Investigation of ash deposition in PF boiler during combustion of torrefied biomass

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Abstract. The paper presents an analysis concerning the propensity of torrefied biomass to slagging and fouling and impact of its combustion on heat exchange in existing pulverized fuel boiler in reference to Polish coal. The impact of torrefaction on slagging properties was also investigated. Based on the results of ash composition and fusibility analyses the most common ash deposition indices were determined. The effect of ash composition and its particle sizes on thermal efficiency of convective heating surfaces in boiler was analysed. Additionally, influence of fuel change at the nature of heat transfer in boiler, mainly at the flue gas temperature distribution and boiler efficiency, was also presented. The results may be used as a basis of experimental, in lab-scale as well as in technical-scale, research planning and of slagging and fouling prevention guidelines for boilers operators.

1. Introduction

Higher heat participation of biomass in Polish energy mix is required due to environmental policy of the European Union [1]. Polish power industry is dominated by pulverized fuel (PF) boilers equipped mainly with bowl or ring-ball mills in which the milling of raw biomass is inefficient due to its fibrous nature. One of technologies concerning biomass pre-treatment in order to improve its grindability is thermal (200-300°C) disintegration of cellulose and lignin in inert atmosphere and in nearly atmospheric pressure, called torrefaction [2-4].

The majority of performed research related to biomass torrefaction concern also changes in fuel chemical and physical properties, inter alia increase of fuel energy density, heating value and hydrophobicity and decrease of moisture content as well as O/C and H/C ratios [5-8]. Likewise, it is established that some kinds of torrefied biomass may substitute coal in existing PF boilers, changing nevertheless the nature of heat transfer in the boiler heating surfaces [9, 10]. Consequently, it is necessary to determine the impact of torrefaction on the tendency of biomass to slagging and fouling the boiler heating surfaces in order to fully characterize the process effect. This issue is gaining more and more research interest but there could be found a limited published experimental data related to combustion of torrefied biomass.

Published data concern mostly co-combustion of raw palm kernel shell (PKS) (Latin: *Elaeisguineensis*) with coal. It normally contains less sulphur, chlorine and ash as well as potassium and sodium in it, and is characterized by higher heating values than other types of biomass. Owing to that, it is considered as a biomass with a relatively low tendency of causing difficulties during its combustion in large-scale boilers [11-14].
In [15,16] there are shown the results of experimental and numerical research related to ash deposition characteristics during co-combustion of palm kernel expeller (PKE) with coal in three different thermal ratios (20%, 40% and 60%). Deposition efficiency (DE), defined as a mass percentage of fuel ash collected at the surface of uncooled ceramic deposition probe, is generally higher in case of PKE co-combustion than of coal combustion, but it is not a fixed-course dependency. Overall, the trend of the deposition efficiency values is increasing with the increase in PKE thermal ratio in combusted mixture until it reaches value of 40% and then, depending on the type of coal, DE values are constant or even decrease. This points to the relatively low tendency of PKE to slagging and fouling, but not excludes it completely. However, it should be noted that there is no significant difference between PKE and PKS in terms of chemical and physical properties, but chemical composition of their ashes are slightly different. Primarily PKS ash contains significantly more SiO$_2$ and K$_2$O and less CaO, MgO and P$_2$O$_5$. Therefore, the tendency of PKS to slagging and fouling of heating surfaces could be different than that of PKE thus its analysis has to be carried out.

Due to that, the main aim of the study is to determine the propensity of torrefied biomass to slagging and fouling during its combustion in 140 t/h PF boiler in reference to Polish coal combustion. The studies focus on preliminary characterization of raw and torrefied PKS through commonly used ash deposition indices and on its impact on heat exchange in the boiler. The study provides a background to further experimental research in lab-scale pulverized fuel fired vertical combustion chamber.

2. Methodology

2.1. Experimental section

In this research selected fuels were investigated in certified laboratory using procedures authorized by European Standard Technology Committee. The same methodology was used in [17, 18]. Investigation includes proximate and ultimate analysis of fuel, ash fusibility experiments in oxidizing conditions and ash oxides analysis. In the case of ash fusibility experiments analytical sample of fuel PKS and torrefied PKS were ashed at 600°C and for coal at 815°C. Ash samples were shaped into pyramids. Ash fusibility analysis includes determination of the Initial Deformation Temperature (ITD), the Softening temperature (ST), the Hemispherical temperature (HT) and the Fluid Temperature (FT) by camera and computer system at maximal temperature 1560°C. Major ash components: Al, Ca, Fe, Mg, P, K, Si, Na, Ti, were determined using Plasma Spectrometer ThermoiCAP 6500 Duo ICP.

2.2. Computational section

2.2.1. Ash deposition indices.

Up to now, various predictive coefficients have been developed for the characterization of ash deposition tendency such as: Silica content (SiO$_2$), Chlorine content of the fuel (Cl), Basic to Acidic oxides (B/A), Bed Agglomeration Index (BAI), Babcock index (Rs), Ash Fusibility Index (AFI), Fouling index (F$_r$), Fouling factor (R$_f$), Slag viscosity index (Sr) and Ash Fusion Temperatures AFT in oxidation conditions: Initial Deformation Temperature (ITD), Softening Temperature (ST), the Hemispherical temperature (HT) and the Fluid Temperature (FT) by camera and computer system at maximal temperature 1560°C. Major ash components: Al, Ca, Fe, Mg, P, K, Si, Na, Ti, were determined using Plasma Spectrometer ThermoiCAP 6500 Duo ICP.

Nevertheless applicability of these indicators is limited, because they are mainly established to characterize rather coal than biomass ash properties [17]. In Table 1 ranges of slagging and fouling indices are presented, marked in grey scale to highlight the difference in values and to improve itsvisibility. The same scale is used in Table 5 showing indices calculated for fuels under analysis.

\[
B = \frac{Fe_2O_3 + CaO + MgO + Na_2O + K_2O + P_2O_5}{SiO_2 + Al_2O_3 + TiO_2}
\]

(1)
\[ BAI = \frac{Fe_2O_3}{Na_2O + K_2O} \]  \hspace{1cm} (2)

\[ Rs = \left( \frac{B}{A} \right) \cdot S^d \]  \hspace{1cm} (3)

\[ AFI = (4 \cdot IDT + HT)/5 \]  \hspace{1cm} (4)

\[ F_u = \left( \frac{B}{A} \right) \cdot (Na_2O + K_2O) \]  \hspace{1cm} (5)

\[ R_f = \left( \frac{B}{A} \right) \cdot (Na_2O + 0.659 \cdot K_2O) \]  \hspace{1cm} (6)

\[ Sr = \frac{SiO_2 \cdot 100}{Fe_2O_3 + SiO_2 + CaO + MgO} \]  \hspace{1cm} (7)

**Table 1.** Predictive ash deposition indices with their ranges [17, 21].

| Parameter / Symbol       | Value                  | Unit       |
|--------------------------|------------------------|------------|
| Silica content in ash    | SiO₂                   | Low = <20  |
|                          |                        | Medium = 20 - 25 |
|                          |                        | High = >25 |
| Chlorine content in fuela| Cl<sub>d</sub>         | Low = <0.2|
|                          |                        | Medium = 0.2-0.3 |
|                          |                        | High = 0.3-0.5 |
|                          |                        | Extremely high = >0.5 |
| Basic to acidic compounds ratio | B/A                   | Low = <0.5 |
|                          |                        | Medium = 0.5-1.0 |
|                          |                        | High = 1.0 - 1.75 |
| Bed agglomeration index  | BAI                    | Low = <0.15 |
| Babcock index            | Rs                     | Low = <0.6 |
|                          |                        | Medium = 0.6-2.0 |
|                          |                        | High = 2 - 2.6 |
|                          |                        | Extremely high = >2.6 |
| Fouling index            | F<sub>u</sub>          | Low = 0.6-2.0 |
|                          |                        | Medium = 2.0 - 40 |
|                          |                        | High = >40 |
| Fouling factor           | R<sub>f</sub>          | Low = <0.2 |
|                          |                        | Medium = 0.2-0.5 |
|                          |                        | High = 0.5-1.0 |
|                          |                        | Extremely high = >1.0 |
| Slag viscosity index     | Sr                     | Low = >72 |
|                          |                        | Medium = 65 - 72 |
|                          |                        | High = <65 |
| Softening temperature    | IDT                   | Low = >1100 |
|                          |                        | Medium = 900 - 1100 |
|                          |                        | High = <900 |
| Initial deformation temperature | ST               | Low = >1390 |
|                          |                        | Medium = 1250 - 1390 |
|                          |                        | High = <1250 |
| Ash fusibility index     | AFI                   | Low = >1342 |
|                          |                        | Medium = 1232 - 1342 |
|                          |                        | High = 1052 - 1232 |
|                          |                        | Extremely high = <1050 |

*a in dry state

2.2.2. *Thermal calculations.*

The thermal analysis was performed based on a 0-dimensional model using the method described in [22-24], adjusted to the Polish conditions and underpinned by industrial scale tests. Due to that, completely balanced, considered as reliable, model is obtained. The furnace calculations are based on [22, 23], whereas thermal calculations of the boiler convection part are based on [24].

Thermal calculation of the heating surfaces in boiler includes the thermal efficiency of each heating surface. In the literature there could be found a number of equations expressing the thermal efficiency of heat exchange. However, a long standing industrial experiments, conducted by the staff of the Division of Boilers and Steam Generators of the Silesian University of Technology, allowed to lay down specific correlations for different types of convective boiler heat exchangers [24].

The chemical composition of high temperature deposits differs from composition of fly ashes, whereas composition of deposits formed in temperatures below 800°C is approximate to that of fly ashes. Therefore, B/A was selected as an indicator of fuel tendency of slagging and fouling. According
to that, thermal efficiency depends on B/A ratio, R_{0.03} in fly ash (cumulative retained for sieve 30 µm) and on an average temperature of flue gas T_{fg}. As an example, equation used for determination of thermal efficiency \( \Psi \) of 1\textsuperscript{st}-stage superheater (staggered arrangement) is defined as follows:

\[
\Psi = 0.46 \cdot \sigma_2^{0.111} \cdot \nu_{fg}^{0.056} \cdot \left( \frac{R_{0.03}}{24.5} \right)^{0.09} \cdot \left( \frac{T_{fg}}{373} \right)^{-0.138} \cdot \left( \frac{B}{A} \right)^{-0.394}
\]  

(8)

where: \( \sigma_2 \)—the longitudinal spacing between tubes to tubes diameter ratio, -,
\( \nu_{fg} \) — flue gas velocity, m/s,
\( R_{0.03} \) — cumulative retained for sieve 30 µm, %,
\( T_{fg} \) — average temperature of flue gas, K,
\( \frac{B}{A} \) — basic to acid oxides ratio, -.

The equation for 3\textsuperscript{rd}-stage superheater has a different form because of its different geometry [25].

3. **Input data**

The thermal calculations are based on the 0-dimensional model of 140 t/h PC boiler (Figure 1). The main boiler operating parameters are shown in Table 2.

![Figure 1. 140 t/h PC boiler diagram.](image)

SH I - 1\textsuperscript{st}-stage superheater
SH II - 2\textsuperscript{nd}-stage superheater
SH III - 3\textsuperscript{rd}-stage superheater
ECO – economizer
RAH – rotary air heater.
Table 2. Basic operating parameters of the boiler.

| Parameter                                      | Symbol | Value | Unit |
|------------------------------------------------|--------|-------|------|
| Nominal temperature of live steam              | $t_{s, nom}$ | 540   | °C   |
| Nominal pressure of live steam                 | $p_{s, nom}$ | 9.8   | MPa  |
| Temperature of feed water                      | $t_{FW}$ | 215   | °C   |
| Unburnt carbon in slag                         | $C_s$   | 7     | %    |
| Unburnt carbon in fly ash                      | $C_{fa}$ | 5     | %    |
| Excess air ratio at boiler exit                | $\lambda_{sw}$ | 1.35  | %    |

Parameters of reference coal (WS) and other fuels under analysis are listed in Table 3. Two types of torrefied PKS were taken into consideration (marked as PKS_1T and PKS_2T). First of them (PKS_1T) was torrefied in the temperature of about 350°C with a 10-minute residence time, while PKS_2T was torrefied in 310°C with a 40-minute residence time. Both of them were torrefied in an atmosphere with low oxygen concentrations (tor gas) and close to atmospheric pressure. The process was conducted so that the obtained torrefaction degrees (the loss of volatile matter content in torrefied fuel in dry ash free state with reference to that in raw fuel) have the following values: 31.5% for PKS_1T and 17.5% for PKS_2T.

Torrefaction resulted in the increment of lower heating value (LHV) for about 30% for PKS_1T and about 20% for PKS_2T. It also causes the approximation of biomass O/C and H/C ratios values to that for WS. The divergence in moisture content between torrefied fuels results from differences in their storage after the process.

Table 3. LHV and elemental composition of fuels in as-received state.

| Parameter / Symbol | WS  | PKS | PKS_1T | PKS_2T | Unit |
|--------------------|-----|-----|--------|--------|------|
| Moisture content in fuel | $M^w$ | 17.8 | 16.6 | 1.1 | 11.4 | % |
| Ash content in fuel   | $A^w$ | 13.5 | 2.6 | 6.5 | 4.1 | % |
| Sulphur content in fuel | $S^w$ | 1.3 | 0.05 | 0.04 | 0.04 | % |
| Carbon content in fuel | $C^w$ | 52.8 | 44.8 | 64.82 | 54.68 | % |
| Hydrogen content in fuel | $H^w$ | 3.9 | 4.2 | 4.31 | 4.20 | % |
| Nitrogen content in fuel | $N^w$ | 0.8 | 0.5 | 0.88 | 0.62 | % |
| Chlorine content in fuel | $Cl^w$ | 0.3 | 0.03 | 0.04 | 0.02 | % |
| Phosphorus content in fuel | $P^w$ | 0 | 0.04 | 0.07 | 0.04 | % |
| Oxygen content in fuel | $O^w$ | 9.6 | 31.2 | 22.3 | 24.9 | % |
| Volatile matter content in fuel | $V_{daf}^w$ | 33.4 | 74.7 | 51.2 | 61.7 | % |
| Lower heating value | $LHV$ | 19.968 | 16.226 | 23.78 | 20.384 | MJ/kg |
| O/C ratio            | $O/C$ | 0.182 | 0.698 | 0.343 | 0.456 | - |
| H/C ratio            | $H/C$ | 0.075 | 0.094 | 0.067 | 0.077 | - |

*in dry ash free state*

Results of ash composition and fusibility analyses are shown in Table 4. Torrefaction nearly does not cause modification of ash composition. Nevertheless, it has to be noticed that both biomass, raw and torrefied PKS, are characterized by significantly higher CaO, K$_2$O, P$_2$O$_5$, MgO and Fe$_2$O$_3$ contents in relation to coal and, in addition, by lower Al$_2$O$_3$ content. That may lead to assumption that raw PKS as well as torrefied are characterized by rather high, with reference to coal, slagging and fouling tendency.
Table 4. Results of ash composition and fusibility analyses.

| Parameter / Symbol       | Value / Fuel | Unit |
|--------------------------|--------------|------|
|                         | WS           | PKS  | PKS_1T | PKS_2T |
| Silica content in ash    | SiO₂         | 54.3 | 55.50  | 59.08  | 53.25  | %    |
| Calcium content in ash   | CaO          | 1.93 | 22.48  | 20.2   | 22.39  | %    |
| Potassium content in ash | K₂O          | 2.36 | 5.81   | 5.35   | 5.51   | %    |
| Phosphorus content in ash| P₂O₅         | 0.18 | 3.37   | 2.55   | 2.73   | %    |
| Aluminium content in ash | Al₂O₃        | 24.70| 3.46   | 4.36   | 3.41   | %    |
| Magnesium content in ash | MgO          | 1.35 | 2.65   | 2.47   | 2.31   | %    |
| Iron content in ash      | Fe₂O₃        | 9.81 | 4.11   | 3.82   | 8.24   | %    |
| Sulphate content in ash  | SO₃          | 0.79 | 1.83   | 1.27   | 1.64   | %    |
| Sodium content in ash    | Na₂O         | 2.44 | 0.57   | 0.69   | 0.37   | %    |
| Titanium content in ash  | TiO₂         | 0.86 | 0.21   | 0.21   | 0.17   | %    |

Cumulative retained for sieve 30 µm R₀.₀₃ 40.80 39.80 26.23 36.71 %

Sieve analysis was made for ash from fuel ground in semi-technical milling plant equipped with a ring-ball mill. Granulation of torrefied PKS_1T was different from that of PKS_2T. As it could be noticed, better milling quality of PKS_1T results in finer ash particles (R₀.₀₃ is higher of about 10 pp for PKS_2T than for PKS_1T). It may be caused by higher ratio of homogeneity in fuel material associated with higher temperature of process.

4. Results and discussion

4.1. Prediction of ash deposition using indices

Preliminary ash characterisation using ash deposition coefficients may indicate slagging and fouling fuel properties. Results of research are shown in Table 5. All investigated fuels are characterised by high silica content, which represents high potential of ash deposition tendency. During combustion silica may react with alkali metals especially potassium and sodium which results low-melting point eutectics creation [17, 25]. These compounds are mainly responsible for formation of difficult removable deposits from boiler heat exchangers [26]. Chlorine plays a significant role with ash melting behaviour. Chlorine may form alkali chlorides reducing ash melting temperature to the level around 750°C and influence of slagging initiation [17, 27]. Chlorine leads to KCl formation, which is responsible for ash deposition on low temperature heating surfaces [9]. High chlorine content is also responsible of chlorine corrosion which successfully may damage a boilers water panels and bank of tubes [28]. Investigated two types of PKS and its torrefied residues are described with low chlorine content compared to coal WS.
Table 5. Results of ash deposition indices of fuels under analysis.

| Parameter / Symbol                  | Value / Fuel | Unit |
|-------------------------------------|--------------|------|
|                                     | WS           | PKS  | PKS_1T | PKS_2T |
| Silica content in ash SiO₂          | 55.00        | 55.45 | 59.08   | 53.25   | %     |
| Chlorine content in fuel\textsuperscript{a} Cl\textsubscript{d} | 0.36         | 0.03  | 0.04    | 0.02    | %     |
| Basic to acidic compounds ratio B/A | 0.23         | 0.66  | 0.55    | 0.73    | -     |
| Bed agglomeration index BAI         | 2.04         | 0.64  | 0.63    | 1.40    | -     |
| Babcock index Rs                    | 0.34         | 0.04  | 0.02    | 0.01    | -     |
| Fouling index Fu                   | 1.10         | 4.21  | 3.32    | 4.28    | -     |
| Fouling factor Rf                  | 0.92         | 2.92  | 2.32    | 2.92    | -     |
| Slag viscosity index Sr            | 80.58        | 65.47 | 69.04   | 61.79   | -     |
| Initial deformation temperature IDT | 1200         | 1150  | 1190    | 1160    | °C    |
| Softening temperature ST           | 1270         | 1200  | 1210    | 1190    | °C    |
| Ash fusibility index AFI           | 1226         | 1166  | 1198    | 1172    | °C    |

\textsuperscript{a} in dry state

Basic to Acidic ratio (B/A) describe general melting behaviour of basic compounds (decreasing the melting point) and acidic (opposite behaviour) [17]. In comparison to coal WS, raw and torrefied PKS show the medium ash deposition tendency. Obtained results demonstrate that process of torrefaction does not always decrease the ash deposition indices. For instance B/A ratio for PKS, PKS_1T and PKS_2T are as follows: 0.66, 0.55 and 0.73. In the case of BAI index developed to characterise bed agglomeration tendency for fluidised combustion, all investigated fuels are above the limit – 0.15 (Table 3). Another coefficient Rs is upgraded B/A index which consider sulphur content in the fuel. Sulphur with potassium leads to formation K_2Ca(SO_4)_2 which may increase the deposition tendency on high temperature heating surfaces. In the case of slagging K_2Ca(SO_4)_2 and K_3Na(SO_4)_2 play considerable role [29]. In the matter of Rs index all fuels are placed on acceptable range – low risk of ash deposition. Fu index takes into account two main responsible compounds for slagging and fouling (Na+K). All investigated fuels show medium ash deposition tendency; raw and torrefied PKS is described by 3 – 4 times higher Fu index than coal WS, however still in medium range. One more fouling factor Rf follows these tendencies, though raw and torrefied PKS lay in Extremely High Range (see Table 1) compared to High Range for coal. One can observe Rf factor for PKS_2T is the same as for raw PKS. Answer for that might be a lower temperature of torrefication process -310°C for PKS_2T compared to 350°C for PKS_1T. High Slag viscosity index Sr is coupled with high ash viscosity decreasing the slagging properties. Nevertheless extensive research from study [17] show Sr index is far from the real slagging tendency [17, 18]. In the case of raw and torrefied PKS confirm these suppositions. Next three coefficients IDT, ST and AFI index described ash deposition probability using ash fusibility experiments. One can conclude process of torrefaction results on a slight increase the ash fusion temperatures (Table 3). For instance results of AFI index are as follows: for PKS – 1166°C to PKS_1T – 1198°C and to PKS_2T – 1172°C and for WS – 1226°C.Differences between the torrefied biomass should be further explored during experimental combustion tests. At this moment, it can be assumed that mainly the process temperature affects the torrefied biomass properties.

4.2. Results of boiler thermal calculations

The main results of calculations for different boiler loads (100% and 75%) are shown in Table 6. The nominal live steam temperature is maintained for all of fuels under analysis. The nature of the flue gas temperature distribution is approximate for each fuel (Figure 2). However, fuel change causes increase of flue gas outlet temperature. This results in an increase of stack loss (Figure 3) and,
consequently, in a decrease of boiler efficiency (by max. 4.5 pp for PKS and PKS_1T combustion and 3 pp for PKS_2T). The difference between PKS_1T and PKS_2T is caused by their different chemical composition, hence different amount of air needed to combustion resulting in different amount of flue gases.

The thermal efficiency $\psi$ of convective heat exchangers is decreasing in case of raw and torrefied PKS combustion. Decrease in $\psi$ causes decrease in heat exchanged between flue gas and steam, as showed by the example of 1st-stage superheater (Figure 4). It has to be notices, that $\psi$ has higher values for PKS_1T than PKS_2T. It may results not only from the differences in ash composition but also from the difference in the ash particle sizes ($R_{0.03}$ parameter) – generally, the larger the ash particle sizes, the less tendency of its agglomeration at heat exchange surfaces.

### Table 6. The main results of thermal calculation

| Parameter / Symbol                                      | Value / Fuel | Unit |
|---------------------------------------------------------|--------------|------|
| Nominal boiler load                                     |              |      |
| Flue gas temperature at the furnace outlet $t_{FEFG}$   | 1092         | °C   |
| Live steam temperature $t_5$                            | 540          | °C   |
| Stack loss $S_2$                                        | 5.06         | %    |
| Boiler efficiency $\eta$                                | 93.03        | %    |
| Fuel mass flow $\dot{m}$                                | 5.10         | kg/s |
| Thermal efficiency of 3rd-stage superheater $\psi_{SHIII}$ | 0.806        |      |
| Thermal efficiency of 1st-stage superheater $\psi_{SHI}$ | 0.812        |      |
| Thermal efficiency of economizer $\psi_{ECON}$          | 0.842        |      |
| Boiler relative load of 75 %                            |              |      |
| Flue gas temperature at the furnace outlet $t_{FEFG}$   | 1009         | °C   |
| Live steam temperature $t_5$                            | 540          | °C   |
| Stack loss $S_2$                                        | 5.61         | %    |
| Boiler efficiency $\eta$                                | 92.54        | %    |
| Fuel mass flow $\dot{m}$                                | 3.79         | kg/s |
| Thermal efficiency of 3rd-stage superheater $\psi_{SHIII}$ | 0.796        |      |
| Thermal efficiency of 1st-stage superheater $\psi_{SHI}$ | 0.801        |      |
| Thermal efficiency of economizer $\psi_{ECON}$          | 0.830        |      |

**Figure 2.** Flue gas temperature path in the boiler.
5. Conclusion
In this study raw and torrefied PKS fuel properties were characterized and compared with reference to Polish coal. The research carried out shows that torrefied biomass approach coal properties. Similarities could be pointed, in particular, in calorific value and volatile matter as well as moisture content. Torrefaction significantly improved energy density of investigated biomass. Moreover, torrefaction slightly decreases ash deposition tendency affecting ash melting properties. Additionally, higher torrefaction temperature affects favorably fouling and slagging properties. Nevertheless, process of torrefaction could be optimised in the field of slagging and fouling properties. It is suitable to carry out experimental tests in lab-scale pulverized fuel fired vertical combustion chamber, which would help to extend knowledge concerning ash deposition tendency of torrefied biomass and an impact of torrefaction parameters on fuel tendency of slagging and fouling. Furthermore, thermochemical calculations of ash properties using FACTSAGE© may be considered.

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