



*Original Article*

## Effect of mineral oxides on slag formation tendency of Mae Moh lignites

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### Abstract

Slagging is one of major ash deposition problems experienced in the boilers of coal-fired power plants especially the plants that use lignite, like Mae Moh lignites. The occurrence of slag is a complex phenomenon depending on several factors such as ash properties, furnace operating conditions, and coal properties. The main objective of this work is to study the effect of mineral components in Mae Moh lignite on ash fusion temperatures (AFTs), which is commonly used as a key indicator for slag formation tendency under pulverized combustion conditions. Two Mae Moh lignites from the coal seams planned to be used in the future were selected for the study to represent low CaO and high CaO lignite. The two lignites, namely K1 and K3, have 3.6 and 40.4 wt% CaO in ash, respectively. The AFT characterization shows that their initial deformation temperatures (ITs) were almost identical and considered as low for the typical flue gas temperature in the radiation section of Mae Moh boilers, i.e. 1050-1100°C. These observed similar ITs were rather unexpected, especially for K1 considering its sufficiently low base to acid (B/A) ratios. The X-ray diffraction analyses evidently show the presence of illite, pyrite and anhydrite in K1, which explains the observed lower IT of the sample. Anhydrite, which is known to lower the ITs, is also the most abundant mineral in K3. Washing the lignite samples with HCl can significantly reduce CaO, MgO, and SO<sub>3</sub> content in the ash but not Fe<sub>2</sub>O<sub>3</sub> as it is present in the form of pyrite. The addition of Al<sub>2</sub>O<sub>3</sub>, SiO<sub>2</sub> and Fe<sub>2</sub>O<sub>3</sub> can help increase AFTs of the studied samples. The Al<sub>2</sub>O<sub>3</sub> addition gives the strongest effect on increasing AFTs, especially for the sample with low Al<sub>2</sub>O<sub>3</sub> content. When the CaO is added to the low CaO samples, the fluxing effect will initially occur. However, when the CaO content is higher than a critical value (i.e. CaO > 38%), the effect of its high melting point will dominate hence the AFTs increased. Ternary phase diagrams of CaO-SiO<sub>2</sub>-Al<sub>2</sub>O<sub>3</sub> and Fe<sub>2</sub>O<sub>3</sub>-SiO<sub>2</sub>-Al<sub>2</sub>O<sub>3</sub> system were constructed based on the obtained ash composition and IT data to investigate the effect of SiO<sub>2</sub>/Al<sub>2</sub>O<sub>3</sub> ratio and basic oxide composition (CaO or Fe<sub>2</sub>O<sub>3</sub>). The upper limit of the ITs measured from lignites supplied to the power plant during the severe slagging period, i.e. 1220°C, was used as a rough indication of slag formation propensity.

**Keywords:** lignite, combustion, *pf* boiler, slag, ash fusion temperature

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## 1. Introduction

Slag formation is one of the typical problems experienced in operation of coal-fired *pf* boilers. Soot blowing is a common technique used in boilers to prevent excessive deposition of slag on water walls resulting in reduction of boiler efficiency and in extreme cases shutdown. However, some slag deposits have been reported to make soot blowing insufficient. One such case is reported for Mae Moh power plant, the only lignite-fired power plant in Thailand, which has recently experienced slagging problems in some of its boiler units. All the ten boiler units were designed as pulverized coal combustion (PCC) steam boilers with a combined capacity of 2400 MW and they are fired with lignite blends processed from the nearby Mae Moh mine.

The mechanisms of slag formation are determining the quantity and properties of the slag formed and both characteristics depend on the fuels used and the operating parameters. Although the mechanism of the slag formation has not yet been fully understood, a number of studies (Vassilev *et al.*, 1995; Scott, 1999; Russell *et al.*, 2002; van Dyk, 2005) have already shown a relationship between mineral oxide compositions in the feed coals in all ranks ranging from lignites to anthracites and slag formation propensity. For high-rank coals of which the content of acidic oxides, i.e. SiO<sub>2</sub> and Al<sub>2</sub>O<sub>3</sub>, together exceeds 70% of all mineral oxides, the tendency of slag formation is normally low as often indicated by the high melting temperatures of the resulting ashes. On the other hand, lignites, which have comparable contents of acidic and basic oxides, the relative amount of basic oxides plays a significant role in determining the melting behavior of the ashes and hence the slag formation propensity.

A recently published study by Pipatmanomai *et al.* (2009), which investigated the characteristics and composition of Mae Moh lignites and boiler ashes in the 300 MWe boiler units, has confirmed the high slagging propensity of Mae Moh lignite. One interesting finding was that CaO and Fe<sub>2</sub>O<sub>3</sub> in isolation cannot be the main indicator, and that all major oxides in lignites (SiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, CaO, and Fe<sub>2</sub>O<sub>3</sub>) should be taken as indices during mining and blending. Therefore, detailed investigations of the quantitative effects under different combination of oxides in Mae Moh lignites should be carried out in order to identify the suitable blending criteria apart from the currently recommended value of CaO < 23%, SO<sub>3</sub> free (Electricity Trust of South Australia, 1990) and to determine whether the proper blending (i.e. coal chemistry solution) can prevent slag problem or other causes are also needed to be investigated.

In this study, two Mae Moh lignites representing the low and high CaO lignite were selected from the coal seams planned to be used in the future. The relationship between the present oxide combination in lignites and the ash fusion temperature (AFT), which was taken as an indicator for slagging tendency, was investigated. The AFT determines the temperatures at which the various stages of ash softening and melting takes place, and therefore can tell the deposition

characteristic of coal in pulverized fuel combustion. In particular, the initial deformation temperature (IT), which is the temperature where the ash first softens and becomes sticky, has significant implications for the boiler design. It needs to be ensured that the furnace exit gas temperature (FEGT) at the radiant section of the boiler is sufficiently below the IT of the feed coal to avoid ash softening. Addition of pure oxides (SiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, CaO, and Fe<sub>2</sub>O<sub>3</sub>) at various proportions into original and acid-washed lignite fractions was also carried out to obtain a full range of oxide combination while maintaining the identification of each lignite sample.

## 2. Experimental Methods

Two lignite samples from Mae Moh Mine, namely K1 and K3, were selected from the coal seams planned for future use to be representatives of low CaO and high CaO lignite in this study. The samples were prepared to the 60-mesh size following ASTM D2013 and then subject to proximate analysis, measurement of sulfur content and calorific value performed following ASTM D5142, ASTM D4239, ASTM D5865, respectively.

Each lignite sample was divided into two parts. For the first part, each of the pure CaO, Fe<sub>2</sub>O<sub>3</sub>, Al<sub>2</sub>O<sub>3</sub>, or SiO<sub>2</sub> was added at various weight ratios (5, 10, 15, 20, and 25%). The pure oxides were analytical reagent (AR) grade chemicals in powder form. The second part was first washed with strong acid to eliminate the basic oxides and subsequently added with pure CaO, Fe<sub>2</sub>O<sub>3</sub>, Al<sub>2</sub>O<sub>3</sub>, or SiO<sub>2</sub> at weight ratios that were the same as those for the first part of the sample. The method used for the elimination of basic oxides from the lignite samples followed van Dyk *et al.* (2005). Approximately 3 mL of 1 M hydrochloric acid (HCl) per gram of sample was added into the lignite sample. The mixture was stirred at room temperature for 24 hours and filtered. The solid fraction was oven-dried to remove the remaining acid.

The ash composition was analysed following ASTM D3682. The lignite ash was fused with lithium tetraborate (Li<sub>2</sub>B<sub>4</sub>O<sub>7</sub>) and the melt was dissolved in diluted acid (HCl). The solution was then analyzed by ICP-OES (Perkin Elmer Optima 5300DV). The measurement of ash fusion temperatures was performed using ash fusibility determinator (LECO AF700) following ASTM D1857 under an oxidizing atmosphere. The lignite ash was formed into a cone (triangular pyramid). Upon heating, the four characteristic ash fusion temperatures were observed, which are defined as follows: (1) initial deformation temperature (IT), the temperature at which the first rounding of the apex of the cone occurs, (2) softening temperature (ST), the temperature at which the cone has fused down to a spherical lump in which the height is equal to the width of the base, (3) hemispherical temperature (HT), the temperature at which the cone has fused down to a hemispherical lump at which point the height is one-half the width of the base, and (4) the fluid temperature (FT), the temperature at which the fused mass has spread out in a nearly flat layer. The X-Ray diffraction (XRD) analysis was

performed to examine the mineral transformation behavior of lignite. To prepare samples for XRD analysis, the sample was ashed at low temperature (350°C) until reaching a constant remaining weight for complete removal of the organic matters. The low temperature ashing is necessary to ensure that no minerals are transformed. Bryers (1996) found that there are no minerals transformed at temperatures below 400°C.

### 3. Results and Discussion

#### 3.1 Characteristics of lignite samples

Table 1 presents the analysis of the original (unwashed) lignites, K1 and K3, and acid-washed lignites, K1 washed and K3 washed.

Considering the samples on their original basis, it is clear that apart from the difference in the CaO content of these two samples, other properties were also different. K3 had slightly higher volatile and moisture content than K1 but its higher calorific value was importantly attributed to its higher fixed carbon and lower ash content. Although K1 had significantly higher sulfur content, i.e. double that of K3, it appears not to be transformed into SO<sub>3</sub> in ash. The opposite behavior was observed for K3, which yielded very high SO<sub>3</sub> content in ash.

Both samples had almost identical Fe<sub>2</sub>O<sub>3</sub> content. K1 had low CaO content (3.6%) and high in acidic oxides, i.e. Al<sub>2</sub>O<sub>3</sub> (25.3%) and SiO<sub>2</sub> (52.6%); while K3 had substantial level of CaO (40.4%) and low in acidic oxides, Al<sub>2</sub>O<sub>3</sub> (8.0%) and SiO<sub>2</sub> (16.9%). Despite the large difference in ash composition, the SiO<sub>2</sub>/Al<sub>2</sub>O<sub>3</sub> ratios, which are the parameters affecting the viscosity and melting characteristics of coal ash (Huggins *et al.*, 1981), of K1 and K3 are very close, i.e. 2.08 and 2.11, respectively. For minor oxides, relatively low but significant levels of alkali were also found in both K1 and K3. K1 was richer in K<sub>2</sub>O; while K3 was richer in Na<sub>2</sub>O. Although these alkali species are unlikely to contribute to slag formation, their presence could form low melting point compounds and subsequently fouling deposits at the low-temperature convection section of the boiler (Benson *et al.*, 1993).

The calculated base to acid (B/A) ratio x S % values, the traditional slagging index, of K1 and K3 were 0.63 and 3.29, respectively. From previously reported literature (Lawrence *et al.*, 2008), coals of lower B/A ratios generally have lower slagging propensity. Both K1 and K3 were likely to cause slag problem at medium and severe level of slagging. After acid washing, large fractions of CaO and MgO in ash, especially for K3 which originally had high levels of base oxides, were removed; while SO<sub>3</sub> was only moderately

Table 1. Chemical analysis and AFT characteristics of the unwashed coal and acid washed coal samples (air dry basis).

	K1	K1 washed	K3	K3 washed
Moisture, wt %	12.12		18.93	
Ash, wt %	26.67		9.05	
Volatile matter, wt %	32.94		39.81	
Fixed carbon, wt %	28.27		32.21	
Sulfur, wt %	2.43		1.29	
Calorific value(Gross), Kcal/Kg	3935		4667	
Ash composition, wt % in ash				
Fe <sub>2</sub> O <sub>3</sub>	11.2	9.7	12.3	21.4
Al <sub>2</sub> O <sub>3</sub>	25.3	23.1	8.0	10.4
MgO	2.6	1.9	8.0	5.6
SiO <sub>2</sub>	52.6	59.4	16.9	24.1
CaO	3.6	1.7	40.4	22.0
K <sub>2</sub> O	2.8	2.8	0.2	1.4
Na <sub>2</sub> O	0	0.8	2.5	2.6
TiO <sub>2</sub>	0.4	0.5	0	0.2
Mn <sub>3</sub> O <sub>4</sub>	0	0	0.1	0.2
SO <sub>3</sub>	1.4	0.2	11.6	12.2
Ash Fusion Temp, °C (oxidizing atmosphere)				
IT (initial deformation temperature)	1055	1011	1062	1232
ST (softening temperature)	1391	1437	1340	1309
HT (hemispherical temperature)	1405	1453	1369	1317
FT (fluid temperature)	1423	1479	1400	1349

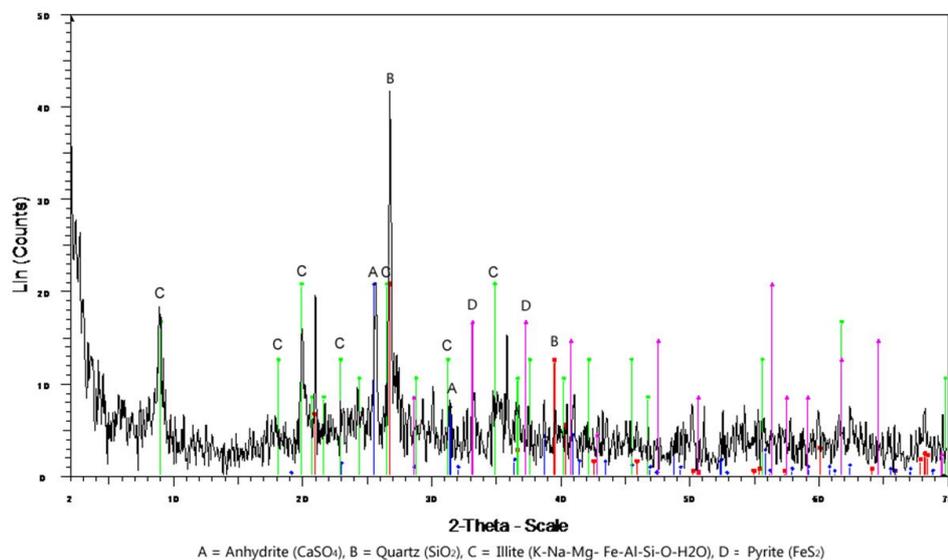
reduced. The  $\text{Fe}_2\text{O}_3$  contents remained almost unchanged for both samples. The apparent increase in  $\text{Fe}_2\text{O}_3$  content in K3 was probably due to the considerable portion of CaO removed. This insolubility of  $\text{Fe}_2\text{O}_3$  in HCl implies that most iron is associated with sulfur in the form of pyrite. The calculated B/A ratio of acid washed K1 was almost unchanged, while that of acid washed K3 dropped to 1.53.

### 3.2 Correlation between the lignite ash characteristics and AFTs

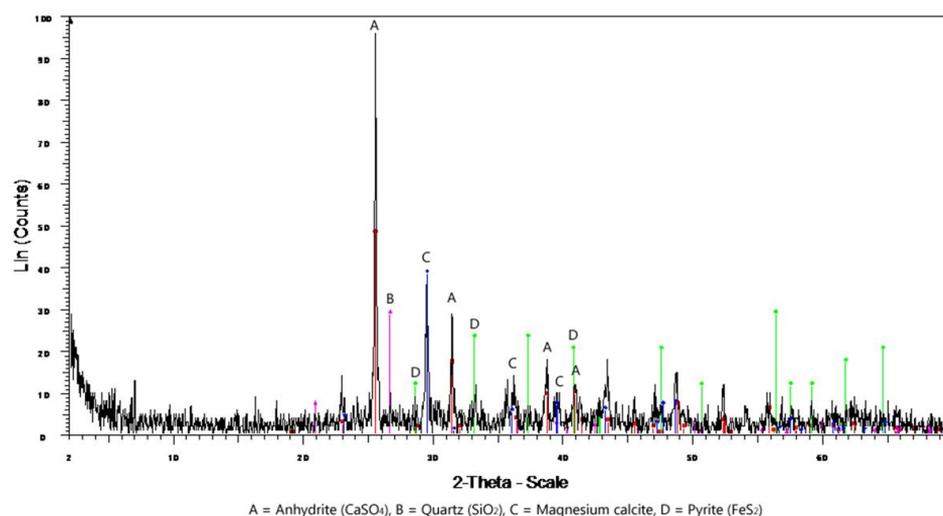
From the results of the ash fusion temperature measurement given in Table 1, the ITs of K1 and K3 were almost identical and considered as low for the typical flue

gas temperature in the radiation section of Mae Moh boilers, i.e. 1050-1100°C (Pipatmanomai *et al.*, 2009). These observed similar ITs were rather unexpected, especially K1 considering its sufficiently low B/A ratios as discussed above. However, the XRD analyses of K1 and K3 samples as shown in Figure 1 may explain the observed lower IT of both samples. As expected from the bulk composition, K1 contains quartz and illite as the major minerals with also significant amounts of pyrite and anhydrite. Anhydrite is the most abundant mineral in K3 with lesser amounts of quartz, magnesium calcite and pyrite. The presence of anhydrite is known to lower the ITs.

The differences of temperature between IT and other AFTs were extremely large, i.e. ST ~300-350°C higher than IT. The larger range was observed for K1, which is probably



(a) K1 sample



(b) K3 sample

Figure 1. X-Ray Diffraction pattern of lignite samples.

due to its higher content of SiO<sub>2</sub> and Al<sub>2</sub>O<sub>3</sub>. Vassilev *et al.* (1995) found that the longer AFT intervals are the characteristics of ashes rich in quartz, metakaolinite and Ca silicates which produce melts with higher viscosity and lower solution activity.

The removal of base oxides by acid washing differently affected the AFTs of samples. The IT of acid-washed K1 became somewhat lower while the other AFTs were slightly higher (i.e. ~50°C) than those of the unwashed K1. In contrast, the IT of K3 considerably increased by almost 200°C, but the other AFTs slightly decreased after acid washing.

### 3.3 Effect of oxide addition on AFTs of lignite ashes

To investigate the effect of oxide composition on the AFTs of ashes, each oxide (i.e. CaO, Fe<sub>2</sub>O<sub>3</sub>, Al<sub>2</sub>O<sub>3</sub>, and SiO<sub>2</sub>) was added into the original (unwashed) lignites and acid-washed lignites at various ratios (i.e. 5, 10, 15, 20, and 25% by weight). The compositions of the ashes after mixing the oxides are given in Table 2 and 3 for K1 and K3, respectively. The samples were then ashed and subject to the AFT measurement. Then, the correlation between the total % of each oxide in sample (after addition) and the AFTs were made.

#### 3.3.1 Effect of oxide addition on AFTs of ashes from original (unwashed) samples

The correlations between total % of each oxide in K1

samples after oxide addition and the AFTs are presented in Figure 2 (a-d). By adding CaO into K1 (the low CaO lignite), all the AFTs except FT slightly decreased initially. The IT substantially increased by ~150°C within a narrow range of CaO content, i.e. ~37-43%, before it became largely independent of CaO content. The addition of Fe<sub>2</sub>O<sub>3</sub>, also known as a fluxing material, moderately increased the AFTs, but in general had less influence on AFTs than did CaO addition. The low correlation between Fe<sub>2</sub>O<sub>3</sub> and AFTs was also found in other studies (van Dyk, 2005; van Dyk *et al.*, 2005). As expected, the Al<sub>2</sub>O<sub>3</sub> and SiO<sub>2</sub> addition consistently increased the AFTs, the former of which gave the more pronounced effect. The study by van Dyk (2005) reported that the stronger ion-oxygen attraction obtained for Al<sub>2</sub>O<sub>3</sub> in comparison with SiO<sub>2</sub> and TiO<sub>2</sub> was a possible explanation for the biggest effect on AFTs for Al<sub>2</sub>O<sub>3</sub> addition. However, unlike the effect of CaO and Fe<sub>2</sub>O<sub>3</sub>, other AFTs, especially FT, are on the high side, completely insensitive to the change in Al<sub>2</sub>O<sub>3</sub> or SiO<sub>2</sub> composition in the sample.

The effects of oxide addition on AFTs of K3 samples are presented in Figure 3 (a-d). After oxide addition, the ranges of CaO and Fe<sub>2</sub>O<sub>3</sub> for K3 samples were higher than those for K1 samples, while the ranges of Al<sub>2</sub>O<sub>3</sub> and SiO<sub>2</sub> were comparable. The CaO addition to K3 samples, which originally had almost 40% CaO content, was found to increase the AFTs throughout the range of total % CaO in ash. However, the generally low ITs when compared to those of K1 samples are likely due to very low Al<sub>2</sub>O<sub>3</sub> content of the K3 samples. The Fe<sub>2</sub>O<sub>3</sub> addition also similarly had a positive

Table 2. Compositions of K1 ashes after mixing the oxides.

Unwashed K1	wt % in ash				Acid washed K1	wt % in ash			
	CaO	Fe <sub>2</sub> O <sub>3</sub>	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>		CaO	Fe <sub>2</sub> O <sub>3</sub>	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>
K1 – 5% CaO	19.5	12.2	33.6	17.1	K1W – 5% CaO	16.4	5.9	44.1	19.1
K1 – 10% CaO	29.4	9.6	28.6	15.0	K1W – 10% CaO	25.8	5.1	37.9	15.0
K1 – 15% CaO	37.5	8.4	24.7	12.9	K1W – 15% CaO	32.2	4.2	32.3	14.3
K1 – 20% CaO	42.8	6.5	23.2	12.3	K1W – 20% CaO	36.8	5.4	29.6	11.4
K1 – 25% CaO	47.3	6.3	21.1	11.3	K1W – 25% CaO	40.4	4.3	25.4	12.5
K1 – 5% Fe <sub>2</sub> O <sub>3</sub>	2.8	21.5	43.2	19.4	K1W – 5% Fe <sub>2</sub> O <sub>3</sub>	1.5	22.2	48.6	19.2
K1 – 10% Fe <sub>2</sub> O <sub>3</sub>	2.5	30.3	37.5	19.1	K1W – 10% Fe <sub>2</sub> O <sub>3</sub>	1.2	32.3	40.7	16.6
K1 – 15% Fe <sub>2</sub> O <sub>3</sub>	2.3	38.1	32.5	16.7	K1W – 15% Fe <sub>2</sub> O <sub>3</sub>	1.4	39.9	35.8	14.5
K1 – 20% Fe <sub>2</sub> O <sub>3</sub>	2.1	43.4	30.4	14.6	K1W – 20% Fe <sub>2</sub> O <sub>3</sub>	1.1	47.2	32.1	12.9
K1 – 25% Fe <sub>2</sub> O <sub>3</sub>	2.2	48.5	27.9	14.5	K1W – 25% Fe <sub>2</sub> O <sub>3</sub>	0.6	50.2	28.0	14.0
K1 – 5% SiO <sub>2</sub>	2.9	8.0	63.2	20.0	K1W – 5% SiO <sub>2</sub>	1.0	5.0	64.8	22.5
K1 – 10% SiO <sub>2</sub>	2.4	6.7	70.9	17.2	K1W – 10% SiO <sub>2</sub>	0.9	4.0	68.2	18.5
K1 – 15% SiO <sub>2</sub>	2.1	5.7	73.8	14.6	K1W – 15% SiO <sub>2</sub>	0.7	3.4	68.5	15.1
K1 – 20% SiO <sub>2</sub>	1.7	4.8	77.0	12.6	K1W – 20% SiO <sub>2</sub>	0.6	3.0	73.4	13.9
K1 – 25% SiO <sub>2</sub>	1.6	4.5	78.5	11.7	K1W – 25% SiO <sub>2</sub>	0.7	2.5	71.2	11.2
K1 – 5% Al <sub>2</sub> O <sub>3</sub>	3.5	7.3	39.5	32.2	K1W – 5% Al <sub>2</sub> O <sub>3</sub>	0.7	5.5	48.5	37.9
K1 – 10% Al <sub>2</sub> O <sub>3</sub>	2.5	6.8	37.0	42.1	K1W – 10% Al <sub>2</sub> O <sub>3</sub>	0.6	3.9	43.1	44.1
K1 – 15% Al <sub>2</sub> O <sub>3</sub>	2.2	7.2	31.0	45.8	K1W – 15% Al <sub>2</sub> O <sub>3</sub>	0.5	4.4	37.5	49.6
K1 – 20% Al <sub>2</sub> O <sub>3</sub>	2	5.6	30.1	51.8	K1W – 20% Al <sub>2</sub> O <sub>3</sub>	0.6	3.7	33.6	52.3
K1 – 25% Al <sub>2</sub> O <sub>3</sub>	1.8	5.5	27.0	55.5	K1W – 25% Al <sub>2</sub> O <sub>3</sub>	0.4	3.2	29.8	57.1

Table 3. Compositions of K3 ashes after mixing the oxides.

Unwashed K3	wt % in ash				Acid washed K3	wt % in ash			
	CaO	Fe <sub>2</sub> O <sub>3</sub>	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>		CaO	Fe <sub>2</sub> O <sub>3</sub>	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>
K3-5% CaO	49.3	7.4	3.1	2.7	K3W-5% CaO	35.1	9.3	5.8	2.8
K3-10% CaO	56.0	7.3	2.4	2.3	K3W-10% CaO	42.2	7.3	3.5	1.7
K3-15% CaO	59.7	5.4	1.9	2.4	K3W-15% CaO	45.7	4.6	3.5	2.5
K3-20% CaO	64.9	3.6	1.7	1.1	K3W-20% CaO	52.5	3.8	1.7	1.3
K3-25% CaO	62.3	3.0	1.5	2.8	K3W-25% CaO	59.5	3.7	2.7	1.3
K3-5% Fe <sub>2</sub> O <sub>3</sub>	22.9	38.0	3.1	2.6	K3W-5% Fe <sub>2</sub> O <sub>3</sub>	14.2	34.6	4.7	2.4
K3-10% Fe <sub>2</sub> O <sub>3</sub>	17.6	50.3	4.7	4.0	K3W-10% Fe <sub>2</sub> O <sub>3</sub>	9.2	45.0	3.2	1.5
K3-15% Fe <sub>2</sub> O <sub>3</sub>	14.1	54.4	2.9	2.7	K3W-15% Fe <sub>2</sub> O <sub>3</sub>	8.8	55.1	2.2	1.1
K3-20% Fe <sub>2</sub> O <sub>3</sub>	10.7	59.2	2.8	3.0	K3W-20% Fe <sub>2</sub> O <sub>3</sub>	8.8	65.1	2.1	1.0
K3-25% Fe <sub>2</sub> O <sub>3</sub>	10.6	63.5	2.8	2.6	K3W-25% Fe <sub>2</sub> O <sub>3</sub>	3.7	78.8	3.1	1.4
K3-5% SiO <sub>2</sub>	20.5	7.6	39.4	2.2	K3W-5% SiO <sub>2</sub>	8.9	8.6	55.8	2.8
K3-10% SiO <sub>2</sub>	16.5	6.1	54.8	1.8	K3W-10% SiO <sub>2</sub>	6.0	6.0	72.0	1.9
K3-15% SiO <sub>2</sub>	13.7	5.1	64.8	1.4	K3W-15% SiO <sub>2</sub>	5.6	4.5	77.4	1.4
K3-20% SiO <sub>2</sub>	11.1	4.3	70.6	1.4	K3W-20% SiO <sub>2</sub>	4.1	3.6	81.1	1.4
K3-25% SiO <sub>2</sub>	9.4	3.6	74.8	1.1	K3W-25% SiO <sub>2</sub>	2.8	3.2	79.9	1.6
K3-5% Al <sub>2</sub> O <sub>3</sub>	23.4	9.2	3.4	30.9	K3W-5% Al <sub>2</sub> O <sub>3</sub>	9.3	9.0	6.8	46.6
K3-10% Al <sub>2</sub> O <sub>3</sub>	17.5	5.9	2.6	45.6	K3W-10% Al <sub>2</sub> O <sub>3</sub>	5.9	5.8	4.5	58.1
K3-15% Al <sub>2</sub> O <sub>3</sub>	14.0	5.7	2.1	52.3	K3W-15% Al <sub>2</sub> O <sub>3</sub>	4.7	4.7	4.2	66.2
K3-20% Al <sub>2</sub> O <sub>3</sub>	10.7	3.8	1.9	59.1	K3W-20% Al <sub>2</sub> O <sub>3</sub>	3.5	3.4	3.5	66.0
K3-25% Al <sub>2</sub> O <sub>3</sub>	9.4	3.8	1.8	61.8	K3W-25% Al <sub>2</sub> O <sub>3</sub>	2.6	2.7	4.0	63.1

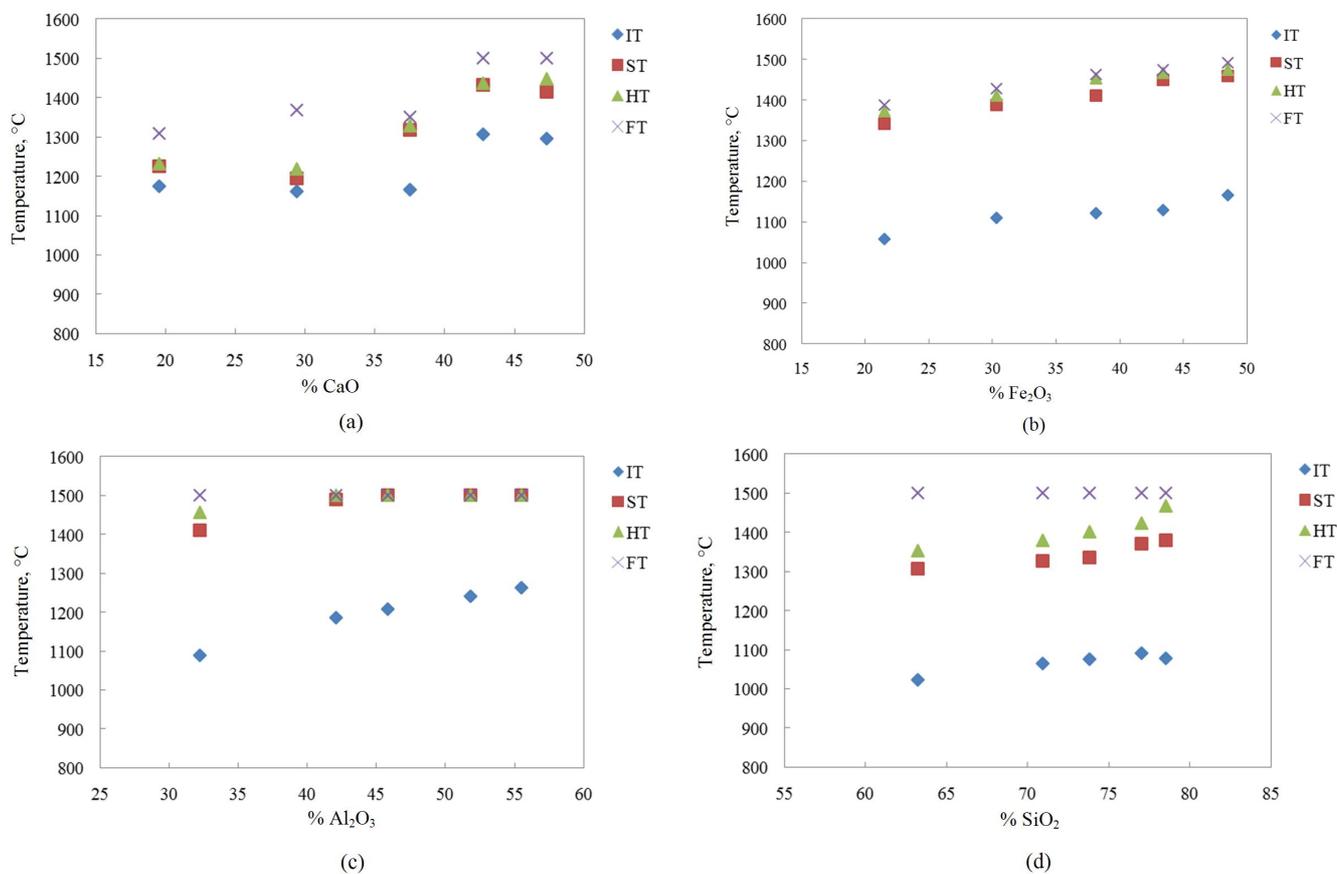


Figure 2. Correlation between oxides content and AFTs of unwashed K1.

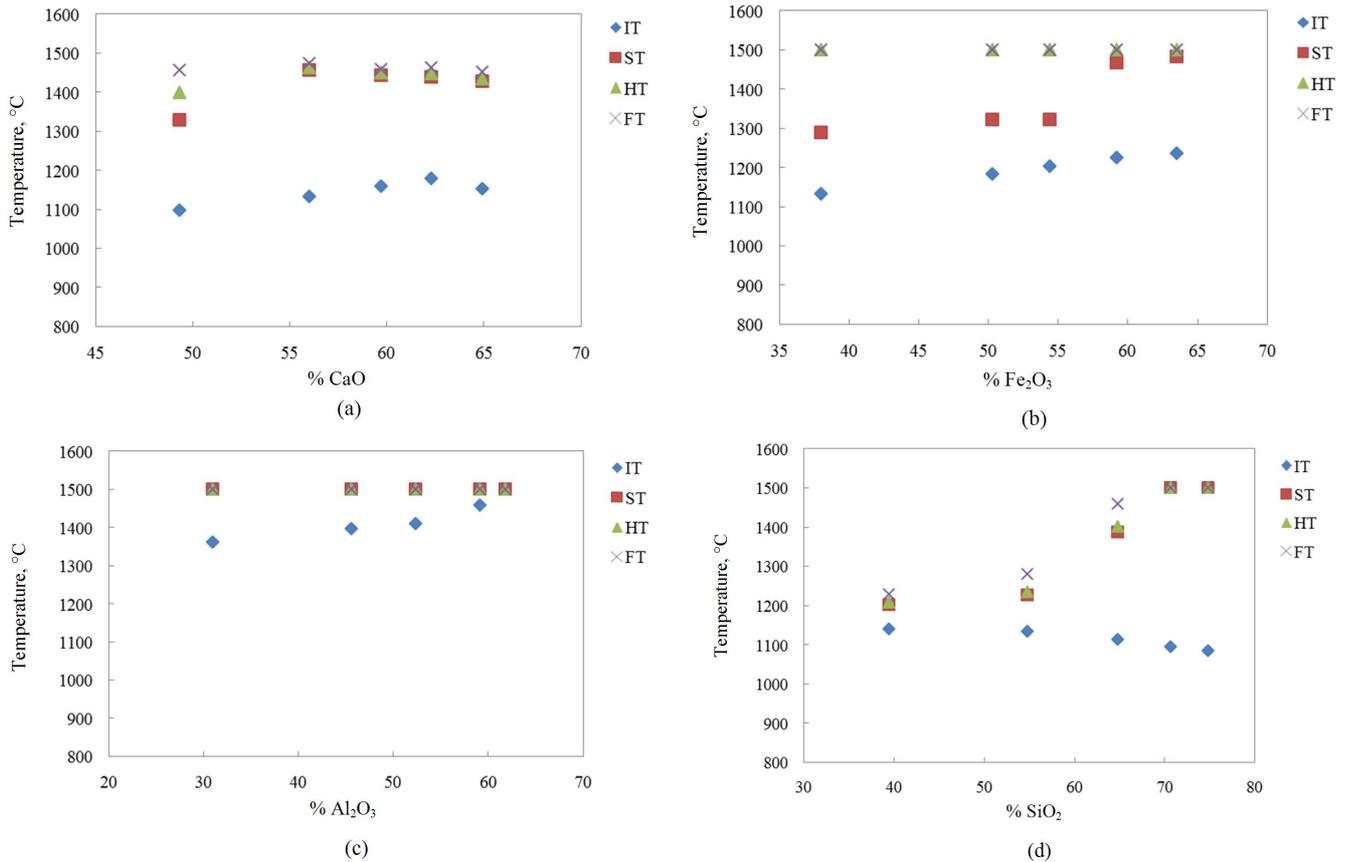


Figure 3. Correlation between oxides content and AFTs of unwashed K3.

effect on the AFTs.

Despite a similar range of  $\text{Al}_2\text{O}_3$ , the observed ITs of K1 and K3 samples were different as the ITs of K3 samples were always higher and the range of AFT were narrower than those of K1 samples. The effect of  $\text{SiO}_2$  addition for K3 samples was also different from that for K1 samples. The IT appeared to decrease as increasing the  $\text{SiO}_2$  in a similar range, although all other AFTs increased.

### 3.3.2 Effect of oxide addition on AFTs of ashes from acid-washed samples

The correlations between the total % of each oxide in each sample (after addition) and the AFTs of the acid washed K1 samples and acid washed K3 samples are shown in Figure 4 (a-d) and 5 (a-d), respectively. Since the initial oxide compositions for the acid washed K1 samples prior to oxide addition were almost identical to those of the original K1 samples (as already discussed in Section 3.1), similar ranges of total % of oxide were to be compared and, as expected, the effect of the oxide addition was not significantly different from that for the original (unwashed) K1 samples.

However, a large fraction of basic oxides was removed by acid washing of K3 samples, resulting in the concentration ranges of oxides lower than those of original samples.

Varying the CaO addition into the acid washed K3 samples produced a minimum value of IT and ST; while HT and FT increased with increasing CaO addition. The drop of IT as well as ST by more than  $100^\circ\text{C}$  giving the IT below  $1000^\circ\text{C}$  represents an unacceptably low initial melting point of ash. Since K3 originally has low  $\text{Al}_2\text{O}_3$  content, adding other oxide components will naturally lower its role in diluting the fluxing materials. Observation in the previous study (Pipatmanomai *et al.*, 2009) has shown that the IT became unacceptably low when  $\text{Al}_2\text{O}_3$  content was 8% or below. However, at sufficiently high CaO content, i.e. above 50%, the IT and ST would once again rise.  $\text{Al}_2\text{O}_3$  addition can help to increase AFTs significantly – IT increased to about  $1380^\circ\text{C}$  even at low level of addition. Increasing  $\text{SiO}_2$  addition could not raise the IT unless the total  $\text{SiO}_2$  content became above 75%, which strongly favored the improvement of other AFTs.

### 3.4 Discussion

Despite the difference in the ash elemental composition of K1 and K3 samples especially the CaO content, the AFT characteristics were very similar. Both samples exhibited high AFTs except IT and therefore may initiate slagging. Their CaO contents and the coal blending index currently used at Mae Moh power plant did not lie within the critical

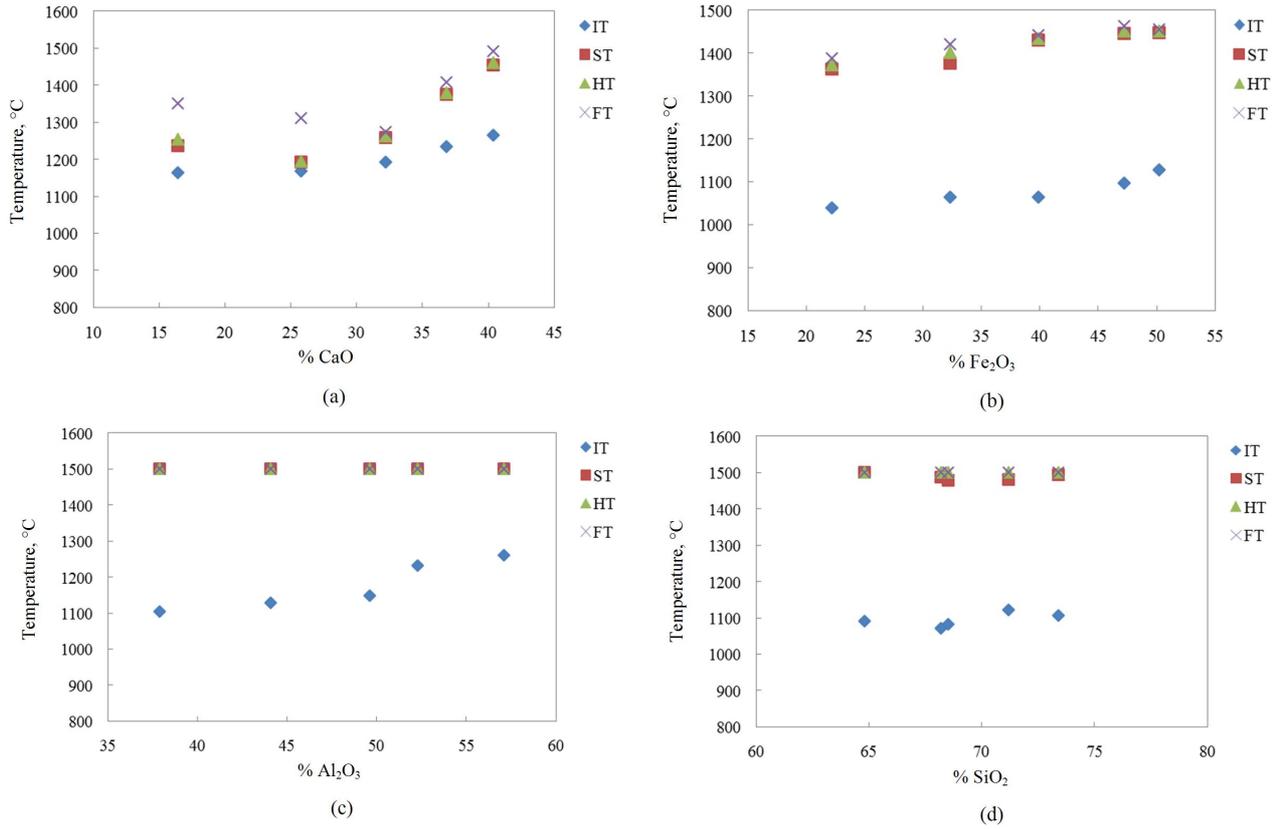


Figure 4. Correlation between oxides content and AFTs of acid washed K1.

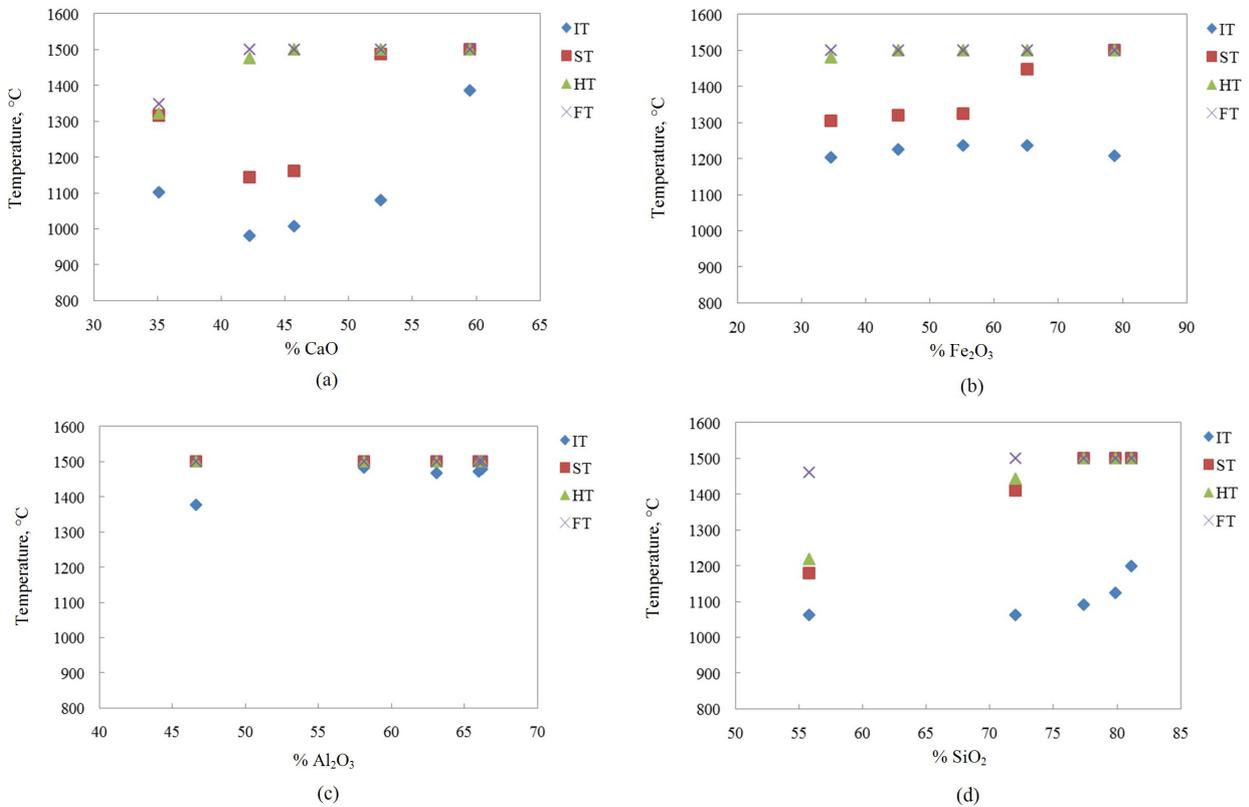


Figure 5. Correlation between oxides content and AFTs of acid washed K3.

range that is likely to yield low IT as shown in other study (Huggins *et al.*, 1981) and therefore should not be considered as the only reason for the observed low IT. As a result, alkali elements, i.e. K and Na are thought to also play a role in controlling IT but may shift the ash deposition in the low-temperature convective zone rather than in the radiative zone of the boiler.

From the results of ash composition and ash fusion temperature data in Section 3.3, ternary phase diagrams of CaO-SiO<sub>2</sub>-Al<sub>2</sub>O<sub>3</sub> and Fe<sub>2</sub>O<sub>3</sub>-SiO<sub>2</sub>-Al<sub>2</sub>O<sub>3</sub> system were constructed as shown in Figure 6 and 7, respectively. The effect of each combined three selected oxide compositions on the

range of corresponding ITs was investigated. The data of lignite supplied to the power plant during the severe slagging period were used as a rough indication of slag formation propensity. Since the ITs of those lignite ashes all fell below 1220°C, the temperature of 1220°C was selected to distinguish the level of slagging potential of the studied samples.

Considering the composition of lignite samples from the severe slagging period, both CaO and Fe<sub>2</sub>O<sub>3</sub>, which are very effective fluxes for aluminosilicates, lie within the ranges, which give rise to sticky ash particles and lowering the melting point of the ash. Increasing refractory oxides (i.e. Al<sub>2</sub>O<sub>3</sub>, SiO<sub>2</sub>) generally raised the ITs. However, Al<sub>2</sub>O<sub>3</sub> was the

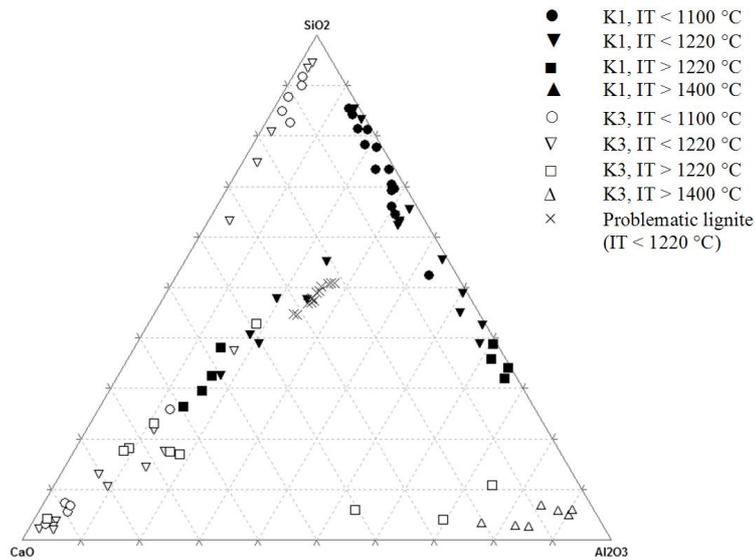


Figure 6. Ternary phase diagram of CaO-SiO<sub>2</sub>-Al<sub>2</sub>O<sub>3</sub> system.

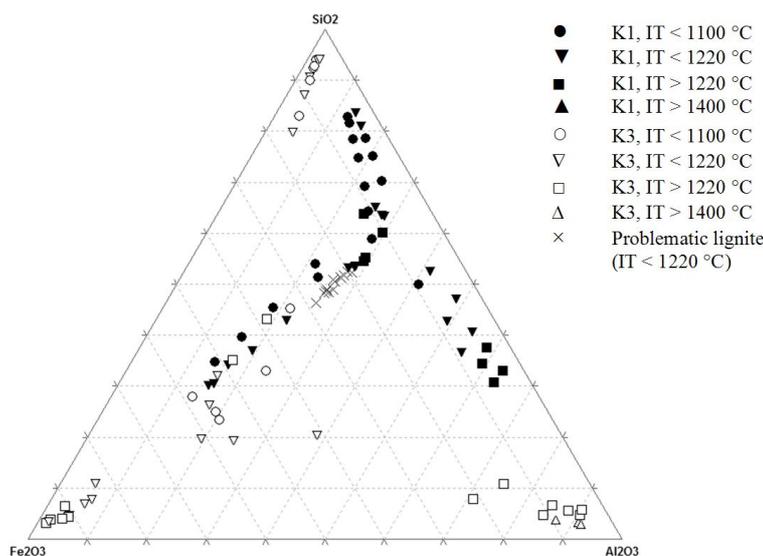


Figure 7. Ternary phase diagram of Fe<sub>2</sub>O<sub>3</sub>-SiO<sub>2</sub>-Al<sub>2</sub>O<sub>3</sub> system.

more effective additive than  $\text{SiO}_2$ , since increasing  $\text{SiO}_2$  also somewhat depressed the ITs. ITs even below  $1100^\circ\text{C}$  were observed. Samples having a low  $\text{SiO}_2/\text{Al}_2\text{O}_3$  ratio (i.e.  $\text{Al}_2\text{O}_3$  content in the ternary system above 60%) would always have the IT over  $1220^\circ\text{C}$  and, with reference to the lignite used during the severe slagging period, would possibly cause no slagging problem. This finding agrees with previous studies (Huggins *et al.*, 1981; Russell *et al.*, 2002) that the higher AFT ash is generally richer in  $\text{Al}_2\text{O}_3$  and lower in the  $\text{SiO}_2/\text{Al}_2\text{O}_3$  ratio (richer in kaolinite). Therefore, mixing with materials containing high refractory oxides especially Al-rich materials, either by blending with other coals or introducing chemical additives, may be applied to raise the ash melting temperature.

When the basic component (either CaO or  $\text{Fe}_2\text{O}_3$ ) was present at a very high content (approaching the apex) the IT would generally increase exceeding  $1220^\circ\text{C}$ . However, some ITs below  $1220^\circ\text{C}$  were still observed even when the coal ash was extremely rich in that particular component. It is thought likely that in such sample, the effect of CaO and  $\text{Fe}_2\text{O}_3$  in combination will become even more critical when compared to the samples rich in  $\text{Al}_2\text{O}_3$  and  $\text{SiO}_2$ .

#### 4. Conclusion

Detailed characterization of the two selected Mae Moh lignites was carried out in this study. The samples, K1 and K3, are the lignites classified during the study by low CaO and high CaO lignite, respectively. The lignite characterization by XRD analysis indicated that the major minerals present in K1 sample, having low CaO but high in  $\text{SiO}_2$  and significant  $\text{Na}_2\text{O}$  content, were illite and quartz. Anhydrite was the most abundant mineral in K3, which had about 40% CaO in ash. The presence of illite and anhydrite is known to lower the ITs. For both lignites,  $\text{Fe}_2\text{O}_3$  was abundantly present in form of pyrite.

Acid washing could remove large fractions of CaO and MgO in ash, especially for K3. The insolubility of  $\text{Fe}_2\text{O}_3$  in HCl implies that most iron is associated with sulfur in the form of pyrite. The removal of base oxides by acid washing differently affected the AFTs of samples. Changes observed for the ITs of K3 were more significant than those of K1. The effects of CaO depend on its relative content in ash. When present in a relatively low content, it will act as a fluxing agent leading to the reduction of the AFTs; however, when present in a high content (> 38%), its high melting point characteristic will dominate. Generally, the addition of acidic oxides (i.e.  $\text{Al}_2\text{O}_3$  and  $\text{SiO}_2$ ) could increase the AFTs.  $\text{Al}_2\text{O}_3$  was the more effective additive than  $\text{SiO}_2$ .

The ternary phase diagrams of CaO- $\text{SiO}_2$ - $\text{Al}_2\text{O}_3$  and  $\text{Fe}_2\text{O}_3$ - $\text{SiO}_2$ - $\text{Al}_2\text{O}_3$  system showed that increasing refractory oxides (i.e.  $\text{Al}_2\text{O}_3$ ,  $\text{SiO}_2$ ) was found to generally raise the ITs. However, the lower  $\text{SiO}_2/\text{Al}_2\text{O}_3$  ratio the higher IT would be.

When the basic component (either CaO or  $\text{Fe}_2\text{O}_3$ ) was present at a very high content, the ITs would generally be increased with exceeding  $1220^\circ\text{C}$ . The presence of such samples having ITs well below  $1220^\circ\text{C}$  is thought due to the effect of CaO and  $\text{Fe}_2\text{O}_3$  in combination, which will become even more critical when compared to the samples rich in  $\text{Al}_2\text{O}_3$  and  $\text{SiO}_2$ .

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