustion atmosphere (air or N_2/CO_2) on submicron particles. In the same device, Takuwa et al. [36] studied the influence of particle residence time on PM emissions from combustion of two different coals while Costa and Costa [37] investigated the impact of this parameter for different biomass combustion. The solid fuel nature is also investigated by different researchers [22,36]. Furthermore, some authors [38–41] were interested on the effect of co-firing coal and biomass on PM emissions. In their experiments, Jia and Lighty [35] analyzed the impacts of the maximum of parameters: furnace temperature, coal type, and gas phase conditions.

It is important to note that in the DTF experimental conditions, high heating rates (approximately 10^4–10^5 K s^{-1}) have to be achieved in order to characterize solid fuels under conditions similar to those which take place in actual power plant furnaces. The previous works [42,43] proved that the DTF is a fast and accurate tool for conducting combustion studies of coal and/or biomass and associated emitted particle analyses. The evaluation of a large set of parameters is then less expensive and less complicated when the experiments are realized in DTF than in industrial scale furnaces.

The present work aims at investigating how the amount of fine and ultrafine particles ($PM_{0.1}$ to $PM_{2.5}$) measured by an Electrical Low Pressure Impactor (ELPI) is affected by the type of solid fuel fired and the combustion conditions. The experiments have been carried out in a lab-scale drop tube furnace. Two well-characterized pulverized fuels South African coal (AFS1) and woody biomass (WB) already characterized in the previous study [44] have been selected to study the influence of combustion conditions. In a first step, the reference samples have been burned in air and different oxygen concentrations in CO_2 in order to determine the influence of the combustion atmosphere on the amount of PM emitted. Then, the influence of residence time within the reaction zone has been examined for both AFS1 and WB combustion. Only biomass was tested to characterize the influence of temperature. A selection of coals with different characteristics has been burned in the DTF to determine the influence of the coal characteristics on PM emissions. Finally, PM emissions from coal-biomass co-firing have been investigated.

2. Experimental section

2.1. Fuel samples

Five different types of coal (AFS1, AFS2, AFS3, Ciuden and Sebuku) and a woody biomass (WB) have been tested in this work. WB is a forest residue (chips harvested) produced in Alsace (France). This fuel is used in urban combustion facilities in Alsace for heat and electricity production. Wood chips are previously reduced in size by grinding and sieving. The particle size for coals and woody biomass are ranging from 38 to 63 μm and from 200 to 280 μm, respectively. AFS1 coal and woody biomass are used as reference materials for the parametric study of the effect of combustion conditions – gas, residence time and temperature – on $PM_{2.5}$ emissions. AFS2 and AFS3 coals are used to investigate the effect of ash content on $PM_{2.5}$ emissions. Ciuden and Sebuku coals are considered to study the effect of volatile matter (VM) content on $PM_{2.5}$ emissions. The fuels proximate, ultimate and ash analyses of these materials are shown in Table 1.

2.2. Solid fuel combustion

The pulverized solid fuels are burned in a drop tube furnace (DTF) which has been already described in details in [44]. The experimental set-up is depicted in Fig. 1. It consists in a reactor, a fuel feeding system, mass flow controllers and an Electrical Low Pressure Impactor (ELPI) device. The ash collection stage is an impaction chamber with one 150 mm diameter inlet orifice and three outlet vent tubes. The outlet tubes are 250 mm above the impaction surface. This design results in very low turbulence