CHAPTER 8

Slagging and Fouling Risks Derived from the Combustion of Solid Biofuels

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Abstract

The interest in biomass combustion has grown exponentially in the last years, as it represents a means of renewable heat and energy that also promotes local development and mitigates climate change. However, the slagging and fouling risks of many potential feedstocks, given their high alkali, silica or chlorine contents, currently limit their application in combustion processes. This chapter presents various methods for monitoring biomass slagging and predicting fouling hazard. Discussion also addresses how the presence of such components may affect the formation of deposits in biomass boilers.

Keywords: Slagging, fouling, biomass combustion.

1 Introduction

One problem associated with biomass combustion concerns the ash generated in the process. Ash is a by-product that calls for appropriate management, and it moreover can lead to problematic phenomena such as slagging and fouling during the thermal conversion process itself \cite{1}. It is, thus, a problem deriving both the quantity and the quality of the biomass ash. Both aspects are strongly influenced by the origin and characteristics of the biomass used \cite{2,3}.

Biomass composition, together with boiler design and operation, influences the composition of the ashes produced and consequently their final behaviour. Problems caused by low melting temperatures of the ashes may include fireside deposits of sintered or molten ash, which are due to the presence of very high contents of mineral oxides in some biomasses \cite{4–7}.\footnote{www.witpress.com, ISSN 1755-8336 (on-line) doi:10.2495/978-1-84566-062-8/008}
All facilities suffer economic loss from fireside deposits, but especially those firing more of the agricultural and urban fuels and less of the clean wood fuels. Although wood fuels are inherently low in slagging tendencies, adventitious materials such as clays and other soil components brought in with the fuel can also lead to fouling [8].

Ash deposits deteriorate burning, retard heat transfer, cause high-temperature corrosion and super-heater explosion, and can provoke mechanical failures [9–11], meaning greater maintenance costs and availability losses. Predicting sinter and slag formation in biomass combustion is essential to establish the biofuel quality and quality standards, and to determine which alternatives could minimize these effects in combustion furnaces [12].

2 Methods to Predict the Slagging and Fouling Tendencies of Biomass Fuels

Slagging occurs in the boiler sections that are directly exposed to flame irradiation. The mechanism of slag formation involves stickiness, ash melting and sintering. Slagging deposits consist of an inner powdery layer followed by silicate and alkali compounds [6,13].

On the other hand, fouling deposits are formed in the convective parts of the boiler. The mechanism of fouling is mainly due to the condensation of volatile species vaporized in previous boiler sections and is loosely bonded [13].

Slagging and fouling tendencies are directly related to the composition of the biomass fuels, as explained in this section.

2.1 Threshold values for critical elements of fuel composition and slagging and fouling indexes

2.1.1 Silicon

Fuels with high silicon content, either from intrinsic contamination or external contamination, generally show relatively high slagging tendencies [14–16]. In the study by Öhman et al. [15], a significant number of wood pellets reported to be either problematic or else problem-free regarding slagging were collected from ordinary residential pellet burners on the Swedish market. They showed that the problematic stem wood pellets had a significantly higher amount of Si in the fuel.

Si content in the fuel has correlated relatively well to the sintering tendencies in burners in several studies [14,17–19]. Exceptions to these general trends exist as well, i.e. fuels with very high Si/K ratios [16,17].

From these results, Öhman et al. [15] proposed a threshold of SiO$_2$ of 20%–25% of the fuel ash, the pellets with levels in or over this range being those that resulted in slagging problems in residential burners. Similarly, Vega-Nieva et al. [18–20] observed higher slagging tendencies in fuels with a lower basic ash percentage (e.g. higher amounts of silica and phosphorus in their composition); they proposed similar threshold values for the basic ash percentage in the fuel to prevent slagging. These
indexes have been validated by combustion tests of agricultural and forest biomass fuels and have shown the potential to predict slagging occurrence and to design mixtures of fuels with a composition that minimizes slagging [19–21].

2.2 Alkali metals

Fuels with large contents of silica and potassium can result in the formation of K silicates [4,6,22], which create deposits in the boiler. Alkali metals react with silica contained in the ash, forming silicates with a very low melting point (<800°C) that deposit near the bed surfaces [23]. This is typical of some herbaceous fuels such as wheat or sorghum, fuels with potential slagging and fouling problems at temperatures above 700°C–800°C [24,25].

Miles et al. [26] found the alkali content of the fuel to be a key indicator of the slagging and fouling problems in the boilers and proposed the alkali index in eqn (1) to monitor the amount of alkali in fuels to minimize slagging and fouling occurrence

\[
\text{AlkaliIndex} = \frac{(K_2O + Na_2O) \cdot Ash(\%)}{HHV}
\]  

(1)

here HHV is the higher heating value (MJ/Kg) at \(H = 0\%\); and \(K_2O\) and \(N_2O\) are expressed as the percentage of these components in the fuel composition in d.b.

According to this index:

• Alkali index > 0.17 kg alkali/MJ \(\rightarrow\) probable fouling.
• Alkali index > 0.34 kg alkali/MJ \(\rightarrow\) fouling is certain to occur.

Nevertheless, some limitations have been identified when this index is used with low alkali fuels that present high melting risk at low temperatures, such as some agricultural shells [27]. Alternative alkali indexes have been presented by Fernández Llorente et al. [12] or Vega-Nieva et al. [18–20,27,28], among others.

2.3 Chlorine

Chlorine plays a shuttle role, facilitating the transfer of potassium in the gas phase, where it participates in further reactions or is deposited on cold surfaces. On these surfaces, the chlorine is substituted by sulphur, forming potassium sulphate deposits and/or reacting with the metal’s protective oxide layer, thereby initiating corrosion [13,23].

Bryers [6] and Pronobis [7], among others, have established the following values to limit Cl-based slagging and fouling in biomass fuels, where Cl represents the chlorine content (%) of the sample dry weight:

• \(\text{Cl} < 0.2\) \(\rightarrow\) low slagging trend.
• \(0.2 < \text{Cl} < 0.3\) \(\rightarrow\) medium slagging trend.
• \(0.3 < \text{Cl} < 0.5\) \(\rightarrow\) high slagging trend.
• \(\text{Cl} > 0.5\) \(\rightarrow\) very high slagging trend.
Obernberger et al. [29] gave a more conservative threshold, indicating that when Cl is higher than 0.1, there is a risk for corrosion and HCl emissions.

2.4 Ash melting temperatures

The ash fusibility test (AFT) is based on a continuous process that can be characterized by different temperatures according to norms ISO 540 [30] and DIN 51730 [31]. These temperatures are defined below and shown graphically in Fig. 1:

(a) Deformation temperature (DT): Temperature at which the first signs of rounding occur, due to melting of either the tip or edges of the test piece.
(b) Sphere temperature (ST): Temperature at which the edges of the test piece become completely round, the height becoming equal to the width of the baseline.
(c) Hemisphere temperature (HT): Temperature at which the test piece is approximately hemispherical, the height being equal to half the base diameter.
(d) Flow temperature (FT): Temperature at which the test piece material has spread out so that its height is one-third of that at the hemisphere temperature.

A large number of authors have proposed predictive functions of ash fusion temperatures from ash composition for coals [6]. Information on such predictive functions for biomass, however, remains scarce [32,33].

Figure 1: Ash fusibility temperatures [30,31]: (a) DT, (b) ST, (c) HT and (d) FT.
The standard AFT is extensively criticized in the literature, because of its lack of representativity, the low rate heating conditions utilized in the test, the low method repeatability and the lack of correspondence with observed boiler ash behaviour [34–39].

Hjuler [37] claims that the primary reason for unsuitability of the standard ash fusion test for biomass ashes is that biomass typically contains relatively high amounts of low melting components; these flow down in the test body due to gravity, leaving a skeleton of high melting minerals that may contain, for example, silicon and calcium. The initial low-temperature melt formation is not detected by the standard test because it does not affect the overall shape of the test body.

Many authors have, indeed, reported melting at temperatures below the standard measured ash fusion temperatures [34,38,39]. For instance, Skrifvars et al. [38] found that the ASTM standard ash fusion test generally gave temperatures 50°C–500°C higher than combustion tests. Gilbe et al. [39] found that the results from the standard ash fusion test [30] showed relatively high deformation temperatures in general, and therefore predicted a less problematic behaviour on the part of various biomass fuels in comparison to the actual slagging tendencies observed in controlled combustion experiments involving commercial pellet burner equipment.

2.5 Simple subjective slagging tests

Given the unreliability of ash fusion temperature tests for predicting slagging in biomass boilers during combustion processes, simple and fast slagging tests are used operationally by pellet and boiler manufacturers for the on-site quality control of fuels. Within the European project Domoheat – concerned with the combustion of Mediterranean biomass fuels in small and medium-sized pellet boilers – simple, rapid tests were conducted to study the combustion of a small amount of fuel at temperatures from 900°C to 1100°C, as shown in Fig. 2 [18,19,28].

Similar tests have been tested in the BIONORM and AshmelT projects [40,41]. As these methods can be useful for fast quality control of fuels in situ, they do not offer quantitative results and are subjected to a great degree of subjectivity in the interpretation of the results (e.g. YES/NO slagging scale).

2.6 Slag and ash granulometric (SaG) method

A quantitative slagging test based on the combustion of a representative amount of fuel was developed by the Faculty of Forest Engineering of the University of Vigo. The method entails the combustion of 200–250 g of biomass fuel in a 500-ml crucible following a defined temperature program reaching temperatures of 900°C–1100°C (Fig. 3). It offers a quantitative ranking of the slagging tendency of the fuels, based on the total calcinated weight percentage as well as the ash and slag size distribution. SaG method results were validated with combustion results from the Domoheat Project [18,19,28]. They are now undergoing further testing:
Figure 2: Simple rapid slagging test results for rye straw pellet, pinecone seed shell, almond shell, poplar chip, pine pellets and oak pellets from the Domoheat Project. Boiler bottom ash and slag are shown at the right picture. Slagging risk could be detected with simple rapid tests for rye straw, pinecone seed shell and almond shell samples (marked in red), which showed initial deformation temperatures <1,000°C. Neither ash fusion temperatures nor rapid tests could detect the moderate slagging present in soil-contaminated samples poplar chip and pine pellet (marked in green) [19].

the AshmelIT project is an on-site operational test for measuring slagging risk of woody and herbaceous pellets requiring no special equipment [19,41,42].

This method has been utilized for the quality control of several wood chips and wood pellet SMEs within recent projects focusing on wood chip quality [21,43]. It has demonstrated great sensitivity for spotting moderate slagging tendencies caused by soil contamination and bark in woody biomass fuels (Fig. 4).

The SaG method has demonstrated utility to detect slagging in both woody and herbaceous fuels. These include herbaceous pellets of wheat straw, rapeseed or miscanthus, several types of shells such as almond shell, pinecone seed shell or olive stone, wood chips and wood pellets.
Currently subjected to a Round-robin test coordinated by AshmelonT project partners at various European laboratories, the SaG test has been identified as a potential ISO standard for the measurement of slagging in the context of biomass fuels [42].

3 Conclusions

Biomass slagging represents one of the main barriers for the establishment of reliable certification systems and for the utilization of residual biomass and new...
energy crop biomass sources. Theoretical slagging indices based on ash composition have demonstrated the potential for monitoring and preventing biomass slagging, but further research is needed to validate such indices under varying combustion equipment technologies and varying operating conditions. A main barrier is the absence of a reliable ash slagging test to be included in the certification system of pellets, given the limitations of the current standard to provide reliable slagging risk estimations. New tests such as the SaG test have shown promise in the realm of biomass feedstock, including woody and herbaceous residual biomass, woody chips, agricultural shells and both woody and herbaceous pellets. Ongoing research on the validation of such methods may lead to the establishment of sound biomass slagging monitoring standards.
References


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