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Research article

# Numerical and experimental investigation on co-combustion characteristics of hydrothermally treated municipal solid waste with coal in a fluidized bed

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ABSTRACT

This research describes numerical and experimental studies on the co-combustion characteristics of hydrothermally treated municipal solid waste (HT MSW) with coal by utilizing a bubbling fluidized bed (BFB) reactor. The developed model is supported by some experimental test on co-combustion of coal with HT MSW to simulate the combustion process in a BFB and to evaluate the possibility of co-combustion application in a BFB reactor with different MSW blending ratios. HT MSW mixing ratios of 10, 20, 30, and 50% are chosen and examined at 700, 800, and 900 °C to determine at which temperature coal could be substituted with the HT MSW regarding emissions, such as CO, $SO_2$ and HCl. Emissions of NO, $N_2O$, $NH_3$ and HCN from the mixtures are measured, simulated, and contrasted with the results of only combustion of coal. Hydrodynamics and heat and mass transfer, along with reactions during combustion, e.g., coal/waste devolatilization, volatile combustion and char combustion, are taken into account. The results obtained in this part of the study ensure the possibility of accepting the mixing ratio of the hydrothermally treated MSW, co-combusted with coal up to 30% (wt.%) without major modification of the coal-fired BFB reactor. The simulation results are compared with experimental data, which show that the gas species versus time at different heights from the fluidized bed is reasonably simulated. This indicates that the numerical model presented is valid and provides a promising way to simulate the combustion of solid waste in a BFB, which is the predominant technology for co-combustion of waste. The advantage of the theoretical study lies in its ability to reveal features of the detailed structure of the combustion process inside a solid bed.


## 1. Introduction

In this paper, a full overview is provided on the co-combustion characteristics of hydrothermally treated MSW (HT MSW) with coal by using a bubbling fluidized bed (BFB) reactor. Emissions and combustion efficiencies are examined here because fluidized beds always conduct the co-combustion of biomass and coal at a high efficiency [1].

From parametric studies, numerical modeling of combustion in the FB can help cut down on operation costs. In the last two decades, different numerical models have been created to study emissions from MSW, coal, or biomass combustion. A large amount of these studies have concentrated on the equilibrium and kinetic models, which depict the fluid flow with experimental or semi-empirical correlations, as opposed to understanding the transport equations [2–11]. However, in the current study, an adopted numerical model is presented, simulating the combustion process within a BFB. The significance of the presented model is that it uses a composite fuel (Coal + MSW) to determine the solid temperature and gas emissions in the fluidized bed. This model also includes sub-models for devolatilization and chemical kinetics.

The CFD model is also a very good and economical modeling tool to study the combustion process in fluidized beds. Thus, when a reliable model of CFD is found, it helps in the setting and optimization of the shape and design of the fluidized unit. Experiments conducted with a reliable CFD are considered as one of the most important and best approaches to predict critical results and important requirements for controlling and guaranteeing efficiency.

There are basically three approaches that can be used in numerical simulation, i.e., Euler-Lagrange, Euler-Euler approach, and Discrete Element Method-CFD. In the Euler-Lagrangian approach, the equations are dealt with by resolving the time average. In the Navier equations, particle quantities are given during the primary phases. Primary and dispersed phases can differ in some aspects, such as mass, momentum, and energy. It is supposed in that theory that the fractional amount of the dispersed

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amount is below 10–20% despite the fact that its mass might be larger than in the first phase. The different phases of Euler-Euler are considered as continua, i.e., each one continues with the other, so they are a function of time and place in order to introduce phase volumes. The sum of all phase volume fractions is equal to one in each cell. Formal applied laws are applied in all phases to obtain a set of equations applied in all phases. Additionally, experimental laws set the mathematical equations, and they correlate together. In the Euler-Euler approach, there are three phases that have multiphase flow, i.e., the volume of fluid (VOF), the mixture model, and the Eulerian model. The Eulerian model is essentially used to model fluidized bed systems [12].

The Lagrangian technique is based on the Euler-Lagrange approach where the fluid phase is treated as a continuum by solving the time-averaged Navier-Stokes equations. However, the dispersed phase is obtained by integrating numerically and adding together all equations of mass, which is done by calculating the number of particles in the flow.

The Euler thermal furnace model is considered if compared to CFD models as inexpensive when compared to CFD models, where it is required to put all processes on the particle scale, such as collision, drag, friction, and heterogeneous chemistry. It is also less complicated than the DPM Eulerian-Lagrangian, which simulates individual particles [13–15] as a combination of the Eulerian-Eulerian model and the E-L DPM model. We can observe one or two of the Lagrangian mass particles being introduced to an Eulerian-Eulerian bed of inert sand. Despite this, its approach is helpful to investigate one particle dynamic scale. However, the simulation is only limited to 5 s in physical time, which is why this model does not seem to be applicable for industrial reactors that have many fuel particles and require a longer simulation to obtain realistic and stable results.

Several authors have studied the mechanism of a fluidized bed theoretically because CFD can provide significant amounts of high quality information. Therefore, this technique is a useful and powerful tool for studying, designing, and scaling up fluidized beds. On the other hand, experimental assays are difficult and costly.

Grubor et al. [16] conducted experimental tests and modeling of SSR. The transformations of sulfur forms during devolatilization were taken into account via a correlation for the amount of sulfur that remained in the char after devolatilization. A novel approach was applied for modeling SSR during char combustion, which was closely related to the grain model used for $SO_2$ retention by using limestone as a sorbent. It was assumed that SSR was a result of the reaction between $SO_2$ and CaO in the form of uniformly distributed micro-grains in the char. An unreacted shrinking core model was adopted for the reactions between the CaO micro-grains and $SO_2$.

Manovic et al. [17] investigated a model of inherent $SO_2$ capture in coal particles during combustion under fluidized bed conditions. The model was based on a model of porous char particle combustion and a changing grain size model of sulfation of CaO grains dispersed throughout the char particle volume. The major advantage of the model was the incorporation of all of the known relevant processes related to sulfur self-retention, such as the phenomena of reduction of the produced $CaSO_4$ with CO, sintering, and thermal decomposition of the produced $CaSO_4$, as well as the possibility to include the different reactivities of various forms of calcium.

Mazza et al. [18] developed a non-isothermal particulate model for fluid bed MSW incineration combined with solid waste particle combustion and heavy metal vaporization from the burning particles. The model combined an asymptotic-combustion model for carbonaceous solid combustion and a shrinking-core model to describe the heavy metal vaporization phenomenon. It was in fact an improved version of a local model formulated previously, which dealt with isothermal particles.

Soria et al. [19] developed a model for predicting heavy metal vaporization during single particle MSW incineration in a fluid bed using the commercial CFD tool ANSYS-FLUENT via the porous media approach along with an extensive array of UDFs developed to evaluate the fundamental aspects of kinetic, thermodynamic, and structural characteristics of gas-solid reacting systems. This approach accounted for local variations of compositions and temperature occurring during the processes of instantaneous pyrolysis and homogeneous and residual carbon combustion.

Soria et al. [20] studied the interaction between the burning particle and fluidized bed dynamics, which represented the actual process rigorously. In this two-scale scheme, the fluid bed simulation allowed access to the set of variables in the immediate particle surroundings through its trajectory to accurately define the conditions at the local scale and to improve the representation of the heat and mass transfer phenomena that take place during the residence time of the MSW particle in the bubbling fluidized bed.

Here, a 2D Eulerian-Eulerian model is adopted in the present model to investigate the gaseous emission in a BFB coal/waste combustor. The mathematical model is applied to the BFB riser with a height of 1.1 m and a diameter of 0.077 m. The influences of changing temperature on the emissions of $SO_2$, NO, and $N_2O$ are considered. The results are compared with the experimental data to validate the model, and these results are promising for simulating the combustion of solid waste on a bubbling fluidized bed. The results are compared with the experimental data to validate the model and to provide a promising way to simulate the combustion of solid waste on a bubbling fluidized bed.

## 2. Experimental test rig

### 2.1. Material sources

MSW is generated worldwide every day in large quantities. These wastes are very complex materials requiring handling and processing facilities for disposal. However, unlike coal, in general, the composition of waste characteristics is very different at different times and different places. In addition, moisture content is one of the most serious problems hindering its further use. Therefore, in order to make MSW an eligible fuel resource substitutable for coal in the near future, targets have to be established for effective MSW utilization including pretreatment technology development. In this regard, the development of a pretreatment technology needs to be established. In particular, this condition is worse for countries with no waste separating systems, where organic and plastic wastes are still mixed in the waste disposal.

The main source of one MSW solid fuel is derived from the waste of impregnated plastic polyvinyl chloride (PVC) with high organic chlorine content. The chlorine is believed to be the origin of HCl and also dioxin emissions during the combustion process so the Cl-originated emission deserves special attention in the co-combustion of the HT MSW with coal in a coal-fired furnace. An additional organic chlorine removal process can eliminate this problem, but this usually requires high energy; therefore, a thorough waste treatment system with a dechlorination process is needed.

Based on the above-mentioned requirements, this research aims at investigating the influences of the HT MSW on the co-combustion characteristics with coals in a BFB because this is most widely used in co-combustion applications.

The MSW specimen was made out of organic material; plastic and wood wastes were pretreated in a batch- scale HT facility in Nagoya City, Japan, as shown in Fig. 1 [21]. The hydrothermal treatment technology can lead to changes over the high moisture content in the original MSW, i.e., from irregular shapes and low bulk density into a homogeneous solid powder item with low moisture content. The experimental detail is indicated in Table 1, and the fuel analysis of the coal/MSW is recorded in Table 2. The proximate analysis was performed by using a SHIMADZU D50 simultaneous TGA/DTA analyzer. HHV was measured by a SHIMADZU CA-4PJ auto-calculating bomb calorimeter.

The plant is operated to be capable of handling up to 1 ton of waste per batch and generally can apply saturated steam at approximately 2 MPa to a stirring reactor for about 1 h. Fig. 1 shows the plant process diagram, which implements a closed loop system principle.