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ANALYSIS OF SLAGGING AND FOULING PROPENSITIES OF BIOFUELS IN TERMS OF THEIR COMBUSTION AND CO-COMBUSTION IN THE BOILERS

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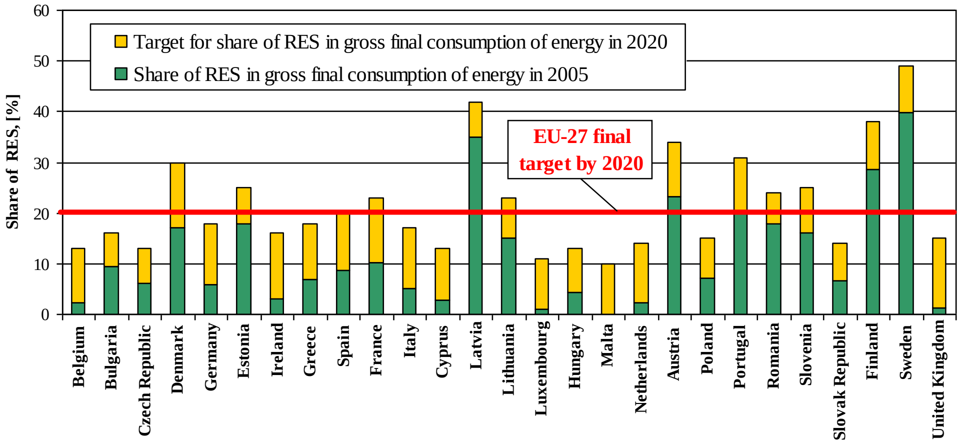
Abstract. The paper presents analysis and significance of the implementation possibility of the existing selected slagging and fouling indexes for solid biofuels. Various biomass and alternative fuels which may be a good energy source for heat and power generation are considered. Basing on the chemical properties of their ashes the fouling and slagging propensity of the biofuels was determined. Moreover, the potential profits in case of their validation and suitability are discussed. The results of the analytical calculations indicated substantial differences in the fouling and slagging tendency of the fuels not only in within the biomass type, but also within the given biomass itself. Additionally it was shown, that smart blending of biofuels (not only with coal) may lead to the increase of biomass share in energy production without deterioration of combustion conditions in the boiler.

Key words: biomass, slagging, fouling, indices, co-combustion

Introduction

The increase of biomass content in the fuel mixture during its co-combustion with coal in traditional power generation systems is very attractive from environmental and economical point of view. Actually, it is claimed that the addition of 10% biomass to the coal does not influence coal-fired boiler operation. However, the *Kyoto Protocol* [Global Environmental Change Report 1997], *Biomass Action Plan* [Biomass Action Plan 2005] and other *EU* regulations [Directive 2009/28/EC] with a goal to raise the share of renewable energy to 20% (Fig. 1) caused that in the near future the biomass share in the fuel blend will reach 20% and more.

This scheme encourages the power producers to a substantial increase of the biomass use for heat and power generation. Keeping in mind the food production, the emphasis is put on the so-called non-food-competing types of biomass, in accordance with the biomass definition [Directive 2001/77/EC], which describes biomass as a biodegradable fraction of products, waste and residues from agriculture (including vegetal and animal substances), forestry and related industries, as well as the biodegradable fraction of industrial and municipal waste.



Source: Directive 2009/28/EC

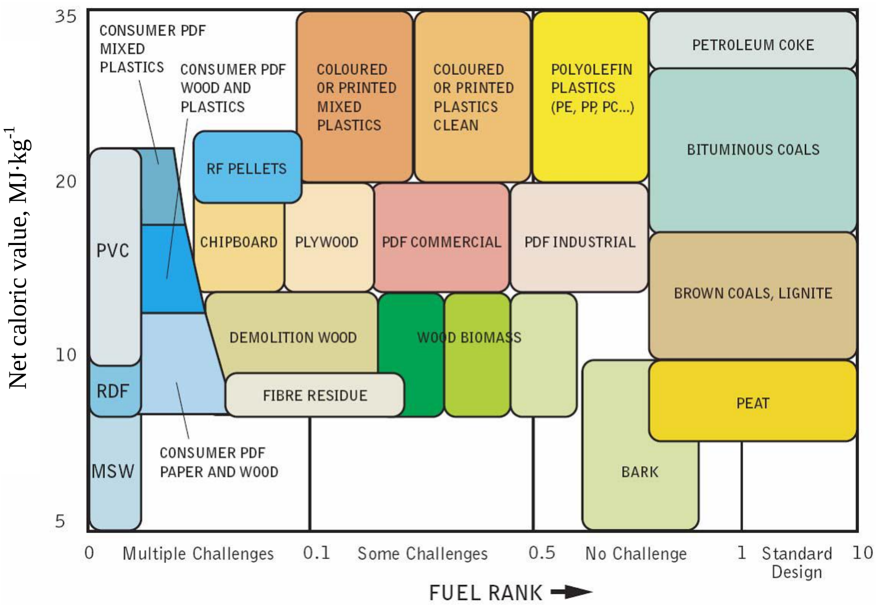
Fig. 1. National overall targets for the share of energy from renewable sources in gross final consumption of energy in 2020 within *EU-27*

Rys. 1. Narodowe cele dla udziału energii z odnawialnych źródeł energii w końcowym zużyciu energii brutto w 2020 roku w ramach *UE-27*

Such increase of biomass in the fuel mixture may drastically change the combustion conditions and influence boiler operation and design (Fig. 2). Because of different chemical composition and properties of biomass in comparison to the coal some exploitation issues, like slagging, fouling, heat transfer, erosion and corrosion are expected. Taking into account the problems indicated above, content of sulphur, chlorine and alkali metals in the fuel play the most important role in the behaviour of biomass and coal during combustion. These specimens influence flue gas composition, ash composition and deposits formation on heat exchange surfaces (waterwall tube, superheater etc.).

In consequence, a high risk of slagging, fouling and subsequent corrosion depending on the fuel characteristics may be expected when co-firing biomass in existing pulverized fuel boilers that are designed for single coal only.

As a result, many investigation methods and analysis technique are under development to understand and predict the behavior of deposits formation during combustion of coal-biomass blends. The most important methods are, as follow: ultimate and proximate analysis, ash mineral analysis, *X*-ray fluorescence analysis (*XRF*), scanning electron microscopy (*SEM*), energy dispersive spectrometer (*EDS*). Many experimental test beds, focused on deposits collection during combustion for different conditions, has been also built and tested, as well [Lopez et al. 2001; Folkedahl et al. 2001].



Source: Veijonen et. all 2003

Fig. 2. Influence of fuel characteristics on boiler design
Rys. 2. Wpływ paliwa charakterystyczny na projekcie pieca

Based on the experimental results and chemical analysis of solid fuels a lot of indexes are suggested that would be useful in the prediction of slagging and fouling hazard of the heat exchange surfaces of the boiler. Although, these indexes have been initially created for coals only, there are attempts to apply and use them for biomass

Analysis of the implementation possibility of the existing selected slagging and fouling indexes for biomass and other alternative fuels is carried out in the paper. Moreover, the potential profits in case of their validation and suitability are discussed. The aim of the analysis is the validation attempt of the indices supported by the chemical ash oxides analysis of the biomass. The method used in the paper has an analytical character and compares the slagging and fouling indices obtained for a given biofuel.

The slagging and fouling indexes supported by chemical composition of biomass

The higher slagging and fouling hazard for biomass arises also from the fact that the main components of ashes from coals are: SiO_2, Al_2O_3, Fe_2O_3 which are not harmful for corrosion processes. Based on the research presented in [Theis et. all 2006a] it is also suggested that biomass containing a lot of SiO_2, Al_2O_3 and Fe_2O_3 have much lower ability to deposition. Hence, the ashes from biomass combustion contain mainly SiO_2, CaO, and K_2O. Such a shift of the chemical composition of ash in the direction of compounds with higher ability to deposition may cause increase of deposition rate even for small amount of biomass in the fuel mixture.

It is known also that sodium and potassium lower dramatically the melting point of ash and, hence can increase ash deposition and fouling of boiler tubes [Baxter et al. 1998]. Experimental studies revealed also that deposition rate depends on the ratio of chlorine and sulphur [Theis et. all 2006b].

As a result, many slagging and fouling indexes are created to determine a risk of deposits formation and agglomeration of biomass ashes during combustion and co-combustion of biofuel in the boiler. The indexes considered in the paper are listed below, and their values range characterizing the tendencies and propensities to slagging and/or fouling rates are presented in table 1.

One of the most popular indexes used as an indicator of the fouling tendency of a fuel ash is the base-to-acid ratio *B/A* (formula 1) that has been introduced for coals with low phosphorous content (the ratio of basic oxides to acid oxides in the ash) [Salour et al. 1993]:

$$B/A = \frac{Fe_2O_3 + CaO + MgO + Na_2O + K_2O}{SiO_2 + Al_2O_3 + TiO_2}, \tag{1}$$

In case of biomass it seems to be justified to include also potassium in the consideration. Potassium, like sodium, is commonly found in the living plants and belongs to the major elements influencing faster plants growing (or faster growing plant components such as seeds). Thus agricultural materials such as straw, nut hulls, fruit pits, weeds, and grasses tend to create more problems during combustion than woods from slow growing trees. Potassium and sodium metals, whether in the form of oxides, hydroxides, or metal-organic compounds tend to lower the temperature melting point of ash mixtures containing various other minerals such as silica (SiO_2). This results in serious slagging, fouling or bed agglomeration in the boiler leading to its unexpected shutdown. Therefore, it is logical to introduce a new index based on a fluxing and sintering oxides ratio *SI* [Kupka et al. 2008]:

$$SI = \frac{Fe_2O_3 + CaO + MgO + Na_2O + K_2O + P_2O_5}{SiO_2 + Al_2O_3 + TiO_2}, \tag{2}$$

For determination of deposition propensities the slag viscosity index *SR* (eq. 3) is also in use [Ots, Żelkowski 2000], Viscosity is one of the fundamental properties of the liquid slags and is the key parameter for many industrial processes. It plays important role in slag adhesion, ash fusion, viscous flow and other phenomena:

$$SR = \frac{SiO_2}{SiO_2 + Fe_2O_3 + CaO + MgO} \cdot 100, \tag{3}$$

The dependence of melting points on basic compounds (Fe_2O_3 + CaO + MgO) has a similar character for various fuels (not only coals but also biomass and municipal wastes [Bryers 1996]).

The biomass is burnt not only in the pulverized fuel boiler, but also in grate and fluidized bed boilers, in which the agglomeration of particles may occur. To estimate this risk the bed agglomeration index *BAI* (formula 4) has been developed, relating ash composition to agglomerations in fluidized-bed reactors [Bapat et al. 1997]:

$$BAI = \frac{Fe_2O_3}{K_2O + Na_2O}, \tag{4}$$

Next index *IC* is based on the ratio of iron oxide and calcium oxide (eq. 5), as a parameter for fouling estimation [Bryers 1996]:

$$IC = \frac{Fe_2O_3}{CaO}, \tag{5}$$

Similar ability to deposits formation is described by quotient (*SA*) of silica oxide and alumina oxide (eq. 6) [Basu et al. 2000]:

$$SA = \frac{SiO_2}{AL_2O_3}, \tag{6}$$

The last parameter considered in that paper is fouling index *Fu* (eq. 7) taking particularly into account the alkali elements (potassium and sodium). The indicator is described by the following formula [Tortosa-Masia et al. 2007]:

$$Fu = \left(\frac{Fe_2O_3 + CaO + MgO + Na_2O + K_2O}{SiO_2 + Al_2O_3 + TiO_2} \right) \cdot \left(Na_2O + K_2O \right), \quad [\%] \tag{7}$$

Table 1. Relations between the indexes and slagging/fouling tendencies during combustion in the boiler
Tabela 1. Związki pomiędzy wskaźnikami i tendencjami do szlakowania i żużlowania podczas spalania w piecu

Index	Slagging/Fouling rate			
	low	medium	high	severe
B/A	*B/A* < 0.5	0.5 < *B/A* < 1.0		*B/A* > 1.0
SR	*SR* > 72	72 > *SR* > 65	*SR* < 65	
SI	*SI* < 0.75 and *SI* > 2.0	-	0.75 < *SI* < 2.0	
BAI	*BAI* > 0.15	-	*BAI* < 0.15	-
IC	*IC* < 0.3 and *IC* > 3.0		0.3 < *IC* < 3.0	-
SA	*SA* < 1.87	1.87 < *SA* < 2.65		*SA* > 2.65
Fu	*Fu* < 0.6	0.6 < *Fu* < 40		*Fu* > 40

Source: Dyjakon

For the analysis of the indexes proposed above, various biomass and alternative fuels are taken into consideration. Their ultimate, proximate and ash oxide analysis is shown in table 2. The selected fuels characterize by wide range of chlorine and sulphur content. The bituminous coal considered in the paper is used as a reference fuel to which other biofuels may be related in terms of slagging and fouling risk.

Table 2. Proximate analysis, ultimate analysis, ash composition and slagging/fouling indexes of selected fuels

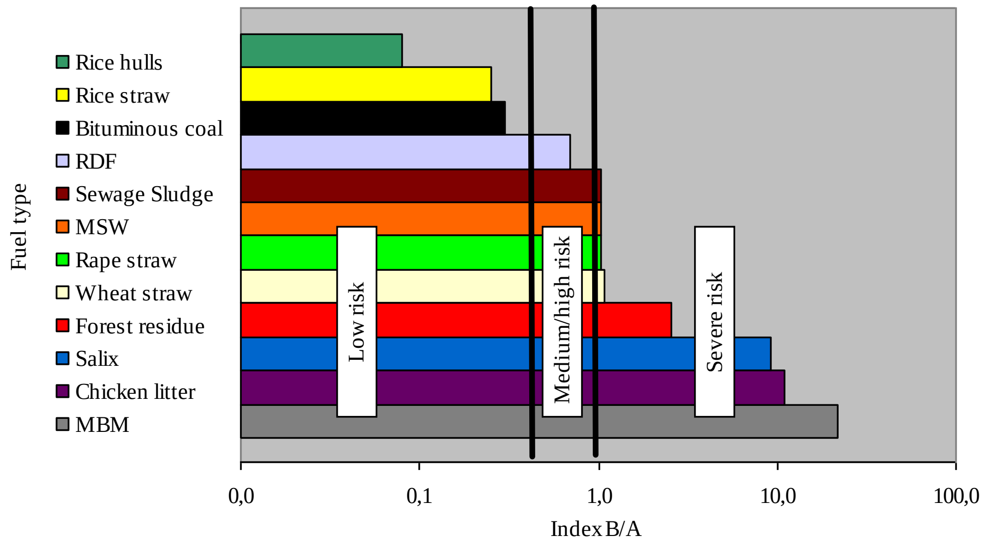
Tabela 2. Analiza techniczna przybliżona, analiza elementarna, skład popiołu oraz wskaźniki szlakowania i żużlowania wybranych paliw

Parameter	Wheat straw	Rice husks	Rice straw	Rape straw	Chicken litter	MBM	Salix	Sewage sludge	RDF	MSW	Forest residue	Bituminous coal
Proximate analysis												
LHV, $MJ \cdot kg^{-1}$	17.7	15.21	15.47	17.00	13.99	17.27	19.57	13.8	21.13	4.19	19.5	27.23
VM, %	80.5	63.52	65.47	76.54	47.82	63.31	48.6	53.48	70.82	92.2	52.0	33.27
Moisture. %	8.2	n.a.	n.a.	8.68	9.29	2.5	11.4	7.43	2.99	43.7	74.7	3.31
Ash. %	5.9	20.26	18.67	4.65	37.79	23.95	1.9	29.93	13	37.5	2.1	10.26
Ultimate analysis, %												
C	47.6	38.83	38.24	46.17	37.38	43.07	48.6	55.46	49.72	54.7	52	67.7
H	5.8	4.75	5.2	6.12	4.19	6.04	6.2	7.71	6.99	6.89	5.8	5.13
N	0.08	0.05	0.18	0.1	0.74	1.27	0.024	2	0.15	0.27	0.07	3.6
S	0.5	0.52	0.87	0.46	3.76	9.16	0.01	7.34	0.82	1.38	0.2	1.18
Cl	0.09	0.12	0.58	0.03	0.5	0.87	0.3	0.14	1.15	1.0	0.1	n.a.
Elemental composition of ash (dry basis), %wt.												
SiO_2	31.4	91.42	74.67	36.7	4.5	0.02	4.3	22.66	35.01	20.7	18.8	54.7
Al_2O_3	3.9	0.78	1.04	4.9	0.79	2.4	2.2	12.78	18.39	10	1.1	20.9
Fe_2O_3	1.8	0.14	0.85	1.8	0.35	0.25	0.9	16.84	2.61	2.7	0.7	14.6
Na_2O	0.6	0.21	0.96	0.4	0.47	6.5	0.1	1.71	4.09	1.4	0.2	1.3
K_2O	22.4	3.71	12.3	12.1	9.5	3.2	25.2	1.78	1.31	1.4	9.8	2.2
CaO	10	3.21	3.01	27.6	44.3	41.8	30.8	13.81	29.76	25.2	35.7	3.5
MgO	3.7	0.01	1.75	1.8	3.2	1.4	3.3	3.11	2.67	2.7	4.4	1.6
TiO_2	0.2	0.02	0.09	0.26	0.02	0.01	0.1	0.69	4.38	1.7	0.1	0.9
P_2O_5	5.1	0.43	1.41	2.0	12.0	41.5	14.7	25.42	0.97	13.6	5.5	0.2
Slagging/fouling index												
B/A	1,08	0,08	0,25	1,04	10,89	21,87	9,14	1,03	0,70	1,03	2,54	0,30
SI	1,23	0,08	0,27	1,09	13,15	38,95	11,36	1,73	0,72	1,45	0,32	0,31
Fu	24,9	0,3	3,3	13,0	108,6	212,2	231,2	3,6	3,8	2,9	25,4	1,1
SR	66,95	96,45	93,01	54,05	8,60	0,05	10,94	40,16	49,98	40,35	31,54	73,52
BAI	0,078	0,036	0,064	0,144	0,035	0,026	0,036	4,82	0,48	0,96	0,07	4,17
IC	0,18	0,044	0,282	0,065	0,008	0,006	0,029	1,22	0,09	0,11	0,02	4,17
SA	8,05	117,2	71,80	7,49	5,70	0,01	1,95	1,77	1,90	2,07	17,09	2,62

Source: Folkedahl et al. 2001; Theis et al. 2006b; Kupka et al. 2008; Tortosa-Masia et al. 2007; Jenkins et al. 1997; Zevenhoven-Onderwater et al. 2002; Changqing et al. 2002; Aubert et al. 2006

Assessment of the fouling and slagging propensities of the biomass

Using the ash composition data of the fuels the fouling and slagging indices were calculated (Table 2). The results, in a graph form, are presented in figures 3-9 on which the fouling/slagging ratio (low, medium, high, severe) are marked, respectively.



Source: Author's own study

Fig. 3. Fouling tendency of biomass in terms of *B/A* index
Rys. 3. Tendencja do szlakowania biomasy pod względem wskaźnika *B/A*

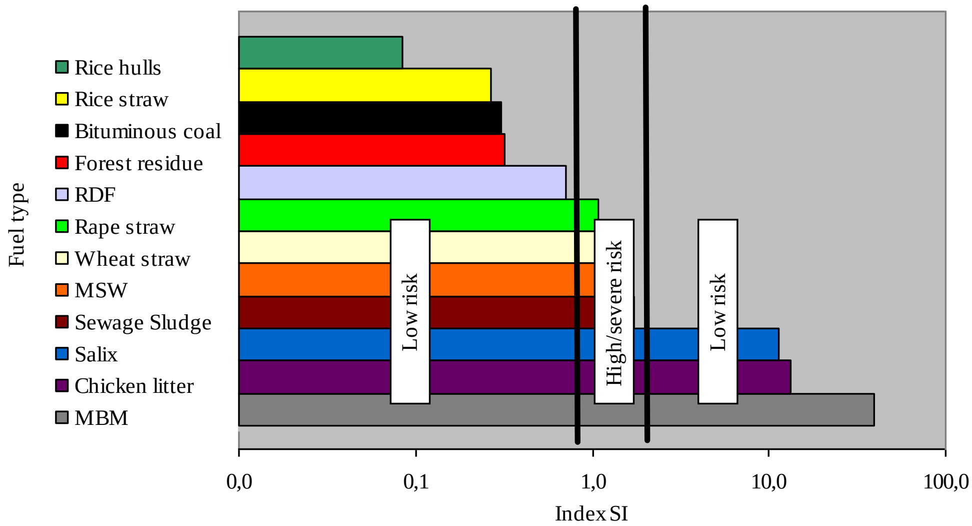


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Fig. 4. Fouling tendency of biomass in terms of *SI* index
Rys. 4. Tendencja do szlakowania biomasy pod względem wskaźnika *SI*

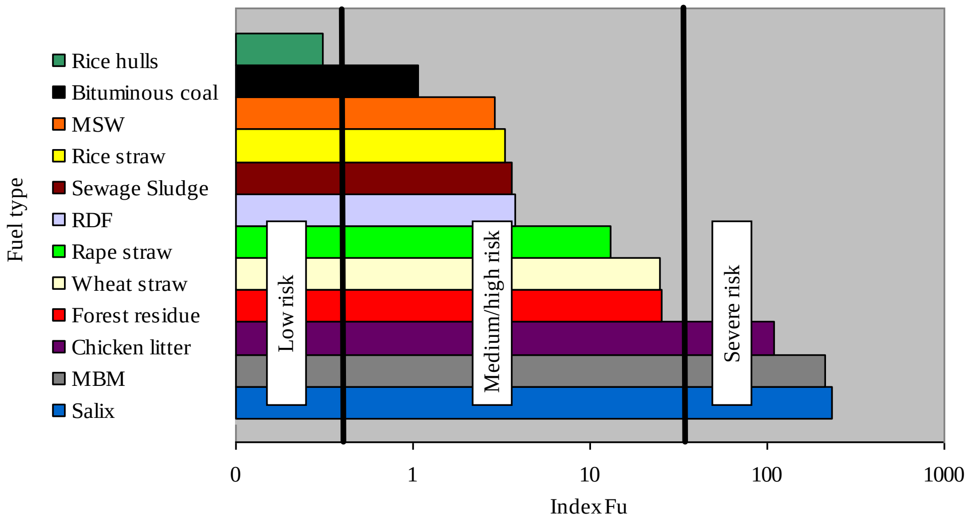

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Fig. 5. Fouling tendency of biomass in terms of *Fu* index
Rys. 5. Tendencja do szlakowania biomasy pod względem wskaźnika *Fu*

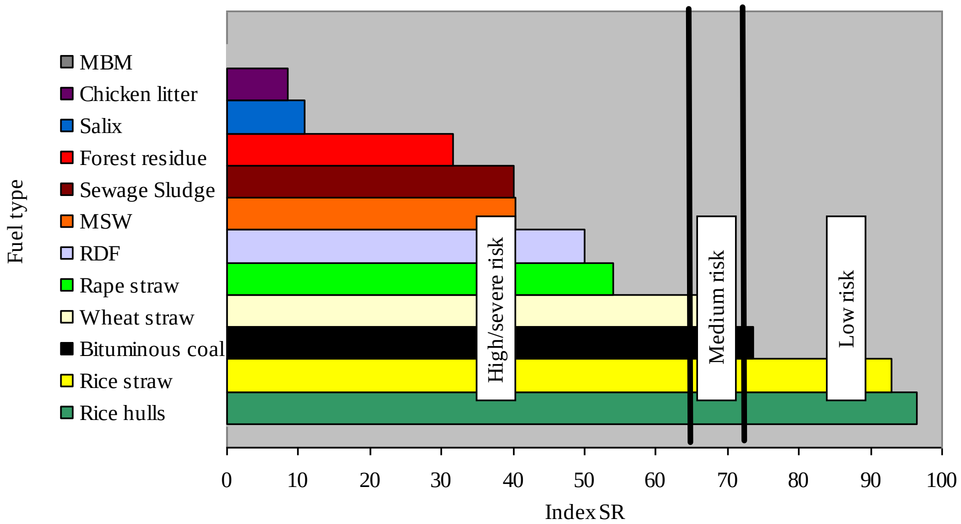

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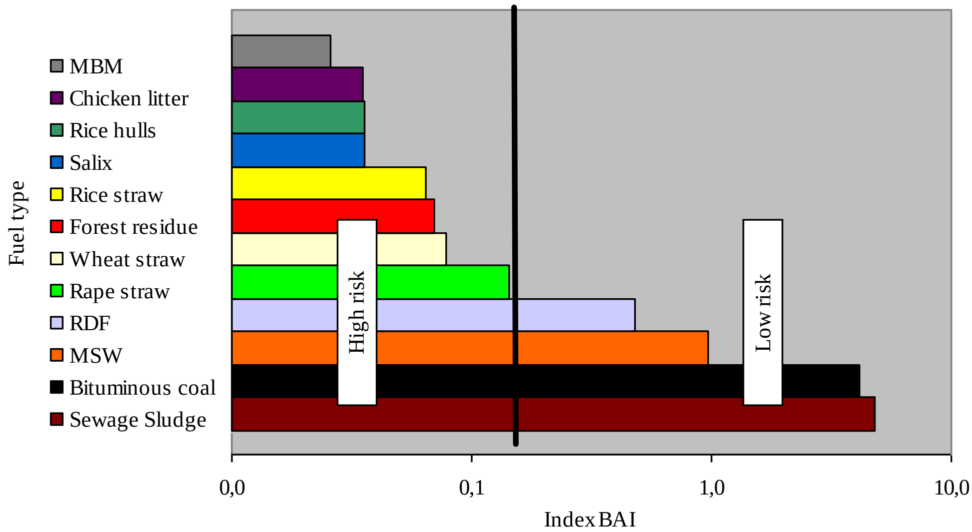
Fig. 6. Slagging tendency of biomass in terms of *SR* index
Rys. 6. Tendencja do żużlowania biomasy pod względem wskaźnika *SR*



Source: Author's own study

Fig. 7. Agglomeration tendency of biomass in terms of *BAI* index
Rys. 7. Tendencja do spiekania biomasy pod względem wskaźnika *BAI*

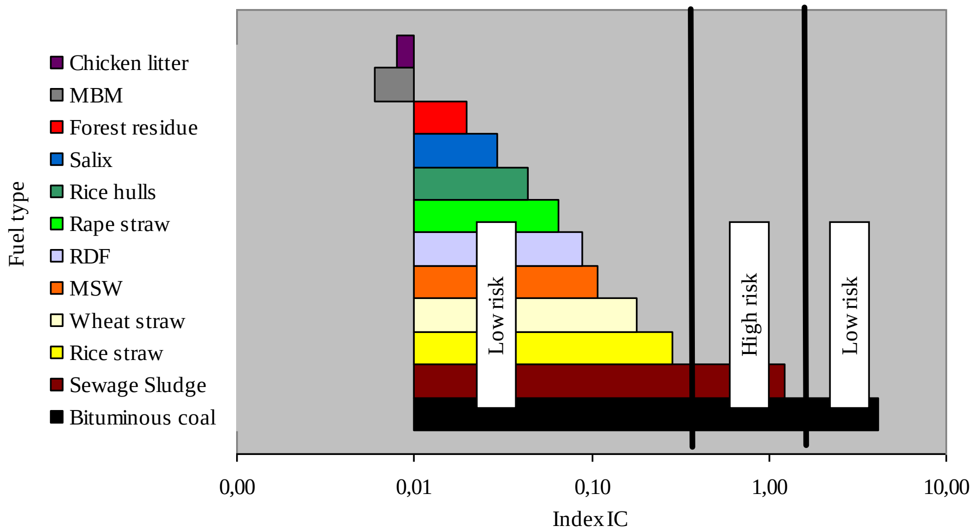


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Fig. 8. Slagging tendency of biomass in terms of *IC* index
Rys. 8. Tendencja do żużlowania biomasy pod względem wskaźnika *IC*

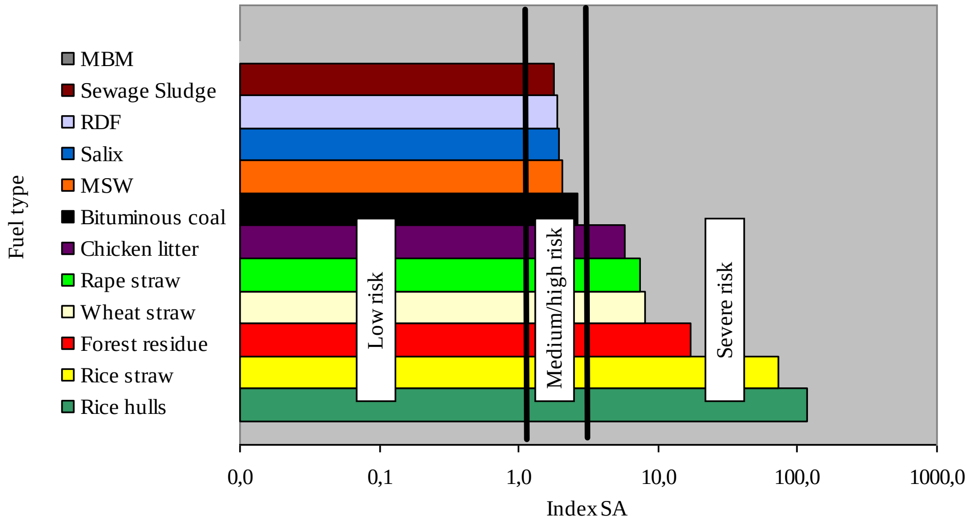

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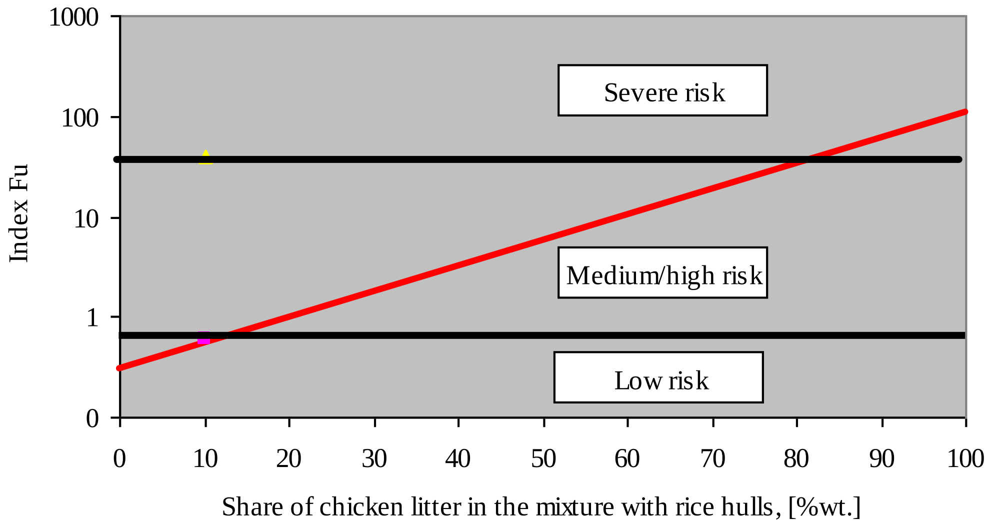
Fig. 9. Slagging tendency of biomass in terms of *SA* index
Rys. 9. Tendencja do żużlowania biomasy pod względem wskaźnika *SA*

As opposed to bituminous coals ashes, the biofuels ashes belong in majority to the lignite one ($MgO + CaO > Fe_2O_3$). Such fuels have much more developed and heterogeneous structure, which causes the troubles in the valuation of their properties.

The results gained from the calculations (Table 2) showed that basing on the indexes only, the determination of biomass and other alternative fuels tendency to fouling and/or slagging is very complex. Moreover, in some cases the results are not convergent. For instance, only for bituminous coal and rice hulls the slagging/fouling indexes were the most stable (with the exception of two indices) in terms of their behavior during combustion. In case of such fuels like: rape straw, wheat straw, forest residue, salix, chicken litter, *MSW* (*Municipal Solid Waste*) and sewage sludge the obtained propensities were less stable, although the trend itself was preserved. In turn, the determination of the deposition probability for *RDF* (*Refuse Derived Fuel*) and *MBM* (*Meat and Bone Meal*) appeared to be not sufficient enough and the results unreliable. It should be marked that only these two alternative fuels are distinguished by much higher content of Na_2O in the ash in comparison to the rest of considered fuels.

It seems that from practical point of view and the improvement of these empirical indexes the estimation of the biomass tendency to slagging, fouling or corrosion should be supported by laboratory deposition test in the operation conditions of the boiler. This combination may bring much more precise data that will be helpful in the characterization of biomass and alternative fuels as well as in the selection of the fuel for combustion or co-combustion in the given boiler.

To underline the importance of the reliability of the slagging/fouling indexes regarding the biomass combustion in the power engineering the *Fu* indexes (as an example) for the blend of two fuels (chicken litter and rice hulls) was created (Fig. 10).



Source: Author's own study

Fig. 10. Fouling tendency of the mixture of chicken litter and rice husks in terms of *Fu* index
Rys. 10. Tendencja do szlakowania mieszanki ściółki kurzej i łusek ryżowych pod względem wskaźnika *Fu*

On the graph the horizontal lines delimit the values of the *Fu* index, for which the fuel (or mixture of fuels) represents the low, medium/high or severe tendency to fouling. The sloped line corresponds to the calculated *Fu* value of the mixture of chicken litter and rice hulls depending of their shares. The lowest *Fu* value is for pure rice hulls (*Fu*=0.3) whereas the highest values belong to the 100% share of chicken litter (*Fu*=108.6). As it is shown in figure 10, even though the chicken litter is a very problematic alternative fuel, due to determination of *Fu* index, its safe utilization is still possible. If the share of chicken litter in the mixture with rice hulls does not exceed ca. 12–13% then there are no problems expected during co-firing of these two fuels (only low risk is foreseen in that conditions). Higher rate of chicken litter co-firing in the blend with rice hulls may lead to the higher and severe fouling tendency, respectively. However, there is a condition that the index is reliable. It shows how important characterization of the biomass prior combustion in the boiler is proper. Moreover, it brings also environmental profits due to the reduction of fossil fuels combustion and CO_2 emission.

Conclusion

1. A number of indices have been developed for coal and other fuels relating the chemical composition to fouling and slagging behavior. These have proved for the most part to be of limited value as predictors for biomass. One simple index, the alkali index, has become popular in recent years as a threshold indicator for fouling and slagging, although all biomass fuels exhibit fouling behavior, but at different rates depending on the composition and ash content. Moreover, no single index has so far been developed that reliably describes the behavior of the ash under all combustion conditions. A good knowledge of the combustion conditions as well as the fuel and ash compositions is needed for any prediction of the fouling characteristics of a biomass fuel.
2. In spite of such wide fuel characterization there are still many questions in correlation of the research carried out on the experimental and technical scale. The main problem is that it is very difficult to perform slagging or fouling tests in the conditions of real boiler operations. From the other hand, it is not possible (because of costs and risk of shutdown) to test every alternative fuel through the combustion in the real boiler at a power plant. Therefore, the fouling and slagging predictors and tools are very welcome.
3. The results obtained from the indexes investigated in the paper have shown that the proper determination of the slagging and fouling properties is not easy. For a time being, it seems to be impossible to rely on the one parameter (indices) only. However, broader amounts of indexes analysis enable to determine a direction of the biomass behavior during combustion. This information is very valuable from practical point of view, as an initial biomass or alternative fuel eliminator. Knowing the biomass characteristic it is better to foreseen a safe fuels shares in the mixture keeping efficient and trouble less energy production from renewable. Finally, there is also a large space for farmers focusing on biomass cultivation with good energetic properties.

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ANALIZA SKŁONNOŚCI BIOPALIW DO SZLAKOWANIA I ŻUŻLOWANIA POD KĄTEM ICH SPALANIA I WSPÓŁSPALANIA W KOTŁACH

Streszczenie. Praca przedstawia analizę i znaczenie możliwości wprowadzenia istniejących wskaźników szlakowania i żużlowania dla biopaliw stałych. Rozważane są różne bio i alternatywne paliwa, które mogą stanowić dobre źródło energii do produkcji ciepła i energii. Opierając się na cechach chemicznych popiołu, określono skłonność biopaliw do szlakowania i żużlowania. Ponadto, omówiono możliwe zyski w przypadku potwierdzenia ich ważności i stosowalności. Wyniki obliczeń analitycznych wskazały na istotne różnice w tendencji do szlakowania i żużlowania paliw, nie tylko w poszczególnym rodzaju biomasy, ale także w poszczególnej biomasie. Co więcej, wskazano, iż inteligentne łączenie biopaliw (nie tylko z węglem) może prowadzić do wzrostu udziału biomasy w produkcji energii bez pogorszenia warunków spalania w kotle.

Słowa kluczowe: biomasa, szlakowanie, żużlowanie, wskaźniki, współspalanie

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