The Prediction of the Tendency of Slagging and Fouling of European Lignites by New Statistical and Experimental Methods

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Introduction

Proper design and operation of coal-fired boilers requires prediction of the tendency of the fuels to foul and slag. A large number of correlations based on the oxides of an ash produced in the laboratory exist (1,2). The success of these correlations has been limited to the range of ash properties for which they were developed, and even then, these relationships may be unreliable. For instance, existing correlations can predict whether a fuel will create deposition problems in boilers rarely, occassionally, or frequently for approximately 50 percent of the fuels. An accuracy only slightly better than random guess (3).

Potential problems using available techniques have been discussed in the literature (2,3,4,5). The problems result from:

- Preparation and analysis of the ash (6)
- Ignoring the distribution and individual nature of mineral matter (4,6)
- Neglecting the influence of ash content (7)
- Ignoring the design of the boilers including heat release rate, heat fluxes and velocity profiles (3,8,9)

In addition the correlation should not be used for coals with properties outside the range for which the correlations were developed.

This paper describes the limited success of applying such techniques to predict performance, efforts to develop and verify new techniques to predict preformance, and application of these techniques to predict the slagging and fouling behavior of European brown coals.

Prediction of Slagging Performance

Slagging performance of coals in boilers has been predicted by:

- temperature of critical viscosity,
- the base to acid ratio,
- and the base to acid ratio multiplied by the sulfur content of the coal.

Predictions of slagging and fouling using these relationships are compared to boiler performance for the six European brown coals listed in Table 1. The calculated indicies and estimated and actual performance of the fuels are shown in Table 2.

The temperature of critical viscosity is the temperature at which the slag changes from plastic to Newtonian behavior. Plastic slags are difficult to remove by soot blowing. As a consequence, fuels with low temperatures of critical vis-

cosity are expected to form difficult to remove plastic and molten slags more readily than other fuels.

The temperature at critical viscosity can be measured in a viscometer, but the measurements are time consuming and expensive and the temperature at critical viscosity is usually estimated using emperical formulae. For instance, Watt and Fereday (10) developed

$$T_{cv} = \sqrt{\frac{107.m}{2.398-c}} + 150 \text{ in } ^{o}C \qquad 1).$$

where $SiO_2 + A\ell_2O_3 + Fe_2O_3 + CaO + MgO = 1$ 2).

and $m = 0.835\ SiO_2 + 0.601\ A\ell_2O_3 - 0.109$ 3).

$c = 4.15\ SiO_2 + 1.92\ A\ell_2O_3$ 4).

The temperature at critical viscosity probably does not adequately predict slagging behavior of the six European brown coals of this study. The qualitative relationship between deposits formed in a boiler and the temperature of critical viscosity estimated by the technique of Watt and Fereday (10) is shown in Figure 1a. The data appear to correlate with observations, but predict improved performance at an intermediate temperature of critical viscosity. No reason is known for this and the correlation may be fortuitious.

The base to acid ratio is the reverse of the previous relationship and probably does not correlate the slagging data either. Figure 1b shows that the base to acid ratio appears to correlate the prediction of performance of brown coals in boilers. This relationship predicts optimum performance at a base to acid ratio of 0.3. This is quite possible with the formation of eutetics. However, comparison of Figure 1a and 1b shows the curves are reversed and the prediction of performance of all the fuels fall in the same relative position on both curves. This again leads to uncertainty as to the reasonableness and the reliability of the correlations in Figure 1.

The standard slagging factor, R_s, could not correlate the performance of all the fuels in the boilers. The slagging factor is defined as

$$R_s = B/A \cdot S \qquad 5).$$

by Attig and Duzy (11). This equation is suggested for ashes which have $Fe_2O_3 >$ CaO + MgO but is applied to all ashes in this study. Only two of the ashes in this study have $Fe_2O_3 >$ CaO + MgO. Leipzig has about equal amounts and Nordbohmen has greater Fe_2O_3 than CaO + MgO. The base to acid ratio (shown in Figure 2a) is recommended to correlate slagging behavior of ashes with CaO + MgO $> Fe_2O_3$ (11). Five of the fuels correlate reasonably with R_s but the slagging of Nordbohmen was greatly underestimated. However, this fuel was the only one with significantly greater Fe_2O_3 than CaO + MgO and might not correlate with the other five fuels.

A good correlation of all six fuels was developed by modifying the slagging factor. The relationship is shown in Figure 2b where the slagging factor, f_s, is defined as:

$$f_s = 1.7 + 1.7\ SiO_2^* + 0.8\ A\ell_2O_3^* - 6.0\ (S)^0 r_{Fe}^2 \qquad 6).$$
$$-2.2\ (CaO^* + MgO^*) - 1.9SO_3^* - 1.3\ (Alk)^*$$

where f_s = 0 is strong slagging

and f_s = 1 is no slagging

and $$[\quad]^* = \frac{[\quad]^*}{1 - SiO_2 + SiO_{2corr}} \qquad 7).$$

$$SiO_{2corr} = 823\ \Gamma_{SO3}^{2.65} \cdot \exp(-9.45\ \Gamma_{SO3})\ Fe_2O_3 \qquad 8).$$

$$\Gamma_{SO3} = \frac{SO_3}{1 - SiO_2} \qquad 9).$$

where S is the weight percent sulfer in the coal as received and all other compositions are weight percent of the ash.

Predictions of Fouling Performance

The fouling performance of the six brown coals of this study could not be adequately predicted by existing or new techniques. The fouling performance of coals with $CaO + MgO > Fe_2O_3$ is usually predicted by the sodium content of the ash. Figure 3a shows the correlation of the qualitative observation of fouling in boilers with the alkali (Na_2O plus K_2O) content of the ash. All the coals except Ungarn correlate with the alkali content of the ash. However, no explanation is available for the fouling of the Ungarn which had 0.0 alkali content in the ash. A new fouling factor, f_F,

$$f_F = \exp\left[\frac{-5.\ Alk^*}{f_s + 0.3}\right]$$

where Alk* is defined by equation (7) was moderately successful, Figure 3b, in correlating the fouling performance of coals. However, considerable scatter still exists in the relationship.

Pilot Scale Prediction of Fouling and Slagging Performance

The limited success of predicting fouling and slagging performance based upon the analysis of the oxides of ashes produced in laboratory apparatus has prompted the Technical University of Dresden to develop pilot scale tests to predict slagging and fouling of ashes in boilers. Two tests are currently being evaluated which determine slagging and fouling characteristics of fuels not determined by current laboratory or other small scale tests. The first, determines the fouling and slagging of the fuel under different combustion conditions. In this test, the coal is burned in a small drop tube furnace. The level of oxygen and the thermal environment of combustion are changed. The particle temperatures are measured with thermographic techniques and the nature and deposition rate evaluated. Such a technique can simulate the limits of the time temperature concentration history in boilers and avoids production of an artifical mean ash. This technique does not account for ash trajectories in boilers.

The tendency of ash to follow streamlines or deposit on surfaces is determined in a second test. In this test, the coal is burned in a small cyclone combustion chamber. This chamber can also simulate the limits of time and temperature history of ashes in boilers. In addition, a cyclone chamber subjects the coal to centrifugal forces, which allows the ability of the fly ash particles to follow streamlines to be assessed.

The ability of these pilot scaled tests to predict the slagging and fouling performance of European brown coals is currently being evaluated. Preliminary results are promising.

TABLE I ASH COMPOSITION OF EUROPEAN BROWN COALS
WEIGHT PERCENT IN THE ASH

	UNGARN	LEIPZIG	NIEDERLAUSITZ	OBERLAUSITZ	NORDBOHMEN	SULZROHLE
SiO_2	47.9	25.5	46.2	41.8	52.9	11.9
Al_2O_3	26.1	3.5	6.8	30.0	25.3	6.9
Fe_2O_3	8.6	24.0	13.4	8.3	12.6	3.0
CaO	8.0	19.5	11.4	9.5	3.4	15.2
MgO	1.7	3.5	7.6	4.0	1.5	2.2
SO_3	4.8	22.5	12.9	3.6	2.5	31.5
Alkali	0.0	1.5	1.3	0.2	1.8	22.0
Not Determined	2.9	0.0	0.4	2.6	0.0	7.3

TABLE II COMPARISON OF ESTIMATED AND OBSERVED PERFORMANCE OF EUROPEAN BROWN COALS

	Performance		Watt & Fereday Critical Viscosity	Prediction									
Coal	slagging	fouling	°C	Slagging B/A		Slagging R_s		Slagging f_s		Fouling f_F		% Alkali	Fouling
Ungarn	considerable	medium	1395	0.247	low	1.088	medium	0.384	medium	1.000	none	0.0	low
Leipzig	strong	medium	904	1.621	high-severe	4.539	very high	0.106	strong	0.863	low	1.5	medium
Niederlausitz	medium	low	1268	0.611	medium	0.734	medium	0.456	medium	0.900	low	1.3	medium
Oberlausitz	none	none	1312	0.304	low	0.061	little	0.963	none	0.988	none	0.2	low
Nordbohmen	very strong	low	1440	0.224	low	0.246	little	0.086	very strong	0.627	medium	1.8	medium
Salzkohle	strong	very strong	963	1.085	high-severe	3.038	very high	0.189	strong	0.091	very strong	22.0	severe

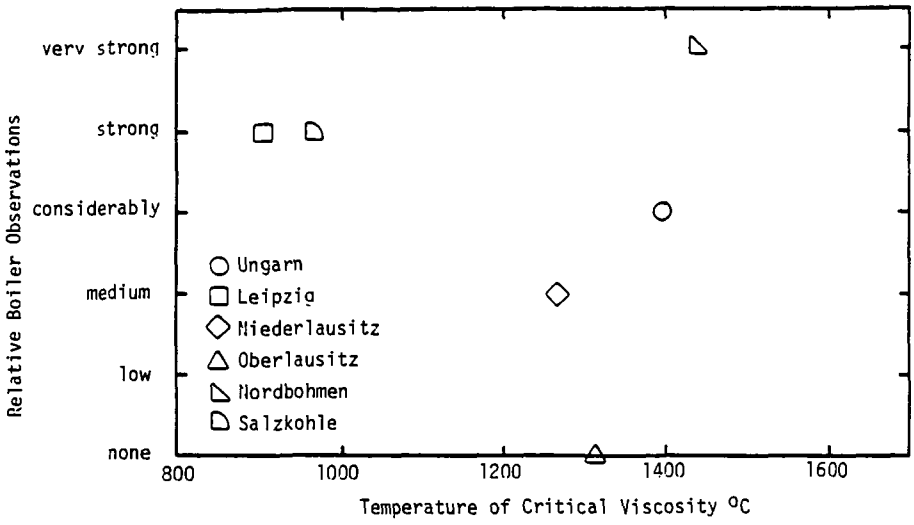

Figure 1a. Comparison of observed and predicted (T_{CV}) slagging performance of brown coal.

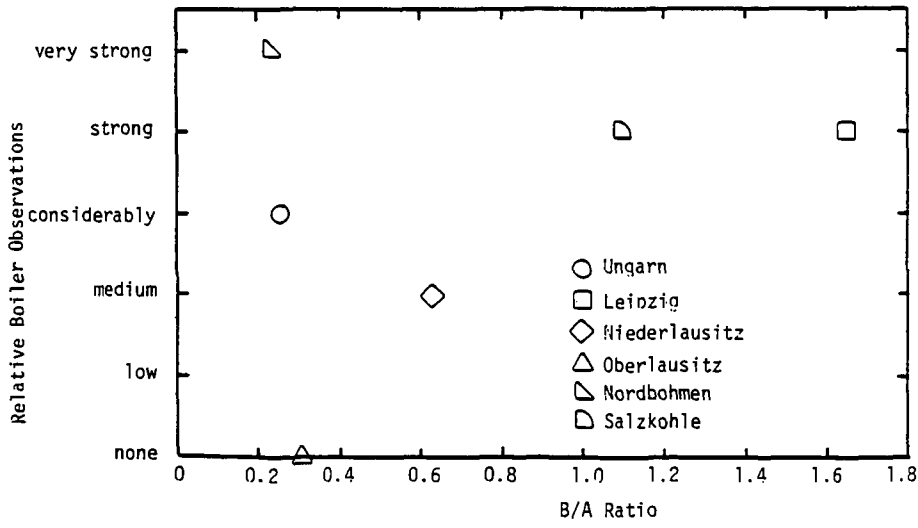

Figure 1b. Comparison of observed and predicted (B/A) slagging performance of brown coal.

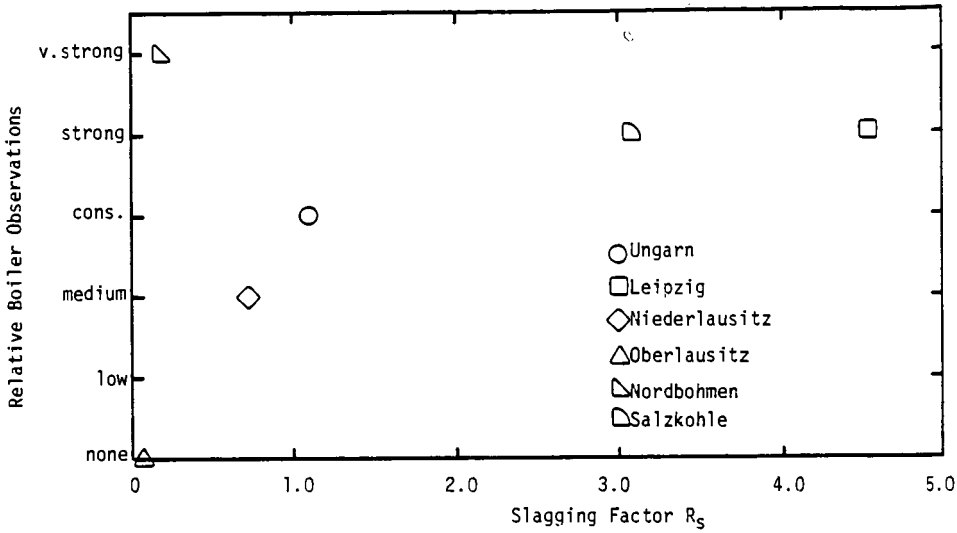

Figure 2a. Comparison of observed and predicted (R_S) slagging performance of brown coal.

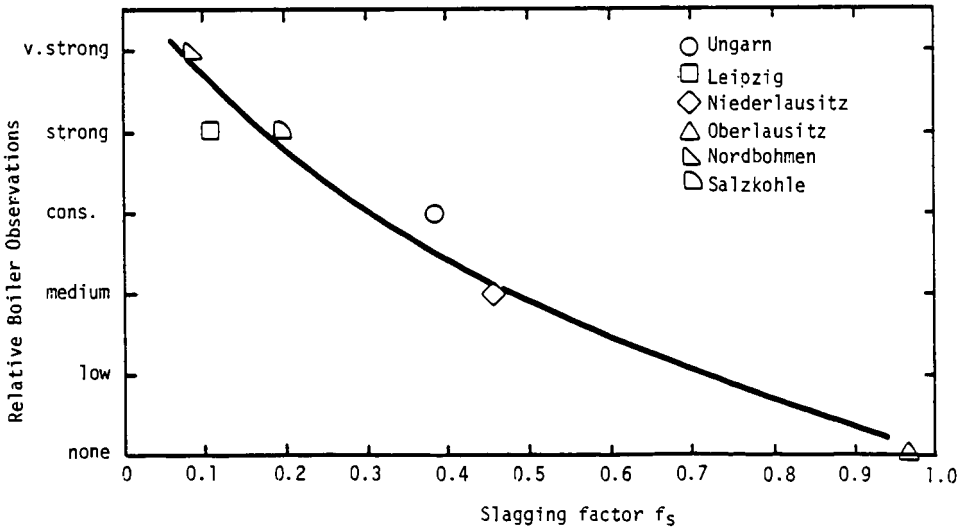

Figure 2b. Comparison of observed and predicted (f_S) slagging performance of brown coal.

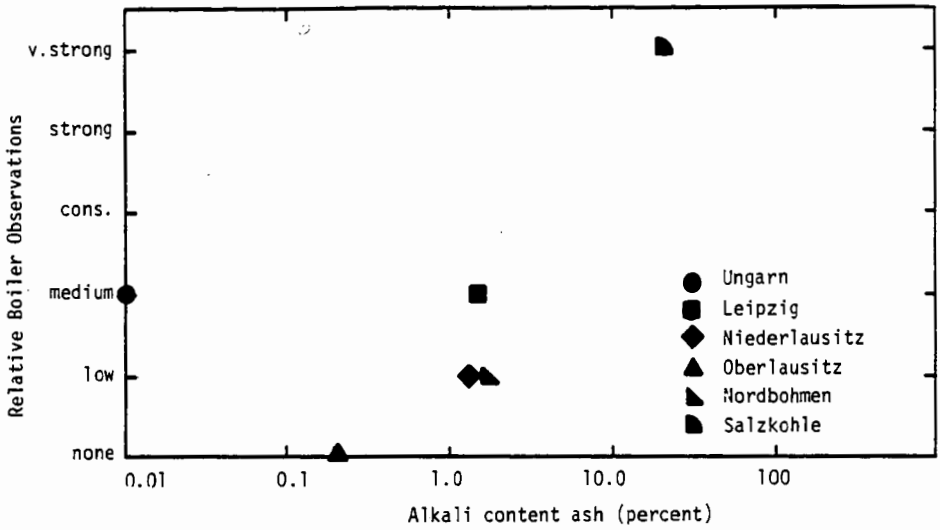

Figure 3a. Comparison of observed and predicted (Alkali content) fouling performance of brown coal.

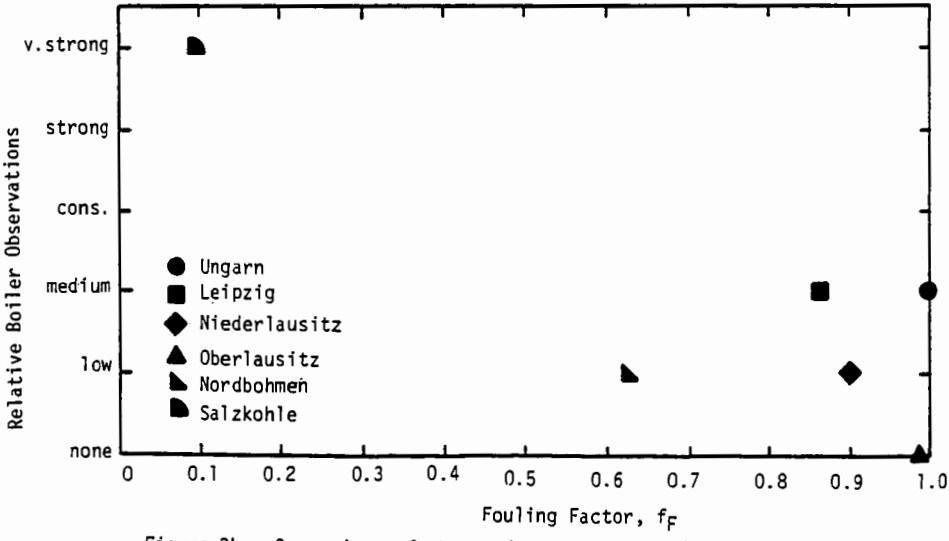

Figure 3b. Comparison of observed and predicted (f_F) fouling performance of brown coal.

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