Prediction of Agglomeration, Fouling, and Corrosion Tendency of Fuels in CFB Co-Combustion

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PREDICTION OF AGGLOMERATION, FOULING, AND CORROSION TENDENCY OF FUELS IN CFB CO-COMBUSTION

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Abstract: Prediction of agglomeration, fouling, and corrosion tendency of fuels is essential to the design of any CFB boiler. During the years, tools have been successfully developed at Foster Wheeler to help with such predictions for the most commercial fuels. However, changes in fuel market and the ever-growing demand for co-combustion capabilities pose a continuous need for development. This paper presents results from recently upgraded models used at Foster Wheeler to predict agglomeration, fouling, and corrosion tendency of a variety of fuels and mixtures. The models, subject of this paper, are semi-empirical computer tools that combine the theoretical basics of agglomeration/fouling/corrosion phenomena with empirical correlations. Correlations are derived from Foster Wheeler's experience in fluidized beds, including nearly 10,000 fuel samples and over 1,000 tests in about 150 CFB units. In these models, fuels are evaluated based on their classification, their chemical and physical properties by standard analyses (proximate, ultimate, fuel ash composition, etc…) alongside with Foster Wheeler own characterization methods. Mixtures are then evaluated taking into account the component fuels. This paper presents the predictive capabilities of the agglomeration/fouling/corrosion probability models for selected fuels and mixtures fired in full-scale. The selected fuels include coals and different types of biomass. The models are capable to predict the behavior of most fuels and mixtures, but also offer possibilities for further improvements.

Keywords: agglomeration, fouling, corrosion, co-combustion, CFB

INTRODUCTION

Prediction of agglomeration, fouling, and corrosion tendency of fuels is essential to the design of any CFB boiler. During the years, tools have been successfully developed at Foster Wheeler to help with such predictions for the most commercial fuels. However, changes in fuel market and the ever-growing demand for co-combustion capabilities pose a continuous need for development. This paper presents results from recently upgraded models used at Foster Wheeler to predict agglomeration, fouling, and corrosion tendency of a variety of fuels and mixtures.

DESCRIPTION OF MODELS

Agglomeration, fouling, and corrosion probability models, which are subject of this paper, are semi-empirical computer tools that combine the theoretical basics of agglomeration/fouling/corrosion phenomena with empirical correlations. Correlations are derived from Foster Wheeler's experience in fluidized beds, including nearly 10,000 fuel samples and over 1,000 tests in about 150 CFB units. As a result, the models generate a probability index (PI), which quantifies a tendency of fuels or fuel mixtures to agglomerate (AgglPI), foul (FoulPI), and corrode (CorrPI). All PI-values range from 0 to 10, with the following meaning: $0 <$ low ≤ 2; $2 <$ medium < 4, $4 \leq$ high < 5, and $5 \leq$ very high < 10. It is important to note that these models do not take into account specific boiler design and operational parameters, but they describe a fuel propensity towards agglomeration, fouling, and corrosion in the boiler design that is Foster Wheeler's standard for that type of fuel. The actual rate of agglomeration, fouling and corrosion in a given design, and a given set of operational parameters are computed with other tools (not subject of this paper) where AgglPI, FoulPI, and CorrPI are among input values.

In all three probability models, fuels are evaluated based on their classification, their chemical and physical properties by standard analyses (proximate, ultimate, fuel ash composition, etc.) alongside with Foster Wheeler own characterization methods. The input data to the probability models are listed in Table 1 for seven selected fuels among coals and biomass. Mixtures are evaluated according to their composition, and not based on the probability indexes calculated for the individual fuels.

Table 1 Fuel properties

		CASE 1			CASE 2			
		Coal A	**Rice husk**	**Eucalypt. bark**	**Coal B**	**Straw 1**	**Straw 2**	**Rapeseed residue**
LHV	MJ/kg a.r.	26.29	12.98	6.05	22.69	14.85	15.08	18.85
Moisture	wt% a.r.	7.2	11.0	54.0	16.0	14.0	12.0	7.8
Ash	wt% dry	17.5	17.3	9.7	17.5	4.9	5.4	7.5
Sulfur	mg/kg dry	5,200	4,00	600	7,500	950	1,000	7200
Chlorine	mg/kg dry	200	1,500	4,070	490	1,300	1,900	2,600
Sodium, pH 3 soluble	mg/kg dry	52	79	78	180	170	97	4,325
Potassium, pH 3 soluble	mg/kg dry	86	3,900	2,429	89	5,900	6,600	12,297
Calcium, pH 1 soluble	mg/kg dry	2,000	900	45,000	5,700	2,300	2,900	7,430
Sodium	wt% ash	0.1	0.0	0.0	0.4	1.2	1.2	6.2
Potassium	wt% ash	4.0	3.4	2.0	1.1	9.4	9.4	16.4
Calcium	wt% ash	1.2	0.9	38.4	3.4	4.8	4.8	9.4
Magnesium	wt% ash	0.5	0.3	1.1	1.0	0.7	2.5	6.0
Aluminum	wt% ash	15.7	0.0	0.6	13.0	0.8	0.8	0.1
Iron	wt% ash	3.1	0.5	1.3	4.1	0.2	2.3	0.2
Silicon	wt% ash	25.1	41.5	1.7	27.0	33.0	33.0	0.3
Titanium	wt% ash	0.5	0.0	0.1	0.8	0.0	0.0	0.0
Phosphorous	wt% ash	0.1	1.1	0.4	0.4	1.6	1.6	15.3

The agglomeration probability model is based on the hypothesis that alkali elements (sodium (Na), and potassium (K)), and phosphorous (P) from fuel, and quartz particles (SiO_2) from bed material can form low-temperature melting compounds and/or eutectics that lead to agglomeration (Barišić et al., 2008; Coda Zabetta et al., 2008). Only alkali that are soluble at pH 3 are assumed to engage in the agglomeration reactions. The probability of agglomeration, which is caused by the presence of suitable forms of alkali in the fuel, is reduced when the fuel contains aluminosilicates, especially from the kaolinite group of minerals (Davidssson et al., 2007; Davidssson et al., 2008).

The fouling probability model is based on the hypothesis that compounds of alkali (sodium (Na), and potassium (K)), and earth alkali elements (calcium (Ca), and magnesium (Mg)) from fuel can initiate fouling while compounds of aluminum (Al) and silicon (Si) can reduce the fouling tendency of a fuel. Alkali soluble at pH 3 are especially prone to deposit on convective heat exchangers. Compounds of zinc (Zn) and led (Pb) that are also known to contribute to fouling of heat exchangers are not included in the current version of the model.

The corrosion probability model is based on the hypothesis that corrosion of heat exchangers is induced by the chlorine (Cl) present in fuel. Corrosion is correlated with fouling so that if fouling is low then corrosion is also low, while if fouling is high the corrosion probability can be high or low depending on the availability of chlorine from the fuel. The availability of the chlorine to induce corrosion can be reduced by the presence of sulfur oxides (SO_2, SO_3) that form from the fuel during combustion, and if fuel contains minerals of kaolinite group (Aho et al., 2008; Davidsson et al., 2007; Davidsson et al., 2008; Hindiyarti et al., 2008; Kassman et al, 2006; Miettinen Westberg et al., 2003; Skog et al, 2008). The corrosion induced by compounds of Zn and Pb as well as by metallic aluminum (Al) is not included in the current version of the model.

The following chapter presents the predictive capabilities of the agglomeration/fouling/corrosion probability models for selected fuels and mixtures fired in full-scale. The selected fuels include coals and biomass of growing commercial interest.

CASE STUDIES

Case 1: co-combustion of coal A, rice husk, and eucalyptus bark

Figure 1 shows the predictive capability of the agglomeration, fouling and corrosion probability models for co-combustion of coal A, rice husk and eucalyptus bark – Case 1. Corresponding fuel properties are given in Table 1.

Agglomeration (Fig. 1(a)): For all three fuels and their mixtures the agglomeration probability is in the low range. This trend has been verified in a commercial CFB boiler (370 MW_{th}, 134 kg/s, 542 ºC) as highlighted by an asterisk on the figure.

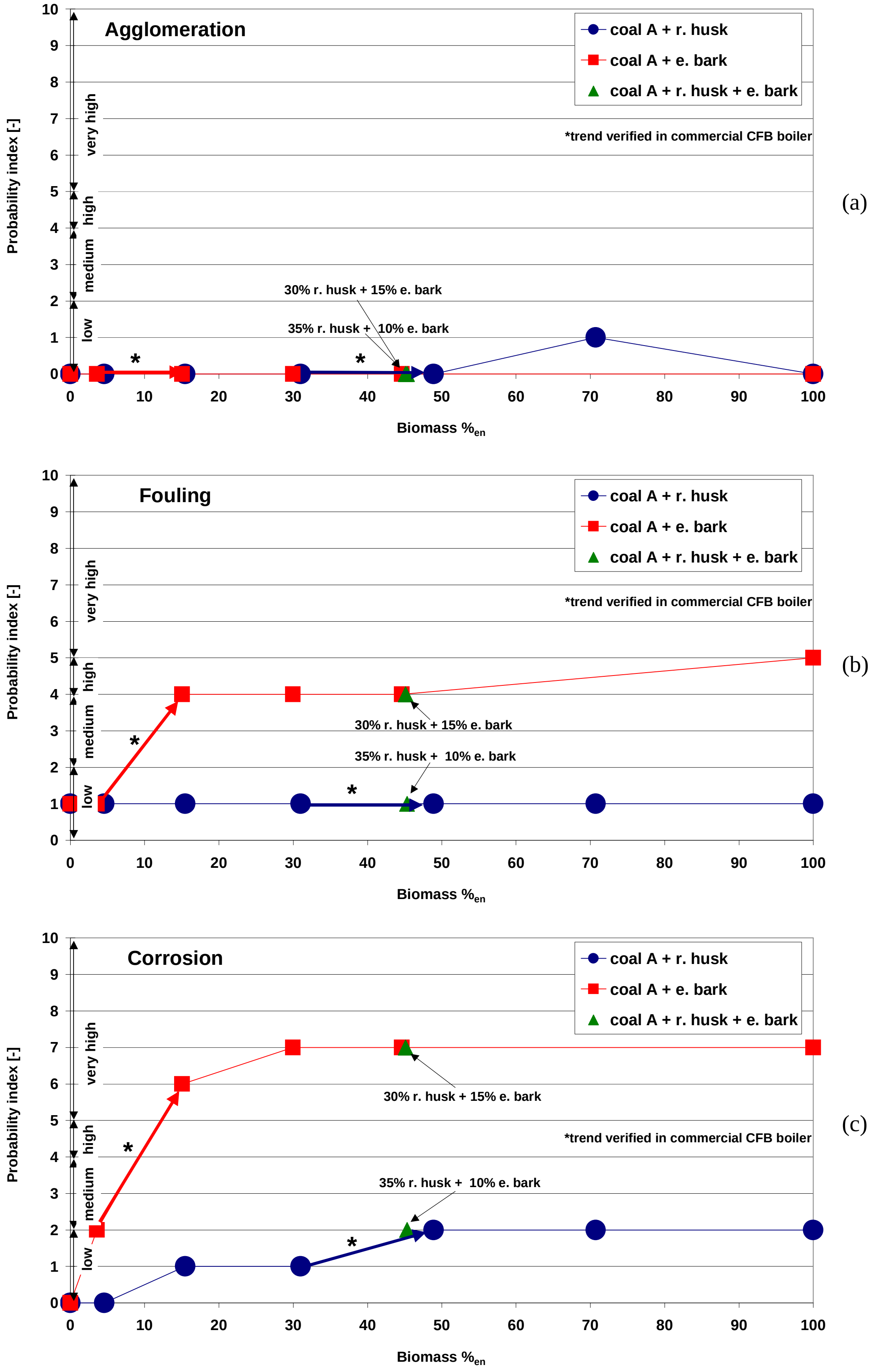

Fig. 1 (a) Agglomeration, (b) Fouling, and (c) Corrosion probability index for Case 1: mixtures of coal A, rice husk, and eucalyptus bark. The symbol “*”indicates that the trend has been verified in tests at 370 MW_{th}, 134 kg/s, 542 ºC CFB boiler

Fouling (Fig. 1(b)): The model clearly predicts different fouling trends for the two types of biomass, and the corresponding co-combustion mixtures. The low fouling tendency of rice husk results from its high ash content for biomass, and silica-based composition. Since coal A is also non-fouling, all mixtures of rice husk and coal A show low fouling probability. Contrary to rice husk, eucalyptus bark is prone to increase fouling of convective heat exchanges due to its elevated contents of chlorine in connection with high potassium and calcium. The fouling probability model predicts that an addition of more than $5\%_{en}$ of eucalyptus bark to coal A can increase the fouling probability from low to high level.

Figure 1b also shows two calculations for a mixture of $55\%_{en}$ coal and $45\%_{en}$ biomass, where biomass includes both rice husk and eucalyptus bark. The fouling tendency of the fuel mixture is strongly dependent on the share of eucalyptus bark: the model predicts significantly higher fouling probability for the mixture that includes $15\%_{en}$ eucalyptus bark, compared with the mixture with $10\%_{en}$.

The behavior of rice husk has been reported previously (Skrifvars et al., 2005; Hupa, 2008; Hiltunen et al., 2008), and the calculated trend during co-combustion has been verified in test at 370 MW_{th}, 134 kg/s, 542 ºC CFB boiler (see asterisk in Fig. 1(b)).

Corrosion (Fig. 1(c)): Similarly to fouling, the corrosion probability results depend strongly on the type of biomass in the fuel mixture. Rice husk shows low corrosion probability, even though not entirely insignificant for shares of more than $30\%_{en}$. Eucalyptus bark shows very high corrosion probability due to its high chlorine content, and lack of fuel components that can counteract chlorine-induced corrosion tendency. Addition of eucalyptus bark to coal A significantly increases the corrosion probability of the fuel mixture, and shares of more than $5\%_{en}$ lead to very high corrosion probability. When both rice husk and eucalyptus bark are mixed with coal A, the share of eucalyptus bark can be higher compared with the mixture without rice husk, $10\%_{en}$ and $5\%_{en}$ respectively, due to the favorable effect of silica-based ash of rice husk. The asterisk in Figure 1c indicates the trend calculated by corrosion probability model that has been verified in tests performed at commercial CFB boiler (370 MWth, 134 kg/s, 542 ºC).

It is important to underline once again that the results presented here refer solely to fuel properties, and do not take into account design and operational adjustments that can by applied to favor the utilization of demanding fuel mixtures.

Case 2: co-combustion of coal B and straw, or rapeseed residue

Figure 2 shows the predictive capability of the agglomeration, fouling and corrosion probability models for co-combustion of coal B with two varieties of straw, or co-combustion of coal B with rapeseed residue. Corresponding fuel properties are given in Table 1.

Agglomeration (Fig. 2(a)): Even though the two considered straws have the same agglomeration probability when fired alone, the model predicts different behaviors during their co-combustion with coal B. Straw 1 can be fired up to $40\%_{en}$ with low agglomeration tendency, while already at $30\%_{en}$ straw 2 shows medium probability of agglomeration due to the higher content of alkali compared with straw 1. The probability of agglomeration is higher for rapeseed residue compared with straws, and that is due to high alkali and especially high phosphorous content in this type of fuel (Barišić et al., 2008).

The agglomeration tendency of straw and rapeseed residue has been reported previously (Hiltunen et al., 2008; Barišić et al., 2008), and the calculated trend during co-combustion has been verified for straw in test at 77.5 MW_{th}, 29 kg/s, 505 ºC CFB boiler, and for rapeseed in tests at 12 MWth CFB boiler of Chalmers University of Technology.

Fouling (Fig. 2(b)): Higher content of soluble potassium and calcium in straw 2 increases the fouling tendency of the mixture with coal B compared with the co-combustion of the same coal with straw 1. Co-combustion with either straw, however, shows very high fouling probability for mixtures of more than $50\%_{en}$ of straw. The fouling as well as the agglomeration model (see also Fig. 2(a)) predicts that mixtures with $70\%_{en}$ of straw have higher fouling/agglomeration tendency than $100\%_{en}$ of straw. This behavior is unlikely, but it is a recognized imperfection of the models which, at the current stage of their development, tend to misestimate some of co-combustion scenarios. However, the coal mixtures with over $70\%_{en}$ of straw are currently of marginal commercial interest due to well known severe agglomeration, fouling, and especially corrosion propensity of this fuel in CFB combustion.

The fouling probability of rapeseed residues is higher compared with straws. Calculations show that firing more than $15\%_{en}$ of rapeseed residue leads to high fouling and increases with further addition of this type of fuel to the mixture with coal B. Very high fouling tendency is connected with high content of alkali, calcium, chlorine and phosphorous in rapeseed residue. The asterisks in Figure 2b indicates the trend calculated by fouling probability model that has been verified in tests performed at commercial CFB boilers.

Corrosion (Fig. 2(c)): Both straws show very high corrosion probability, and the co-combustion share of $40\%_{en}$ leads to high corrosion. Similarly to the trend observed for agglomeration and fouling, straw 1 with

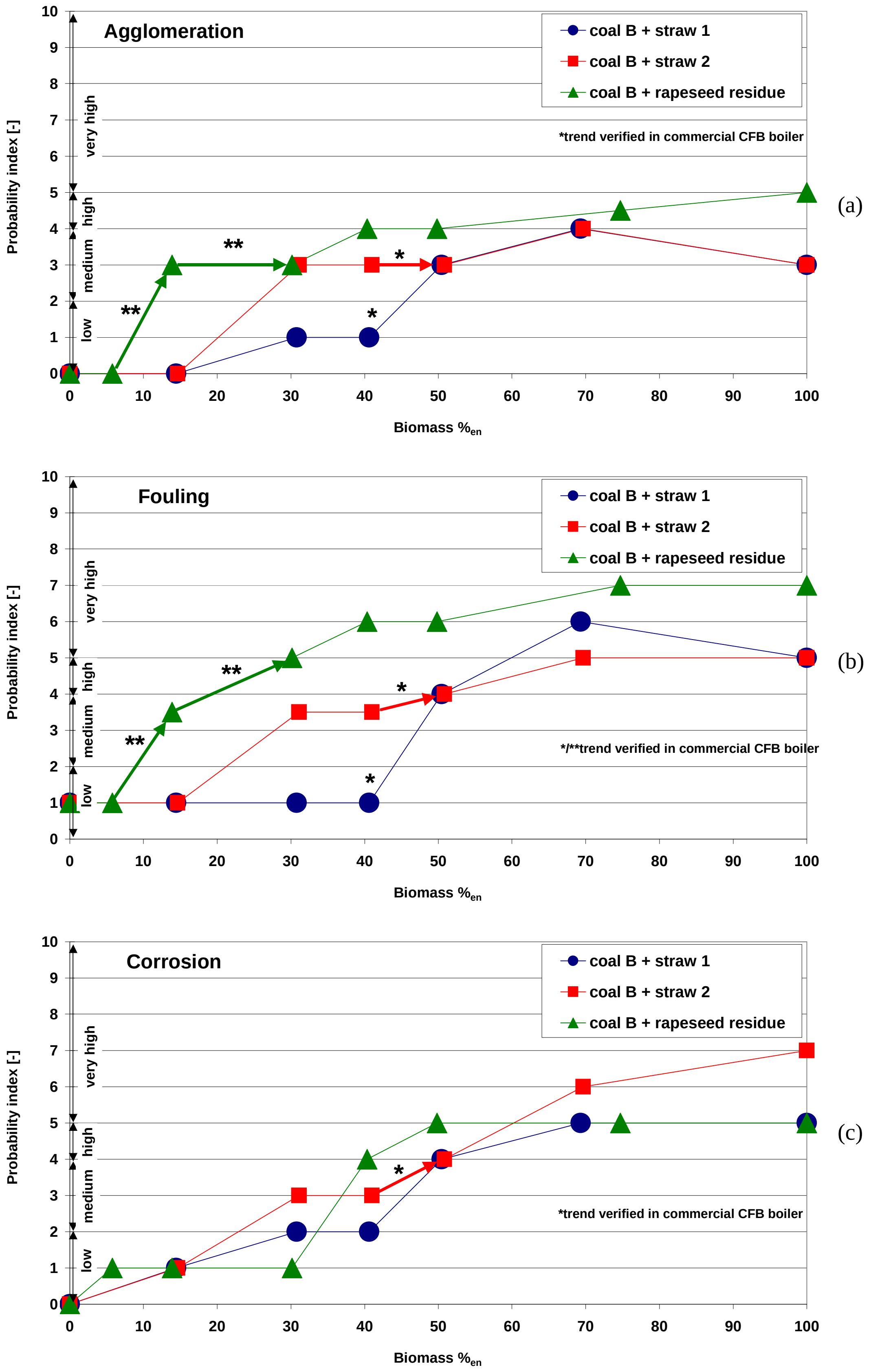

Fig. 2 Agglomeration, Fouling and Corrosion probability index for Case 2: mixtures of coal B and two straws, and coal B and rapeseed residue. The symbol "*" indicates that the trend has been verified in tests at 77.5 MWth, 29 kg/s, 505 ºC CFB boiler; the symbol "**" refers to tests at 12 MWth CFB boiler of Chalmers University of Technology

lower content of chlorine (and alkali) can be fired up to 40%$_{en}$ while maintaining low corrosion probability. The corrosion behavior of rapeseed residue is somewhat different compared with straws. The model shows that in mixtures with coal B rapeseed residue can be used up to 30%$_{en}$ with low corrosion probability, but already at 40%$_{en}$ the corrosion probability is high and increases with further increase of rapeseed share. These results appear realistic compared with observations in full-scale, though they also show a need for further developments of the corrosion probability model when used with high-phosphorous fuels such as rapeseed residue.

FURTHER DEVELOPMENTS

Agglomeration, fouling, and corrosion probability models are capable to predict trends observed during co-combustion of a variety of fuels in commercial CFB boilers, and especially to reflect diversity of combustion behaviors that exists among biomass fuels. Nevertheless, the models exhibit certain limitations, and the following items have been identified for further development:

- Extension of the probability models to fuels of growing commercial interest.
- Introduction of the effect of zinc, led, and metallic aluminum.
- Improvement in description of the effect of phosphorous.
- Improvement in description of the effect of kaolinite.

CONCLUSIONS

Changes in fuel market and ever-growing demand for co-combustion capabilities pose a continuous need for tools that can predict agglomeration, fouling, and corrosion tendency of fuels fired in CFB boilers. This paper presents results from recently upgraded models used at Foster Wheeler to predict agglomeration, fouling, and corrosion tendency of a variety of fuels and mixtures.

The probability models well predict the agglomeration, fouling, and corrosion trends observed during co-combustion in commercial CFB boilers. Results shown in this paper refer to cases co-firing coals of different carbonification degree with various types of biomass. In addition, the models have shown good agreement in combustion of other fuels, including peat, sludge, and wastes (not shown here).

Further model developments are needed to i) extend the model validity to fuels of growing commercial interest, ii) take into account the effect of zinc, led, and metallic aluminum especially in waste fuels, iii) improve the description of the effect of phosphorous especially in grain-derived fuels, and iv) improve the description of the effect of kaolinite especially in coals.

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