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SUB-BITUMINOUS COALS FIRED IN BOILER DESIGNED FOR BITUMINOUS COALS

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ABSTRACT

In the last two decades there has been little capacity added to coal-based power plants. However, much of the existing plants had to comply with the Clean Air Act amendments. Using sub-bituminous coals has become an important solution for emissions compliance due to their unique constituents and combustion characteristics; these coals are often referred to as *enviro* coals. The considerable advantages of these coals, like Melawan, Adaro or PRB coals, is their low sulfur compared to typical bituminous coals, which makes its burning more economic as scrubbers or other SO_2 reduction technologies are not required. Low nitrogen and ash content as well as their high volatile matter are other advantages of these coals. Hence, firing sub-bituminous coals alone or as blends with bituminous coals is deemed economically attractive.

Power generation plants were originally designed to operate on a particular bituminous coal. In order to fire sub-bituminous coals or their blends some modifications are required in the firing modes. These modifications may affect boiler reliability and as result to reduction of the power plant availability and hence increasing operation and maintenance cost. In order to prevent such undesirable effects we initiated a study to understand the influence of using sub-bituminous coals on the capacity, limitations of furnace size, heat transfer surfaces, firing systems, pulverizers, fans and airheaters.

The present paper discusses issues connected with each of these issues on the combustion system. We also present recommendations for reliable burning of various sub-bituminous coals and their blends in a 575 MW tangentially-fired boiler. For example, we found that firing Indonesian sub-bituminous coals (Adaro and Melawan) considerably reduced NO_x (30% reduction) and SO_x (reduced to 200 $mg/dNm^3@6\%O_2$) emissions without post combustion measures. We also tested various blends of sub-bituminous coals with bituminous coals and found positive and negative synergism in these blends with regard to NO_x emissions.

We used in the present study a series of experiments in a test facility and computational fluid dynamic codes.

INTRODUCTION

Pulverized coal-fired utility boilers are the reliable power generation infrastructure responsible for most global electricity production. However, reduction of combustion generated pollution is of major concern for existing coal plants. Sub-bituminous coals have become an important alternative for emissions compliance because of their unique constituents and combustion characteristics. However, firing sub-bituminous coals in power plants planned for bituminous coals imposes tremendous operational challenges, mainly because of their typical high water content and as result low heat value. A major challenge is to use steam generator systems for sub-bituminous coals in order to claim the substantial environmental benefits these fuels offer while limiting the boiler operation. Firing, sub-bituminous coals such as Indonesian Adaro or Melawan, or US PRB can be a solution for emissions compliance because of their low content of sulfur (for example content of sulfur of Indonesian Adaro is 0.1%), nitrogen (0.9%) and ash content (1-2%) and high volatile matter content (43-45%). The main objective of this paper is to discuss the impact when using such coals on the performance and pollutant emissions of both 575 MW tangentially-fired and 550 MW opposite-wall utility boilers of Israel Electric Corporation (IEC), in particular, but for other similar boilers, in general.

METHODOLOGY FOR COMBUSTION BEHAVIOR

To predict the combustion behavior of sub-bituminous coals and their consequent impact on performance and pollutant emission from IEC coal-fired utility boilers in the pulverized-coal utility boilers, we use a methodology that combines experimental work in a test furnace, data from the boilers and CFD simulations [1, 9].

This methodology comprises three steps: (1) Determining model kinetic parameters required for the simulations from a series of experiments in a 50 kW pilot-scale test facility. (2) Validation of these model parameters by comparing CFD results (obtained by the set of model parameters in step 1) with different experimental data, not used in step 1. (3) The extracted model parameters are then used for simulations of full-scale boilers using the same CFD code. This three-step method has been tested and verified numerous times. Full-scale model predictions with results from a series of full-scale tests were done with different coals fired by various utility companies [10-12].

For the analysis of the operational parameters for firing a sub-bituminous coal in a boiler designed for bituminous coal, we use EXPERT SYSTEM, reported elsewhere [2], which is an on-line supervision system installed in IEC's boilers, but can be also operated off-line with the virtual boiler from the CFD simulation, in a "what-if-then" mode. The objective of this system is to quantify the performance of the combustion and heat transfer processes in real time.

COAL PROPERTIES AND CHARACTERIZATION

The content of sub-bituminous coals used in this study is summarized in Table 1. Ash was classified using the definitions presented by [3,4]. In accordance with this classification, ash may be defined as a lignite type (the content of CaO+MgO is larger than Fe_2O_3) and bituminous type (the content of CaO+MgO is smaller than Fe_2O_3).

Table 1 Summary of properties of the coals typically burned (organic content is in weight percent, dry coal basis). Ind denotes Indonesian and Col – Colombia

Coal Content	Ind KPC	Ind Blend	Ind Adaro	Col Drummond	Ind Melawan	PRB Gillette Field	PRB Sheridan Field	PRB Colstrip Field
Total moisture, %	9.4	15.4	25.7	12.4	22.3	29	24.5	25.7
Volatile matter, %	44.1	45.4	50.1	41.4	47.1	31	32	32
Ash, %	5.3	4.80	1.8	5.5	4.3	5.7	5.3	7.65
Fixed Carbon, %	50.6	49.8	48.1	53.1	48.6	35	38	34.5
Sulfur, %	0.51	0.46	0.12	0.48	0.22	0.35	0.44	0.93
Carbon, %	75.56	72.85	72.57	76.14	71.38	49.5	52	51.3
Hydrogen, %	5.37	5.10	5.1	5.91	5.12	3.55	3.38	3.6
Nitrogen, %	1.48	1.51	0.89	1.35	1.36	0.85	1.05	0.85
Oxygen, %	11.78	15.28	19.54	10.62	17.62	11.3	13.34	9.98
High HHV, Kcal/Kg	6800	6153	5179	6397	5355	4695	5040	4712
Ash content								
SiO2, %	55.03	54.15	29.48	59.83	44.56	27	21	35.3
Al2 O3, %	25.27	18.29	17.95	24.91	12.61	14.5	13.95	17.6
Fe2 O3, %	8.44	11.76	24.62	6.13	14.55	6.25	8.4	7.45
CaO, %	1.7	5.69	14.04	2.16	9.48	21.5	20.5	14.5
MgO, %	2.31	3.26	3.49	0.97	7.48	4.5	5.5	4.6
TiO2, %	0.91	1.08	0.72	1.03	0.83	0.95	1.3	0.65
K2O, %	2.78	2.03	0.66	0.96	1.18	0.345	0.52	0.585
Na2O, %	0.9	0.9	0.24	0.42	0.37	1.63	5.55	1.52
SO3, %	2.1	1.64	7.77	2.23	8.1	12.35	17.5	16.75
Initial deform Temp, C	1160	1170	1170	1400	1230	1180	1127	1199
Softening Temp., C	1350	1220	1180	1480	1160	1221	1181	1228
Hemispheric Temp., C	1380	1290	1185	1482	1190			

The fouling index (R_f) for bituminous ash is derived from the sintering strength characteristics, using the sodium content of the coal ash and the base to acid ratio as follows:

$$R_f = \frac{B}{A} x \, Na_2O, \qquad (1)$$

where Na_2O=weight % in ash.

The fouling classification for lignite ash coals is based on the sodium content in the ash, as follows: when $CaO+MgO+Fe_2O_3<20\%$ (by weight of ash) and $Na_2O<1.2\%$ - the ash has low to medium fouling tendency; when $CaO+MgO+Fe_2O_3>20\%$ (by weight of ash) and $Na_2O<2.0\%$ - the ash has low fouling tendency. Deposition characteristics are generally classified into four categories: low, medium, high and severe.

The slagging index (R_s) for bituminous ash takes into account the base to acid ratio and the weight percent (on a dry basis) of the sulfur in the coal is [3]:

$$R_s = \frac{B}{A} x \, S, \qquad (2)$$

where $B=CaO+MgO+Fe_2O_3+Na_2O+K_2O$ (on a weight % basis), $A=SiO_2+Al_2O_3+TiO_2$; S - weight % sulfur, on a dry coal basis. The slagging index for lignitic ash (R_s) is based on ASTM ash fusibility temperatures. The index is a weight average of the maximum hemispherical temperature (HT) and minimum initial deformation temperature (IT) [3]:

$$R_s = \frac{\max(HT) + 4\min(IT)}{5}, \qquad (3)$$

where $\max(HT)$=higher of reducing or oxidizing hemispherical softening temperatures, F, and $\min(IT)$ = lower of the reducing or oxidizing initial deformation temperature, F.

The categories of the coal slagging and fouling are summarized in Table 2. The slagging indices of the coals are presented in Table 3. For the most part, the indices defined above are based on readily available ASTM ash analyses and fusibility data. These indices can also be used on a comparative basis to rank coals with respect to their slagging and fouling potential when evaluating a new coal supply for an existing unit.

Adaro coal presented belongs to the bituminous ash and to low slagging categories, in spite of low (1185°C) hemispheric temperature. Melawan coal belongs to the lignitic ash and to a high slagging and low fouling factor. PRB coal belongs to the lignitic ash and to a high slagging factor because of low hemispheric temperature. In PRB Sheridan and Colstrip coals, the ash has Fe_2O_3/CaO ratio equals 0.4-0.5, which leads to increase in slagging. PRB Colstrip coal belongs to low fouling category and medium slagging; PRB Gillette coal belongs to medium fouling and high slagging category and PRB Sheridan coal belongs to a high slagging and fouling category. As a result, we conclude that PRB coal can be difficult to operate with nominal parameters at full load.

Table. 2: Coal slagging and fouling indices.

Property	Slagging and fouling categories			
	Low	**Medium**	**High**	**Severe**
Slagging indices				
Base to acid ratio for bituminous ash (B/A)	0.5	0.5-1.0	1.0-1.75	
Slagging index for bituminous ash	<0.6	0.6-2.0	2.0-2.6	>2.6
Fe_2O_3/CaO	<0.3 or >3.0	0.31-3.0		
Slagging index for lignite ash	>1343	1232-1343	1149-1232	<1149
Fouling indices				
Na_2O,% for lignite ash, when $CaO+MgO+Fe_2O_3>20\%$	<2.0	2.0-6.0	6.0-8.0	>8.0
Na_2O,% for lignite ash, when $CaO+MgO+Fe_2O_3<20\%$	<1.2		1.2-3.0	>3.0
Na_2O,% for bituminous ash	<0.5	0.5-1.0	1.0-2.5	>2.5
Fouling index for bituminous ash	<0.2	0.2-0.5	0.5-1.0	>1.0

Table 3. Coal slagging indices and furnace characteristic. Abbreviations: PRB1 – PRB Gilette Field, PRB2 – PRB Sheridan Field, PRB3- PRB Colstrip Field, Adaro-Dr - Adaro(50%)& Drummond(50%), Mel-Dr - Melawan(50%)& Drummond(50%), Mel-KPC - Melawan(40%)& KPC(60%), bit – bituminous, Ind - Indonesia

Parameter	**575 MW tangential-fired boiler**								
	Typical bit	Ind Adaro	Ind Melawan	PRB1	PRB2	PRB3	Adaro-Dr	Mel-Dr	Mel-KPC
Basic, %	16.2	47.0	58.0	44.4	52.3	34.9	16.4	23.1	23.8
B/A	0.20	0.89	0.57	0.8	1.1	0.535	0.20	0.30	0.312
Rs, bit	0.10	0.11					0.05	0.087	0.143
R_s, lig	1348		1160	1188	1138	1205			
Fe_2O_3/CaO	0.319	1.75	1.53	0.29	0.409	0.513	2.2	1.82	2.1
Na_2O	0.13	0.24	0.70	2.3	5.55	1.52	0.39	0.56	0.9
Ash type	lig	bit	lig	lig	lig	lig	bit	bit	bit
R_f, bit		0.21					0.1	0.17	0.28
A/(A+B), %	83.7	53.0	63.7	42.7	47.6	83.4	83	77	76.2
Fouling, $m^2h^oC/kcal$	0.0026	0.0026	0.0018				0.0027	0.0029	0.002
Absorptivity	0.88	0.95	0.75	0.95	0.95	0.87	0.95	0.95	0.95
Coal rank	2.16	0.96	1.032	1.13	1.19	1.08	1.18	1.18	1.1

In order to run simulation for the coals, we had to determine the fouling factor (for thermal resistance on the heat exchanger walls and tubes), emissivity (for radiative heat transfer) and coal kinetic characteristic (model parameters required for the simulation, as describerd above [9]). As for fouling, it was shown [6] that the fouling factor is a function of the basic content of ash (at NCR load for furnace clean condition after sootblowing). The basic content is equal to the ratio:

$$Basic = \frac{B}{A+B} * 100\%. \qquad (4)$$

Using this definition it was found that fouling correlates with the basic content, i.e., increase in basic content, follows increase in fouling propensity.

Water-wall absorptivity was determined as a function of the acid ratio as show in [6]**:**

$$a_w = -6.61\,(\frac{A}{A+B})^2 + 8.05\,(\frac{A}{A+B}) - 1.19\,, \ (5)$$

where $0.82 < \dfrac{A}{A+B} < 0.95$ for bituminous ash; and

$$a_w = 1.81\,(\frac{A}{A+B})^2 + 1.92\,(\frac{A}{A+B}) + 0.49\,, \ (6)$$

where $0.80 < \dfrac{A}{A+B} < 0.87$ for lignite ash.

Due to low acid index of the ash, Adaro, Melawan and PRB coals belong to high emissivity ash and will increase heat absorption in the furnace. On the other hand base index of these coals is very high and may lead to increasing of fouling on the waterwalls. Because of low ash content in Adaro and Melawan coals we assume that the fouling factor will close to the coals typically burned in IEC's boilers. For PRB coal the fouling factor is assumed to be high due to considerable content of the ash.

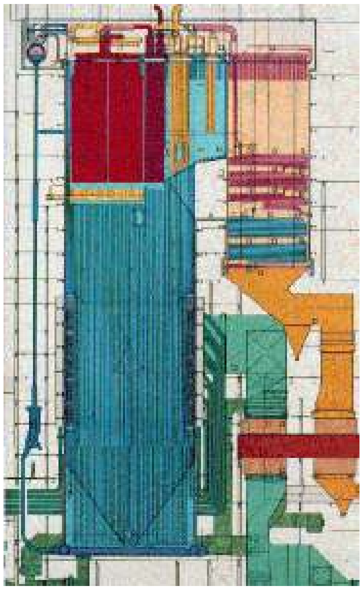

Figure1. Schematics of 575 MW tangentially-fired boiler.

RESULTS AND DISCUSSION

Using the above methodology and coal characterization, we ran CFD simulations of 550 MW opposite-wall and 575 MW tangential-fired boilers for firing all three coals, but we discuss here only results for the latter, which is designed by Combustion Engineering (Figure 1).

The tangentially-fired boilers are equipped with twenty straight flow burners, located in five levels, with five pulverizers, one for each level. A fraction of the secondary air is fed through the closed-coupled overfire air ports located above the burners. Steam capacity of the boiler is 1700 t/h, main steam/reheat steam pressure are 181/43 at. Main steam/reheat steam temperature is 540/540 °C. A detailed description of the boiler and furnace performance is presented in [7,8].

Table. 4: Predicted coal firing performance at NCR unit load. Abbreviations: PRB1 – PRB Gilette Field, PRB2 – PRB Sheridan Field, PRB3- PRB Colstrip Field, Adaro-Dr - Adaro(50%)& Drummond(50%), Mel-Dr - Melawan(50%)& Drummond(50%), Mel-KPC - Melawan(40%)& KPC(60%), bit – bituminous, Ind – Indonesia.

	575 MW tangential-fired boiler								
Parameter	Typical bit	Ind Adaro	Ind Melawan	PRB1	PRB2	PRB3	Adaro-Dr	Mel-Dr	Mel-KPC
Coal consum., t/h	195	247	240	271	263	255	219	215	205
PA+FD Fan Air Flow,t/h	2109.1	2241	2200	220	2182	2166	2150	2153	2080
ID Fan Flue Gas Flow, t/h	2241.7	2508	2460	2485	2460	2432	286	2363	2301
SH spray, t/h	50	30-40	5-20	65	75	50	25	30	0
RH spray, t/h	0	6-10	6-10	0	0	0	0	0	0
Max mill capacity, t/h	55	52	52.5	52	52	50	53	53.5	53.5
Boiler heat losses,%	5.54	6.19	5.4	7.54	7.37	6.31	6.20	6.14	5.92
Unburn. carbon heat los.,%	0.99	0.08	0.28	0.6	0.6	0.76	0.26	0.31	0.41

The results of simulation for tangential-fired boilers are summarized in Table 4. Comparing PRB coal with the other coals may be concluded that this coal will cause the following problem during actual boiler operation: (1) slagging as it belong to lignitic ash category with medium-high slagging and fouling indices mostly because of the low softening ash temperature (1180-1220°C). (2) Coal consumption is 250-280t/h at full load due to its low calorific value; much higher than the typical bituminous coals used by IEC. This means that the boiler cannot be operated at full load due to the limitation of the handling system and pulverizers capabilities. (3) Low efficiency of the boiler because of the high moisture content and high fouling and slagging tendencies. Unit heat rate will considerably increase and boiler efficiency will be reduced. (4) Considerable increase of reheater and superheater spray, due to degradation of airheaters. (5) Decrease period between planning outage, increase O&M and impact boiler reliability. Due to the fact that all coals supplied to IEC are imported coals it was decided to reject PRB coal and to perform the tests with remained Adaro and Melawan subbituminous coals and its blends with bituminous coal.

As follows from the simulation results presented in Table 4 the total air flow for Adaro and Melawan coals is slightly higher in comparison with typical coals fired in IEC's boilers. However, high water content in the two coals causes increase in the flue gas flow (about 3%) and as a result the pressure drop in flue gas path increases by about 7%. Therefore the ID Fan capacity is increased by about 10% and is close to its maximum capacity, especially in the summer period. This limitation may cause maximum achievable excess oxygen content at full load reduction up to 2.8%, which is less than boiler design data and may cause increase in CO and unburned carbon in the ash. The pulverizers will maintain the required load as the coal flow increases. Due to high water content, the pulverizers inlet temperature is increased to about 250-260 ºC, hence limiting the pulverizers outlet temperature. However pulverizers' outlet temperature of 60 ºC can be achieved, which is acceptable for stable ignition and firing. The primary air flow through pulverizers is about 95-98 t/h and together with lower primary air temperature the ignition point moved away from the coal nozzles and provides a reliable operation of the nozzles. Fuel air damper control is handled according to Combustion Engineering recommendation. The fuel oil and auxiliary air nozzle control compensates to keep the required windbox - furnace pressure drop. Superheater spray flow at full load does not exceed reasonable value and reheater spray flow was equal to 0-10 t/h. Sulfur content in burning coals is in the range 0.12-0.22% and coal rank (ratio of fixed carbon to volatile matter content) is equal to 1.0-1.03. Both factors will provide low NO_x and SO_2 emission. Low ash content of 1.0-4.3% in comparison with typical coals decrease the unburned carbon losses and, as a result, the boiler efficiency increases when Adaro and Melawan coals are fired. It should be mentioned that specific coal consumption is retained relatively low in spite of increasing of unit self –consumption.

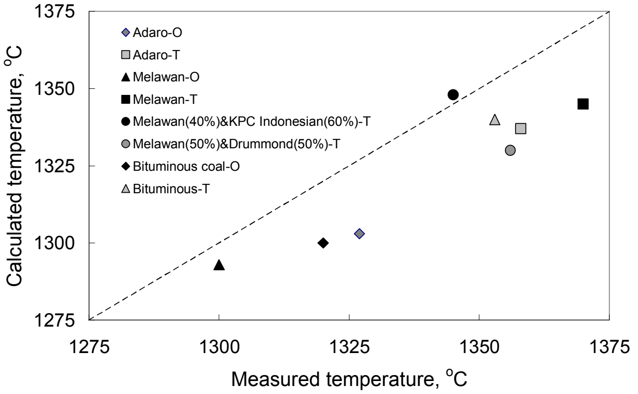

Fig. 2. Comparison of measured and calculated FEGT

Results of full-scale tests were compared with the main predicted results. Figure 2 presenting simulation results for the furnace exit gas temperature (FEGT) as a function of measured FEGT, showing a difference of up to 25°C.

Figure 3 presenting simulation results for the NO_x as a function of measured NO_x, showing an average difference of ~50 mg/dNm^3 (d stands for dry) at 6% O_2. Figure 4 shows comparison of measured and calculated efficiency of a 575 MW tangentially-fired boiler, with an average difference of 0.2%. Figure 5 shows comparison of measured and calculated specific coal consumption (corrected to LHV =6150 kcal/kg) for a 575 MW tangentially-fired boiler, with an average difference of ~0.2 g/kWh (less than 0.1%). These results illustrates an excellent agreement between the simulation results with measured ones.

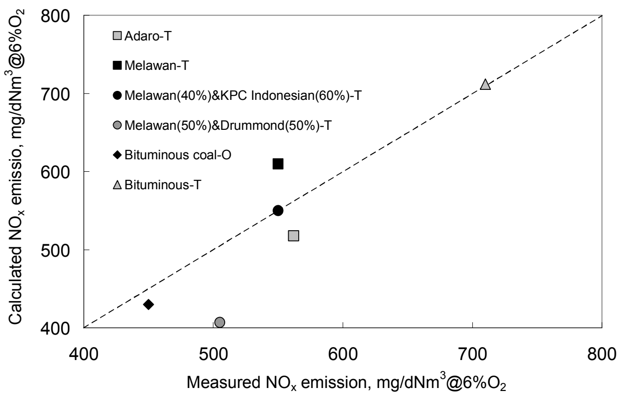

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Figure 3. Comparison of measured and calculated NOx emission.

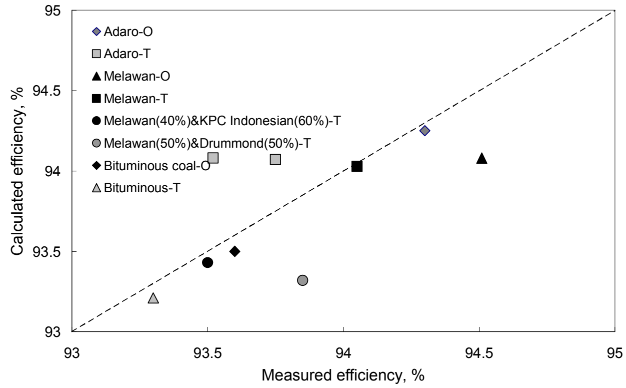

Figure 4. Comparison of measured and calculated boiler efficiency.

As expected there was considerable reduction of SO_2 and NO_x emission during sub-bituminous coal firing. For tangentially-fired boiler typical NO_x emission from a bituminous coal was 717 mg/dNm^3 as compared to 525 mg/dNm^3 for Adaro and 622 mg/dNm^3 for Melawan. For opposite-wall boiler typical NO_x emission from a bituminous coal was 436 mg/dNm^3 as compared to 180 mg/dNm^3 for Adaro and 195 mg/dNm^3 for Melawan. For opposite-wall boiler typical SO_2 emission from a bituminous coal was 1203 mg/dNm^3 as compared to 221 mg/dNm^3 for Adaro and 409 mg/dNm^3 for Melawan.

Based on above may be concluded that the developed methodology is able to optimize coal purchasing policy for maintaining emission reduction while efficiency improvement and may be useful tool for power plant operation staff.

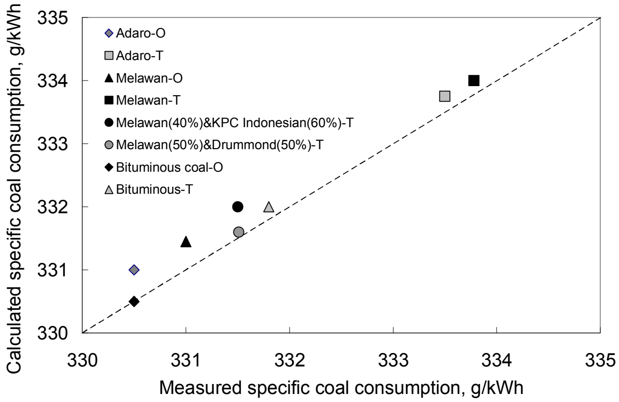

Figure 5. Comparison of measured and calculated specific coal consumption (Corrected to LHV =6150 kcal/kg)

Using the methodology used here we simulated the combustion behavior of coal blends with Adaro and Melawan, presenting sub-bituminous coals, and two bituminous coals (Drummond, Colombia, and KPC Prima, Indonesia) using the set of model parameters for each coal. As a coal blend may have synergism that is causes non-linear behavior, the outcome of this undertaking is not clear. The question is, of course, whether or not this synergism can be predicted. Figure 6 shows NO_x results for three coal blends fired in the test furnace (left), in a 550MW opposite-wall boiler (middle), and in a 575 MW tangential-fired boiler (9 right). In these three cases synergism was observed and was indeed predicted by this method. We fired blends of Adaro and Drummond in the test furnace that showed negative synergism. In the 575 MW tangential-fired boiler we fired a 50%-50% (weight basis) Drummond and Melawan blend showing also negative synergism and in the 550MW opposite-wall boiler we fired 50%-50% (weight basis) Prima and Melawan blend showing positive synergism. In the three cases the simulation reproduced fairly well the experimental results.

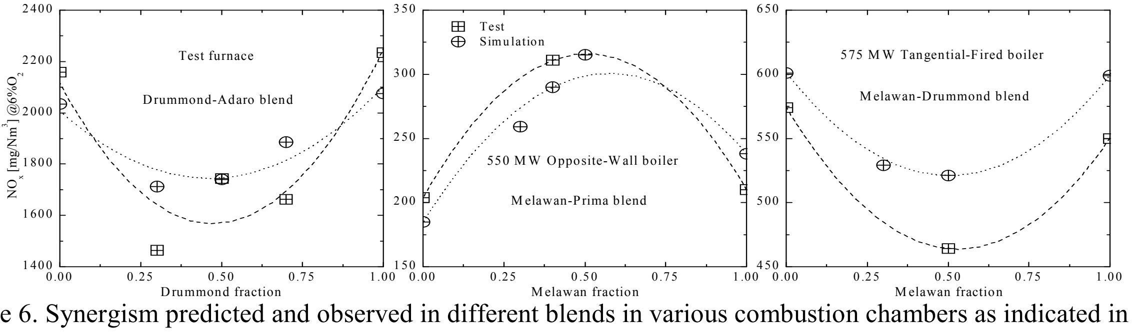

Figure 6. Synergism predicted and observed in different blends in various combustion chambers as indicated in the figures .

CONCLUSIONS

We showed that one can successfully predict the performance and pollutant emissions of sub-bituminous coal types from full-scale pulverized coal utility boilers of two types, opposite-wall and tangential-fired. The prediction was based on a methodology combining measurements in a 50kW pilot-scale test facility with computational fluid dynamic simulations. In addition in order to predict boiler behavior we developed an on-/off-line supervision system referred to as EXPERT SYSTEM that provided quantitative behavior of all important elements for operation. This system calculates the boiler and unit performance and optimizes the unit operation condition. We may conclude that our methodology gives useful results both prior to firing or for optimization purposes.

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