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Review article

Mechanisms and mitigation of agglomeration during fluidized bed combustion of biomass: A review

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ABSTRACT

A key issue associated with fluidized bed combustion of biomass is agglomeration. The presence of high quantities of alkali metal species in biomass ash leads to the formation of sticky alkali silicate liquid phases during combustion, and consequently the adhesion and agglomeration of bed material. This review examines probable mechanisms of agglomeration and the effects of operational variables in reducing its severity. Additionally, an overview of monitoring and prediction of agglomerate formation is given. Two key mechanisms of agglomeration are apparent in literature, and both may occur concurrently depending on fuel composition. Coating-induced agglomeration is defined by the interaction of alkali metals in fuel ash with silica in the bed material to form an alkali silicate melt. Melt-induced agglomeration is defined by the presence of sufficient amounts of alkali metals and silica in the fuel ash which together form a eutectic melt. Physical mechanisms, such as tumble agglomeration and sintering, may further enhance either of the coating-induced or melt-induced mechanisms. Of the operational variables examined in this review, temperature, fluidizing gas velocity, fuel, bed material and additives have been shown to have the greatest effect on agglomeration severity. Prediction of agglomeration propensity may be attempted with mathematical correlations or lab-scale fuel testing before use in the boiler, or with in-situ methods, which are typically focused on temperature or pressure analysis. The review of the literature has highlighted the need for further research in several areas, including: mechanisms when using alternate bed materials, use of dual-fuel biomass blends, technical and economic optimisation of the use of alternative bed materials and additives, and further modelling of coating growth behaviours.

1. Introduction

In recent decades, there has been an increased importance placed on fuels and power generation methods that emit reduced amounts of carbon dioxide (CO_2), a key contributor to anthropogenic changes to the atmosphere [1]. One fuel type that may be used to address this issue is biomass, due to its potential to approach carbon neutrality [2]. Biomass has thus been the subject of research into technical issues that may negatively affect its use in the power generation industry, and policy driven regulation to incentivize its deployment.

Biomass is a direct, low carbon alternative to fossil fuels for power and heat generation, and is abundant in many areas of the world [2,3]. It is used in both combustion and gasification systems [4,5], with Saidur et al. [6] giving abroad review on use of biomass as a fuel. In the UK, it can offer competitively priced power generation versus options such as nuclear and offshore wind [7]. The combustion of biomass comes with several technological challenges for traditional pulverized fuel burner technologies [8–10], such as: low energy density after initial harvesting, variable volumes of non-combustible contaminants, high moisture contents and, in most applications, requiring a large amount of pre-processing/pre-treatment with specialised transportation. Due to these challenges, technologies such as fluidized bed combustion (FBC) boilers have been employed.

FBC boilers are a relatively mature technology, with numerous comprehensive works available detailing their design, design variants, operation, and scale-up challenges [9–13]. FBC offers a number of advantages, such as combustion of different fuel types, blends, and ranges of qualities, features commonly referred to under the umbrella term of "fuel flexibility" [8]. Hundreds of full-scale bubbling fluidized bed (BFB) and circulating fluidized bed (CFB) boilers have been deployed around the world [14,15] for power generation. However, each FBC boiler development has to overcome slagging, fouling, corrosion, and agglomeration issues resulting from the composition and behaviour of the biomass fuel stock [16].

Analytical studies of wide ranges of fuel types have shown biomass fuels to be high in volatiles and moisture, with mineral matter content

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Nomenclature

AFBC	Atmospheric fluidized bed combustion
BFB	Bubbling fluidized bed
CFB	Circulating fluidized bed
d_{bed} (m)	Bed diameter
DDGS	Distillers dried grain using wheat and solubles
FBC	Fluidized bed combustion
h_{bed} (m)	Static bed height
IDT	Initial deformation temperature
MSW	Municipal solid waste
PF	Pulverized fuel
PFBC	Pressurized fluidized bed combustion
SEM/EDX	Scanning electron microscopy with energy dispersive X-ray spectroscopy
T_{aggl} (°C)	Agglomeration temperature
t_{def} (mins)	Defluidization time
U (m/s)	Superficial gas velocity
U/U_{mf} (−)	Fluidization number
U_{mf} (m/s)	Minimum fluidization velocity
XRD	X-ray diffraction

rich in alkali and alkaline earth metals such as potassium and calcium [6,17–19]. A recent extensive review and study by Vassilev et al. [20] examined ash compositions and behaviours during combustion for a wide range of biomass fuels, including the potential effects of biomass blends, and illustrated the high complexity and variation in biomass ash. Saidur et al. [6] placed biomass fuels into one of three different categories based upon their fuel ash composition:

- Ca- & K-rich, Si-lean. Typically woody biomass.
- Si- & Ca-rich, K-lean. Typically herbaceous or agricultural.
- Ca-, K-, & P-rich, e.g. sunflower stalk ash or rapeseed expeller ash.

The above components in biomass ash, together with sodium and chlorine, have been identified as being responsible for agglomeration, slagging, fouling, and corrosion in FBC boilers [17,21].

Agglomeration occurs within the bed itself, and is where bed particles begin to group together into larger particles [21] (Fig. 1). In the case of biomass combustion on a silica sand bed, this is due to the formation of sticky alkali silicate complexes of low melting temperature. These agglomerates may be further strengthened by sintering, in which high, localised temperatures leads to the melting of particles and the fusing together of agglomerates into large, hardened structures. This method of agglomeration, in which fuel ash interacts with bed material, is typically termed coating-induced agglomeration. When fuel ash contains quantities of both silica and alkali metals sufficient to create eutectic melts, the term melt-induced agglomeration is commonly used. The accumulation of agglomerates eventually leads to defluidization of the bed. This is the point at which the bed particles no longer behave as a fluid in response to the fluidizing gas, as the mean bed particle size will have increased and the minimum fluidization velocity, U_{mf}, is no longer achieved [22].

In an industrial installation, operators may control agglomeration by varying fuel feeds, using alternative bed materials and/or additives, moderating combustion temperatures and combustion distribution, altering airflows, or varying rates of bottom ash removal and bed replenishment [23,24]. A full bed defluidization event would necessitate a plant shutdown, as the bed is cooled, replenished, and started up again [25]. The financial cost associated with unscheduled plant outages can mean that the profitability of the plant may be at risk. Moreover, frequent start-up and shutdown cycles may reduce the working lifespan of plant equipment [26, pp. 38–42]. As such, considerable efforts have been made towards methods to predict or prevent agglomeration [27].

Considering the upper sections of the boiler, slagging on the tube walls, fouling on superheater tubes [28–30], as well as corrosion [29,31–33] are driven by reactions with the same chemical components as agglomeration, namely, alkali and alkaline earth metals, and silica, with chlorine aiding alkali transport [34] (see Fig. 2). Therefore, it is important to consider the whole boiler system, and the secondary or consequential negative impacts when evaluating a potential mitigation measure for any of the aforementioned ash phenomena.

Prior reviews in the field of FBC of biomass have looked broadly at all ash challenges (agglomeration, slagging, fouling, corrosion) [16,29], or focused on modelling [36] or the prediction of agglomeration [27], with others only briefly considering the mitigating effects of operational parameters on agglomeration [37,38]. This review sets out to bring together the current literature on the mechanisms of agglomeration, means of mitigating it through varying operational conditions, and the relationships between both areas. Additionally, an overview on work around agglomeration prediction is provided. Literature from lab-scale work through to investigations on full-scale industrial boilers has been selected, so that this review may be of use to both researchers and plant operators. In doing so, this review has also highlighted numerous areas in which further work would be beneficial to both broaden and deepen the knowledgebase.

1.1. Review scope

This review focuses on the issue of agglomeration during FBC of biomass, and is divided into three sections:

- A review of the mechanisms of agglomeration found within the literature.
- A review of the effects of process variables on agglomeration severity.
- A brief overview of the current methods to predict the occurrence of agglomeration, with signposting to the other available articles and reviews on this subject.

Summaries are provided after each section. These act to highlight key findings from the literature evaluated, note the important critiques, and discuss key areas for further work noted within the review. The end conclusion highlights the main areas where further work is needed.

Fig. 1. Image of several agglomerate samples collected from a 50 kW_{th} fluidized bed combustion unit using wheat straw pellets on a quartz sand bed. Picture from the unpublished, in-progress work of the authors.