Journal of Cleaner Production 198 (2018) 54–70

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

# Environmental assessment by dynamic full-field synergy model in co-combustion of coal and sludge with high water content

Yunsong Yu [a], Yingting Hong [a], Tao Fang [a], Zaoxiao Zhang [a, b, *], Geoff Wang [c]

[a] School of Chemical Engineering and Technology, Xi'an Jiaotong University, No.28 Xianning West Road, Xi'an 710049, PR China
[b] State Key Laboratory of Multiphase Flow in Power Engineering, Xi'an Jiaotong University, No.28 Xianning West Road, Xi'an 710049, PR China
[c] School of Chemical Engineering, The University of Queensland, St Lucia, QLD 4072, Australia

ARTICLE INFO

*Article history:*
Received 5 September 2017
Received in revised form
30 June 2018
Accepted 2 July 2018
Available online 3 July 2018

*Keywords:*
Sludge
Co-combustion
$NO_x$
$CO_2$
Dynamic
Full-field synergy

ABSTRACT

The management of industrial sludge generated considerable interest for environmental protection. The cost associated with the treatment of sludge with high water content is considerably higher before the discharge of a clean effluent. In order to reduce this cost, this study developed the co-combustion of coal and sludge with high water content in a 220 t/h boiler, to tackle the sludge and control the $SO_2$, $NO_x$, and $CO_2$ emissions from the boiler. The idea at the basis of this study was to directly eject the sludge with high water content into the boiler. A dynamic full-field synergy model was developed to perform the environmental assessment, which considers the dynamic characteristic and the full-field synergy over two co-combustion fields. Industrial field data were used to validate the model. It was found that boiler efficiency decreased only by 0.1% with sludge ejection, while flue gas moisture was almost unvaried. The $SO_2$ and $NO_x$ emissions were reduced by 14.27% and 8.23% respectively, if compared with emissions without co-combustion of coal and sludge. The results are attributed to the improved synergy effects. The drive forces of liquid and solid particles are the dominant steps for the fluid flow field transformation between the W-shape and the M-shape. The dynamic full-field synergy model, presented in this study, allows the characterization of co-combustion with 92% water content and a nozzle diameter of 1.5–3.5 mm. It accurately describes the full-field synergy effects of the field number over two, a result that could not be obtained by the conventional multi-field synergy model.


## 1. Introduction

Sludge emission from the industry sector, such as from coal chemical plants and paper mills, has a great influence on environmental degradation (Grobelak et al., 2017; Panepinto et al., 2016; Trelles et al., 2017). Sludge seriously pollutes land and water, because it is normally composed of typical pollutants such as COD, ammonia nitrogen, and TDS (Nazari et al., 2017; Yasin et al., 2017). Thus, it is important to manage industrial sludge for environmental protection (Shengquan et al., 2013; Zhang, S. et al., 2017). Technical methods to manage the sludge include separation and combustion (Areeprasert et al., 2017; Skoglund et al., 2016; Zhang, X. et al., 2017). Compared with separation, dry combustion and wet combustion are more effective technologies to mitigate the sludge. Wet combustion shows an economic advantage compared with dry combustion, due to the enormous costs involved in the drying process (Lee and Wilcox, 2017).

Direct wet combustion normally requires a furnace, which has a high cost and is normally difficult to realize, due to the long engineering period required for design and construction. To reduce costs, co-combustion with coal is usually developed. The successful co-combustion of sludge with coal has provided the basic strategy. Pilot plant-run data of 10% PDS at a moisture content of 40% strongly proved its feasibility (Coimbra et al., 2015; Hu et al., 2015). Additionally, the co-combustion of plant off-gas, sugarcane bagasse, and other biomasses in the boiler suggests that the initial size distribution of co-combustion phase like biomass fuel is crucial to achieve an efficient combustion (Bhuiyan and Naser, 2015; Centeno-González et al., 2017). These results support the development of the co-combustion of coal and sludge with high water content. Co-combustion of sludge with high-concentration water has been scarcely studied in literature, and its mechanism is still unknown. The sludge with water content above 90% is quite

* Corresponding author. School of Chemical Engineering and Technology, Xi'an Jiaotong University, No.28 Xianning West Road, Xi'an 710049, PR China.
*E-mail address:* zhangzx@mail.xjtu.edu.cn (Z. Zhang).

https://doi.org/10.1016/j.jclepro.2018.07.009

common in the coal chemical industry, especially in the coal-to-methanol process. Thus, it is worth developing the co-combustion of coal and sludge with high water content for industrial applications. Although the co-combustion of coal and sludge has already been performed at lab-scale and pilot-scale, there is little information available on applications at the industrial-scale. Hence, the aim of this work is to study the industrial-scale co-combustion of coal and sludge in a 220 t/h boiler.

As highlighted by previous studies (Areeprasert et al., 2017; Hu et al., 2015), co-combustion of sludge with coal inevitably impacts on boiler efficiency, as well as on $SO_2$ and $NO_x$ emissions. In order to control the side effects of sludge combustion, it is essential to develop an effective technology to provide a uniform inlet distribution of the sludge. Ejection technology (Sánchez et al., 2013) has succeeded to distribute the liquid uniformly. Thus, it was employed to distribute the sludge with high water content. Additionally, high-pressure air was used to enhance the ejection process and obtain properly atomized sludge. It is anticipated that the ejection with high-pressure air will generate small sludge particles, a fact that has positive impacts on co-combustion performance, while at the same time having a low impact on boiler efficiency. The process of co-combustion of coal and sludge with high water content is illustrated in Fig. 1.

To clearly understand the co-combustion of coal and sludge with high water content, a mechanism model must be developed firstly. The co-combustion of coal and sludge with high water content produces the additional liquid phase for the coal combustion in the boiler. Thus, the conventional coal combustion model can hardly describe the co-combustion process. However, the previous co-combustion CFD models give some useful information (Bhuiyan and Naser, 2015; Centeno-González et al., 2017; Manickam et al., 1998; Tan et al., 2017), which accurately provided the Mixed-is-burnt model, Lagrangian model and eddy break-up model. These CFD models include the important gas phase time-averaged transport models for mass, momentum, and energy, which clearly quantify particle track, temperature distribution, and $NO_x$ emission amount. All these results can be extended to quantify the co-combustion of coal and sludge with high water content. However, the presence in these models of deviations in the empirical correlations or in the simple linear assumptions for the interactive effects, suggest the need to perform more in-depth investigations.

In particular, it is necessary to determine the interactive effects between the combustion of sludge with high water content and coal combustion. These interactive effects are related to the coupling of heat transfer, mass transfer, and reaction. The field synergy model (Minea and Manca, 2017; Yu et al., 2010, 2011) successfully characterizes the interactive effects. For this reason, it has great potential to describe the co-combustion of coal and sludge with high water content. The problem is that the linear coupling multi-field synergy model does not describe the strongly non-linear co-combustion process. In a previous study, field synergy considered the synergy of two fields, which only analyzes the case of field number of two. However, as full-field in the co-combustion of coal and sludge involves more than two fields, the conventional linear coupling can not characterize the full-field. Thus, the field synergy model was extended to the dynamic full-field synergy model, to describe the coupling of heat transfer, mass transfer, and reaction in the co-combustion. The dynamic full-field synergy model was expected to quantify the interactive effects between coal particles, sludge particles, and air since it fundamentally incorporates velocity, concentration, and temperature fields. Additionally, the dynamic full-field synergy model offers a better description of the dynamic effects of sludge ejection on the field synergy, an aspect which is currently not well understood.

The dynamic full-field synergy model was used to study the co-combustion performance, such as boiler efficiency, and $SO_2$ and $NO_x$ emissions. Additionally, the effects of co-combustion positions and inlet pressures and velocities were studied. Subsequently, we determined the optimum conditions for the co-combustion of coal and sludge with high water content. It is expected that ammonia nitrogen, water, and TDS will help the coal burn more completely and reduce the $SO_2$, $NO_x$, and $CO_2$ emission amount by reaction. This will demonstrate the additional value of the co-combustion of coal and sludge, besides managing the sludge.

## 2. Dynamic full-field synergy of co-combustion model

### 2.1. Model

The critical velocity of the liquid particles is quantified according to the field synergy, which describes the synergy effects between the particles and the continuous phase. This is developed by revising the model (Duan et al., 2017) with the synergy angle, in the following way:

$$u_l{}^* = \sqrt{\frac{12\sigma \cos \theta}{\gamma_l d_l}} \quad (1)$$

$$u_p{}^* = \sqrt{\frac{12\sigma \cos \beta}{\gamma_p d_p}} \quad (2)$$

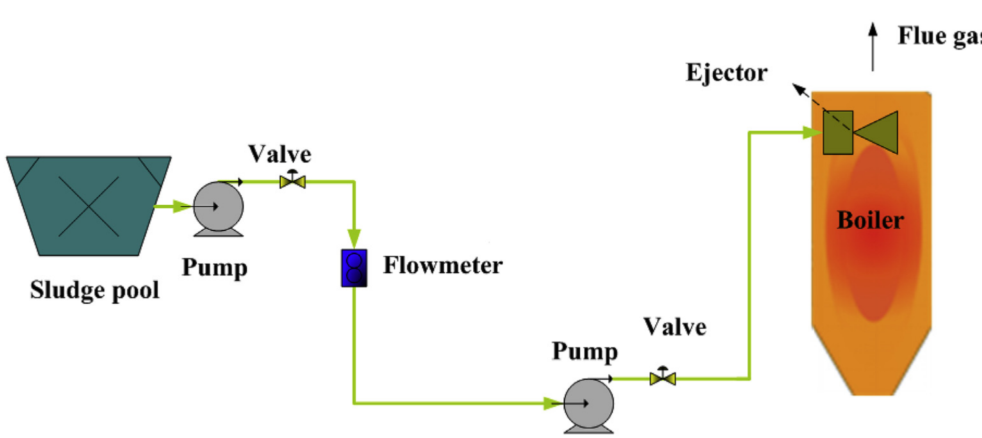


**Fig. 1.** Co-combustion of coal and sludge with high water content by ejection.