NEW EVALUATION STRATEGIES REGARDING SLAG PREDICTION IN PELLET BOILERS

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ABSTRACT: Pellet boilers are widely used for heat production. In most cases only wood pellets with low ash content are suitable for these appliances due to the increased risk of slagging. The ash fusion test (AFT) is the only standardized method currently available for the prediction of slagging but it frequently failed when solid biofuels were investigated. Therefore different laboratory methods for the prediction of slagging were applied in order to identify the most suitable method for reliable prediction of slagging tendencies. Three laboratory test methods were considered in this investigation: a rapid slag test (1), the so-called "CIEMAT method" (2) and the "slag analyser" (3). The suitability of the obtained results was validated by practical combustion tests in up to nine different pellet boilers. As the most promising method the slag analyser was identified. It will be further developed with the aim to be proposing as an additional standard method for determination of slag related problems in fixed bed combustion systems.
Keywords: pellet boilers, slag prediction, ash melting behaviour, laboratory tests

1 INTRODUCTION AND OBJECTIVES

Pellet boilers are widely used for heat production. In most cases only wood pellets with low ash content are suitable for these appliances due to the increased risk of slagging. The ash fusion test (AFT) is the only standardized method currently available for the prediction of slagging but it frequently failed when solid biofuels were investigated. The temperatures were usually over predicted leading to severe slagging during combustion in pellet boilers. Therefore three different laboratory methods for the prediction of slagging tendencies were applied in order to identify the most suitable method for reliable prediction of slagging tendencies for solid biofuels.

In this study 14 different pelletized biofuels were selected. The three selected laboratory tests were "rapid slag test", the "CIEMAT method" and the "slag analyser". For comparison also the standardized method prCEN/TS 15370-1 using ashes which were generated at 550 °C was considered.

Each laboratory method is described in the following and results are shown and discussed. These results are evaluated with respect to the results from combustion tests in the reference boiler where all fuels were also applied.

2 MATERIAL AND METHODS

2.1 Selected fuels

A broad range of pelletized fuels were collected in suitable amounts for the performance of laboratory fuel tests and combustion trials. All 14 fuels were pelletized having a diameter of 6 mm. An overview of all fuels is shown in Table I. Eight fuel types were wood fuels (F01 to F04, F07 to F09 and F12). Herbaceous fuels were F10, F11 and F13; other fuels were F05, F14 and F15.

2.2 Laboratory test method 1: Rapid slag test

This method is very simple and the test is conducted directly on the pelletized fuel itself using about 5 g of pellets per trial. The fuel was placed in heat resistance crucibles and heated up to 1,100 °C applying a constant heating rate of 5 K/min and keeping the final temperature of 1,100 °C constant for 30 minutes. Afterwards, the sample was cooled down to ambient air temperature before a visual judgment was performed. If the sample showed slagging then the results of this method was

"Yes", otherwise the result was "No". Figure 1 shows the samples after thermal treatment. No differentiation between different temperature levels was made. For each fuel three repetitions were conducted in order to collect data for the evaluation of repeatability and reproducibility since this method was tested at three different laboratories in three different countries.

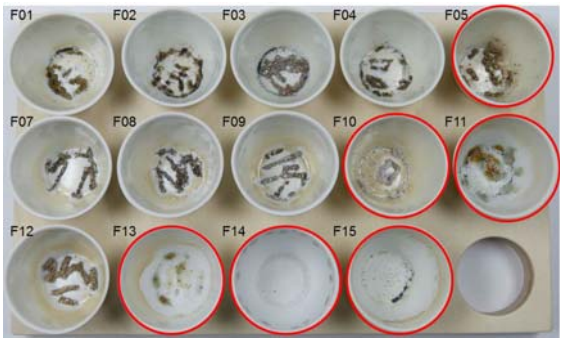

Figure 1: Results of the rapid slag test.

Table I: Overview of fuels and relevant properties for ash melting behaviour.

Fuel No	Fuel name (pellets)	Fuel type	Ash content wt.-%	K	Ca	Mg	Si	P	Al
				mg/kg (dry basis)					
F01	Pine and Spruce	Wood	0.47	626	1,210	170	32	68	21
F02	Stemwood without bark	Wood	0.42	499	904	136	308	48	77
F03	80% Hard wood	Wood	0.77	1,020	2,020	336	116	78	24
F04	Bark rich pellets	Wood	0.41	474	1,050	175	176	39	39
F05	Untreated waste wood	Others	4.79	1,140	4,590	673	10,500	170	1,020
F07	Willow/Spruce (30/70%)	Wood	0.60	937	1,430	175	110	234	18
F08	Willow/Spruce (60/40%)	Wood	0.76	1,060	1,650	195	294	301	47
F09	Willow (100%)	Wood	0.98	1,460	2,310	254	285	493	50
F10	Miscanthus	Herbaceous	3.22	2,780	1,110	480	10,100	298	233
F11	Wheat straw	Herbaceous	9.05	14,600	5,110	1,130	22,100	882	701
F12	Vineyard pruning	Wood	2.72	3,310	6,020	945	1,770	676	371
F13	Corn cobs with hay	Herbaceous	3.07	7,520	1,370	679	5,290	873	315
F14	DDGS (Dried distiller's grains with solubles)	Others	6.21	12,800	1,130	3,320	1,610	9,240	26
F15	Rape seed extraction	Others	7.49	13,200	8,480	4,850	373	11,600	38

2.3 Laboratory test method 2: CIEMAT method

The second laboratory method in this investigation was the so-called CIEMAT method since it was developed by CIEMAT/Spain. Initially the pelletized fuel sample had to be milled down to a grain size below 1 mm. The required fuel amount depended on the ash content of the fuel. About 10 g of ash had to be generated for each fuel type following DIN EN 14775 at maximal 550 °C [1]. The generated ash was sieved to a grain size between 63 and 500 µm. Then about 0.5 g of ash was filled in a heat resistant crucible. Since four temperature levels (800 °C, 900 °C, 1,000 °C and 1,100 °C) with three repetitions were conducted, 12 crucibles were used for each fuel type.

Then the ashes were thermally treated at maximal 800 °C, 900 °C, 1,000 °C or 1,100 °C, applying a constant heating rate of 5 K/min and keeping the set temperature constant for 30 minutes before cooling down. Each sample was visually inspected after thermal treatment. Afterwards, the ashes were sieved for one minute using a sieve with a mesh aperture size of 250 µm. The sample mass before sieving and after sieving above the sieve was determined. The ratio of both values resulted in the slag index. This laboratory method was conducted in three different laboratories.

2.4 Laboratory test method 3: Slag analyser

The slag analyser was developed by DTI (Danish Technological Institute) and only tested at this laboratory. The slag analyser is a small scale downdraft combustion unit and the experimental setup is shown Figure 2.

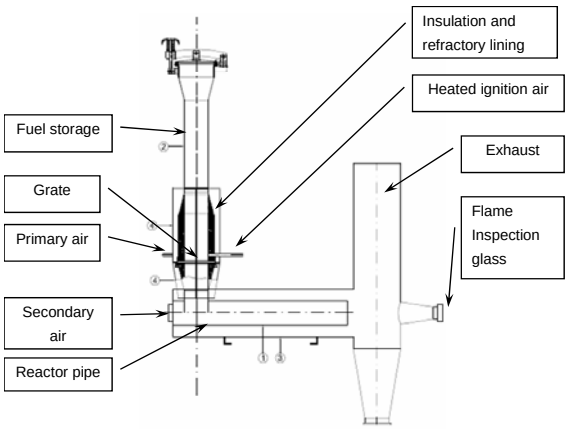

Figure 2: Slag analyser setup (source: DTI)

At the beginning of each test the fuel storage tank is filled with about 4.3 kg (depending on the ash content) of pelletized fuel. The fuel rests on a pre-weighted grate made of 1.5 mm stainless steel plate (150 mm in diameter with 2 mm holes). For ash rich fuels some pellets of a very low ash containing fuel was added in order to dilute the sample in order to prevent clogging of the grate. After closing the storage tank the fuel was ignited by the hot air ventilation and the downdraft combustion took place. During the test the temperature just below the grate was continuously recorded over the test duration of up to two hours. After the fuel was burnt and the system had cooled down all ash and slag residues were carefully collected from the instrument and the grate was removed for further assessment. The assessment included the mass fraction of slag particles larger than 1.6 mm, the mass of slag sticking to the grate after the test run and the average size of the three largest slag lumps. For each parameter different thresholds were defined for final categorization of the fuel into one of five categories where category 1 represented the lowest potential for slagging. Further details can be found in [3].

2.5 Combustion tests in pellet boilers

For validation purposes of the laboratory methods combustion tests with all 14 fuels were conducted in a pellet boiler with a nominal heat output of 15 kW, equipped with a horizontally moving grate for ash removal (reference boiler by Hargassner). In addition, up to five selected fuels were also burnt in eight other pellet boilers (different heat output, fuel feeding systems and ash removal), but these results are not discussed in this paper. All combustion tests were performed following the same description of experimental setup and test procedure. All combustion tests were supposed to last for 24 hours, but this was not always possible for some fuels due to the high ash content of the fuel or due to slagging. After the fuel was burnt and after the cooling down of the boiler a visual inspection of the combustion chamber was performed and photographs were taken. The bottom ash and grate ash were carefully removed from the furnace by a spoon or shovel. The collected ash and slag samples were granulometrically assessed by sieving the entire ash for one minute in a sieving machine while using different sieve sizes (3.15, 2.0, 1.0 and 0.5 mm according to DIN/ISO 3310-1). The weight of the different fractions was determined.

3 RESULTS AND DISCUSSION

3.1 Results of the Rapid slag test

The easiest test of all investigated laboratory methods for the description of slagging behaviour was the rapid slag test and it took about one day until the result was available. After thermal treatment of the pellets and a visual inspection none of the wooden biofuels indicated any slagging. But the other six fuels in this comparison showed slagging (F05, F10, F11, F13, F14 and F15). Moreover, all three laboratories from different countries obtained the same results for slagging tendencies. Therefore, the repeatability (within one laboratory) and reproducibility (between different laboratories) was very high. The main drawback of this method is, however, that no differentiation within the group of wood pellets was possible and slightly lower fuel qualities are not identified.

For further comparison of the results with other laboratory methods as well as with the combustion test all results were normalized to values between 0 (no slagging) and 1 (severe slagging, answer Yes of the test). For the rapid slag test only these two values were achieved as indicated in Figure 3.

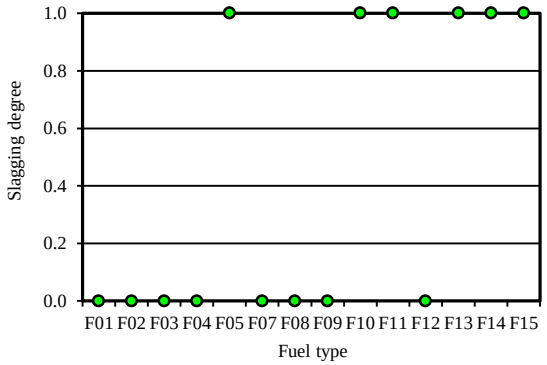

Figure 3: Average slagging degree of the rapid slag test where the value 0 represents "No" slagging and the value 1 represents "Yes" slagging of the fuel.

3.2 Results of the CIEMAT method

The CIEMAT method was much more time consuming than the rapid slag test especially for fuels with a low ash content. For example, for fuel F04 with an ash content of only 0.4 wt.-% a large quantity of about 2.5 kg of the milled fuel had to be used for pre-ashing. This method was investigated by three different laboratories from different countries.

Only for fuels F01, F03, F04 and F08 no thermal ash treatment at 800 °C was then conducted due to their very low ash content as well as due to the fact, that no slagging had been observed for all fuels even at 1,100 °C.

In contrast to that F05 (wood pellets from untreated waste wood) showed some slagging tendencies at especially 1,100 °C, while for the other temperature levels almost no sintering was observed.

The second fuel which had shown slagging in the rapid slag test was F10 (miscanthus). At 1,100 °C the sample was very hard sintered and it could not be removed from the crucible for subsequent sieving. At 1,000 °C the sinter was not as hard.

F11 (wheat straw) was completely sintered at already 1,000 °C. Severe sintering was also detected for F13 (corn cobs with hay) for temperatures above 900 °C. No residue sample material could be removed by a spoon from the bottom of the crucible.

For F14 (DDGS) molten ash in purple colour was sticking to the crucible after thermal treatment at 1,000 °C and 1,100 °C. For the other two temperature levels some melt was observed but it could be removed from the bottom of the crucible and could therefore be sieved for the determination of the slag index.

F15 (rape seed extraction) only showed severe slagging at 1,100 °C. The ash samples from the other temperature levels were white in colour but could be removed from the crucible for subsequent sieving.

After visual inspection the ash sample was removed from the crucible and weighed before sieving. A sieve size of 250 µm was used and the ratio between mass remaining above the grate and the total ash generated during thermal treatment was determined. The mass sticking to the crucible was always added to the slag fraction larger than 250 µm.

The average values for the ratio of mass above 250 µm and the total ash for each fuel and temperature level are shown in Figure **4**. A clear differentiation between all fuels is visible, even for the different types of wood pellets.

All average values obtained through sieving were

normalized so that a slag index of 100 % represents the maximal slagging degree of 1. For each temperature level the calculated values are presented in Figure 4. In contrast to the rapid slag test there are large differences between different fuels and temperatures. A most critical sample fuel F14 was identified as it was molten at almost every temperature level.

A clear differentiation between the wood fuels is possible indicating that fuel F02 and F04 will cause the lowest problems with regard to slag formation.

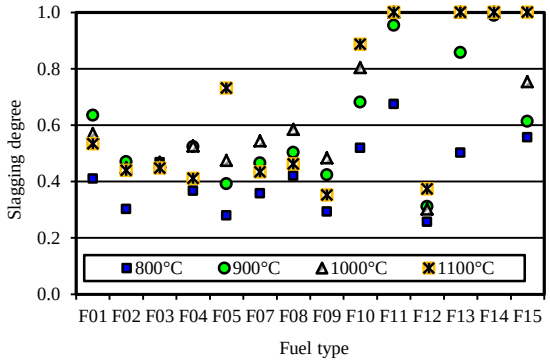

Figure 4: Average slagging degree of the CIEMAT method using a 250 µm sieve at different temperature levels from three laboratories. The value 0 represents no slagging and the value 1 represents severe slagging of the assessed fuel.

3.3 Results of the Slag analyser

All 14 fuels were also investigated in the slag analyser. After each test the residues on the grate was first visually assessed before sieving. Different values such as the largest slag pieces on the grate after the test run were recorded. All residues were sieved by hand using sieves with 6.3 mm, 2.5 mm and 1.6 mm and each mass fraction was recorded for further evaluation. Moreover, the amount of slag sticking to the grate was determined. Therefore, a new grate had to be used for each test run.

All data were evaluated and the appropriate category (between 1 and 5) was determined. These five categories were normalized to values between 0 (category 1) and 1 (category 5 for severe slagging), see Figure 5.

It can be clearly seen that F04 showed the lowest slagging tendency of all fuels in this investigation. A differentiation between the wood fuels is visible. The highest slagging degree was detected for F14 and F15.

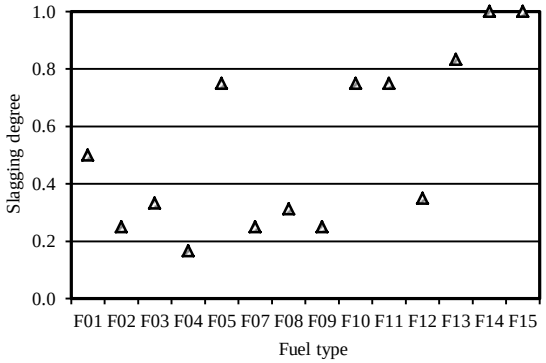

Figure 5: Average slagging degree determined with the Slag analyser for all fuels. The value 0 represents no slagging and the value 1 represents severe slagging of the assessed fuel.

3.4 Results from the combustion tests

For the reliability of slag prediction only the combustion results from the reference boiler with a nominal heat output of 15 kW is discussed here. The accumulated weight fractions using different sieve sizes for each fuel from this boiler are shown in Figure 6.

A clear differentiation between wood fuels is visible from the combustion tests with this pellet boiler. It seems that F02 caused the least problems as here the smallest ash/slag particles were collected after the test runs. Miscanthus (F10) appears less suitable for this boiler compared to wheat straw (F11). It should be also noted that F15 (rape seed extraction pellets) was less problematic than F10 and F11 during the combustion in the other pellet boilers.

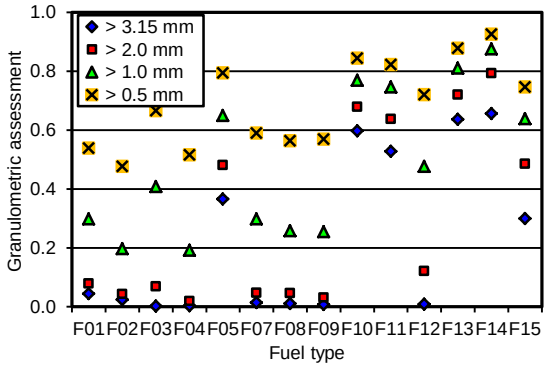

Figure 6: Results of the granulometric assessment of ash/slag residue from the reference boiler.

3.5 Validation of laboratory test results with combustion tests

Since the rapid slag test did not allow any differentiation between wood pellets this method was excluded from the considerations for further development. In the following therefore only the CIEMAT method and the slag analyser are considered.

The fuels F02 and F04 caused the lowest risk of slagging during the combustion test in the reference boiler (Figure 6). This observation was confirmed by the slag analyser test. With the CIEMAT method, however, the lowest risk of slagging was observed for fuel F12.

Fuels F02 and F07 had also been applied in the other pellet boilers. There both fuels had shown quite similar

results after a granulometric assessment of the boiler ash. A slightly higher risk of slagging might be observed for F07 in all investigated pellet boilers. Therefore a good agreement between the combustion tests and the slag analyser results (Figure 5) as well as the CIEMAT method results (Figure 4) could be proven. No differences between both fuels had been detected by the rapid slag test (Figure **2**).

All herbaceous fuels (F10, F11, F13) and also F15 which were combusted in the reference boiler caused higher fractions of large ash and slag lumps. This was also in agreement with the laboratory methods, but still a differentiation between these three fuels were possible with both, the CIEMAT method and the slag analyser (compare Figure 3 to Figure 5). The slag analyser predicted the same slagging tendency for F10 and F11 while a differentiation between both fuels was observed with the CIEMAT method.

Based on the discussed results from the combustion tests as well as the laboratory test methods it may be concluded that the CIEMAT method had the same capability for correct prediction of slag related problems as the slag analyser. Both methods could display smaller differences within the group of wood fuels as well as for herbaceous fuels. But the CIEMAT method is an extremely time consuming method being less practicable. When using the slag analyser, however, the results can be obtained within one day. Moreover, the slag analyser method predicted the slagging behaviour of the different fuels "correctly" (as verified in the combustion tests), except for F15. The slag analyser method can be easily further improved, e. g. by performing the sieving with a sieving machine. Also the evaluation procedure can be adapted (e. g. by introducing a weighting factor for the observations instead of having to select the highest class observed for one of the four evaluation criteria). The CIEMAT method offers much less chances for such improvements.

4 CONCLUSIONS

For the investigation of slagging behaviour 14 different fuels were tested in combustion tests and used in three different laboratory methods.

It could be shown that the rapid slag test provided only very limited information about the slagging behaviour. No differentiation between wood fuels was possible. But the CIEMAT method as well as the slag analyser were capable to differentiate between different fuel types including wood fuels and proved a high capability for a correct prediction of slagging tendency. But the CIEMAT method is an extremely time consuming method so that it may take several weeks for a final evaluation of a fuel type.

The slag analyser provides the result within a day. But the sample needs to be available as pellets.

The slag analyser was determined as a promising method for reliable slag prediction for solid biofuels. Therefore this method is further developed and will be tested in a round robin study.

5 REFERENCES

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6 ACKNOWLEDGEMENT

The research project AshMelT was funded by the Seventh Framework of the European Union, Grant Agreement No. 287062. Furthermore, the authors highly acknowledge the cooperation with the participants of the AshMelT project.

7 LOGO SPACE

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