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# UNBURNED CARBON IN THE CIRCULATING FLUIDISED BED BOILER FLY ASH

Rafał Kobyłecki*

Częstochowa University of Technology, Department of Energy Engineering, ul. Brzeźnicka 60a,
42-200 Częstochowa, Poland

The paper describes the results of various actions and industrial tests conducted in order to decrease the content of unburned carbon in the fly ash of a circulating fluidised bed combustor (CFBC). Several attempts to improve the situation were made and the effects of several parameters on the unburned carbon content in the fly ash were investigated (e.g. bed temperature, cyclone separation efficiency, fuel particle size distribution, boiler hydrodynamics, grid design, and fuel data). Unfortunately, no satisfactory solution to these problems was found. Probably, apart from attrition and char fragmentation, additional factors also contributed to the formation of unburned carbon in the CFBC fly ash.

**Keywords:** CFB boiler, fly ash, unburned carbon, coal combustion

## 1. INTRODUCTION

Due to the implementation of new tight environment protection standards, as well as liberation of the energy market and promotion of the development of fuel-flexible energy conversion technologies, the use of a fluidised bed combustion for clean and efficient generation of power has been rapidly growing throughout the world in recent decades, particularly in the countries and regions where the production of power is, to a large extent, based on coal (Dong, 2011; Scott and Nilsson, 1999; Smith and Nalbandian, 2000). In accordance with the above trend, a rapid development and erection of many fluidised bed combustors for large-scale power generation has also been recently reported in Poland (Kobyłecki et al., 2010). The decision to implement circulating fluidised bed combustion (CFBC) technology to the power sector was forced, on one hand, by the country's aging power production fleet, and on the other hand by the economic changes that Poland underwent at that time. Those facts, along with the requirements regarding high combustion efficiency and fuel flexibility at moderate costs were the most important factors that supported the CFBC. The technology implementation was very successful thus giving voice to the erection of the world's first supercritical once-through CFBC that recently started its commercial operation at Łagisza Power Plant in Będzin (Kobyłecki et al., 2010). The up-to-date list of commercial large-scale fluidised bed boilers in Poland that are either operated or under construction is shown in Table 1.

Nowadays, the Polish 'large-scale CFBC-related' knowledge is quite wide since the experience was gained during numerous startups, shutdowns and commercial operation of several boilers of various designs (e.g. classical, Compact, Cymic, etc.) and fired with a wide variety of fuels (bituminous coal, lignite, coal slurries, wood chips, bark, paper sludge, various types of agromass, etc.). However, the

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*Corresponding author, e-mail: rafalk@is.pcz.czest.pl technology boom in Poland meant that many boiler designs and technical solutions were field tested in a relatively large number of newly built circulating fluidised bed (CFB) combustors (cf. Table 1).

Table 1. The large-scale circulating fluidised bed combustors in Poland

| Commissioning Year | Owner & Location | Boiler Type | Capacity & Fuel |
|---|---|---|---|
| 1993 | Polpharma,<br>Starogard Gdanski | CFB, hot cyclone | 2 x 60.2 $\text{MW}_e$<br>Bituminous coal |
| 1997 | Vattenfall Heat Poland,<br>Żerań CHP[*], Warsaw | CFB, hot cyclones | 315 $\text{MW}_{th}$<br>Bituminous coal |
| 1997 | Tauron – EC Bielsko Power Plant,<br>Bielsko-Biala | CFB, hot cyclone | 177/165 $\text{MW}_{th}$<br>Bituminous coal |
| 1998 | PGE – Turow Power Plant,<br>Bogatynia | CFB #1 and #2,<br>hot cyclones | 2 x 235 $\text{MW}_e$<br>Lignite |
| 1999 | Tauron – Jaworzno II CHP, Jaworzno | Compact CFB #2 and #3 | 2 x 70 $\text{MW}_e$<br>Bituminous coal, coal slurry |
| 1999 | Tauron – Tychy CHP, Tychy | Cymic CFB, internal cyclone | 37 $\text{MW}_e$+70 $\text{MW}_{th}$<br>Bituminous coal |
| 2000 | PGE – Turow Power Plant,<br>Bogatynia | CFB #3, hot cyclones | 235 $\text{MW}_e$<br>Lignite |
| 2000 | Tauron – Katowice CHP, Katowice | CFB, steam-cooled cyclones | 120 $\text{MW}_e$<br>Bituminous coal, coal slurry |
| 2001 | Vattenfall Heat Poland, Żerań CHP,<br>Warsaw | CFB, steam-cooled cyclones | 315 $\text{MW}_{th}$<br>Bituminous coal |
| 2001-2003 | Tauron – Siersza Power Plant,<br>Trzebinia | CFB #1 and #2, hot cyclones | 2 x 338.5 $\text{MW}_{th}$<br>Bituminous coal |
| 2002-2004 | PGE – Turow Power Plant,<br>Bogatynia | Compact CFB #4, #5 & #6 | 3 x 260 $\text{MW}_e$<br>Lignite |
| 2003 | CEZ – Chorzów CHP Elcho,<br>Chorzów | Compact CFB, #1 and #2 | 2 x 113 $\text{MW}_e$<br>Bituminous coal |
| 2009 | Tauron – Łagisza Power Plant,<br>Będzin | Compact CFB, supercritical once-through | 460 $\text{MW}_e$<br>Bituminous coal, coal slurry |
| 2010 | Fortum Heat Poland – Częstochowa<br>CHP, Częstochowa | Compact CFB | 66 $\text{MW}_e$ +120 $\text{MW}_{th}$<br>Bituminous coal, biomass |
| 2012 (planned) | Tauron – Jaworzno II CHP, Jaworzno | CFB, hot cyclones | 50 $\text{MW}_e$<br>Biomass and agromass |
| 2012 (planned) | GdF Suez, Połaniec Power Plant,<br>Połaniec | Compact CFB | 190 $\text{MW}_e$<br>Biomass and agromass |
| 2012 (planned) | ZEPAK, Konin Power Plant, Konin | Compact CFB #12 | 55 $\text{MW}_e$<br>Biomass and agromass |
| 2012 (planned) | Tauron – Bielsko CHP, Bielsko-Biała | Compact CFB | 50 $\text{MW}_e$<br>Bituminous coal |

[*] CHP = combined heat and power station

Unfortunately, as it often happens in the field tests, technological development is very often accompanied by some operational problems that have to be solved during boiler operation, such as e.g. low combustion efficiency and high fuel consumption, poor boiler dynamics, blockage of fuel feed line, difficulty to control fuel particle size distribution, ash discharge problems, poor cyclone separation efficiency due to low flue gas velocity at the inlet section, high emissions of sulfur oxides, insufficient steam capacity, material problems (erosion, refractory brick fell off), or difficulty to control bed temperature (Lee et al., 2003; Tang et al., 1999; Wang et al., 2010). For one of Polish CFB combustors the main difficulty was quite high content of unburned carbon in the fly ash. The issue, however, was not just a distinctive feature of that particular combustor since similar problems were also reported by other researchers (Batra et al., 2008; Kulaots et al., 2004; Lee et al., 2003). A high content of unburned carbon in the fly ash was, however, important for the power plant staff from the economical point of view since it increased the fuel costs and boiler operational costs, and was responsible for lower boiler efficiency due to higher losses caused by incomplete combustion. Apart from the above, too much unburned carbon in the CFB fly ash (i.e. usually more than 5-8%) was also unacceptable as it made it impossible to properly apply ash management strategy and reuse ash e.g. in cement industry. Accordingly, there was a strong need to improve that situation.

The present paper briefly reports some of numerous industrial tests and counteractions taken at one of Polish large-scale CFB combustors in order to decrease unburned carbon content in the boiler fly ash. The presented data may be very useful for readers since so far no such comprehensive report has been published in the literature.

## 2. A BRIEF DESCRIPTION OF THE BOILER

The investigations and industrial tests described in the present paper were conducted at a ‘classical structure’ CFBC that consisted of a CFB loop and a convective section. The boiler furnace chamber was roughly 40 m high and its cross-section area was roughly 90 m$^2$. The lower part of the furnace was covered with ceramic refractory in order to protect the membrane walls from erosion and attrition. Solids and gas carried over from the combustion chamber were separated by two cyclones located between the furnace and the convective section. Separated solids were recirculated into the combustion chamber via two loop seals, while the flue gas passed through the heat transfer surfaces located in the convective section, and then through the electrostatic precipitator (ESP) before being fed into the stack. The schematic of the CFBC is shown in Fig. 1. More details are given elsewhere (Kobyłecki et al., 2008).

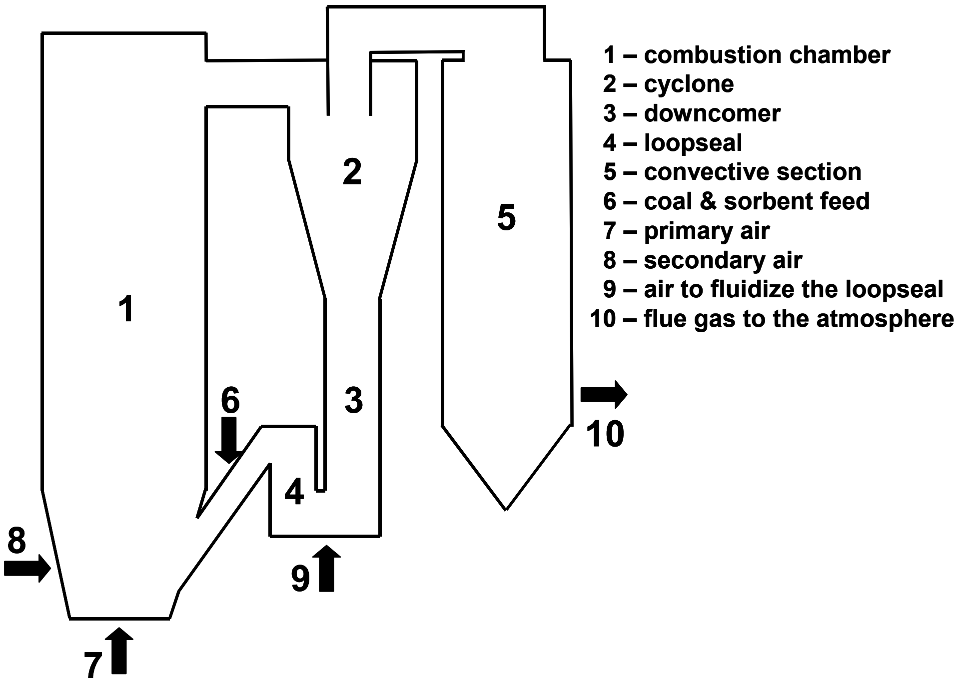

Fig. 1. Sketch of the CFB boiler system

The CFBC was designed to be fired with bituminous coal of particle size <6mm, ash content 8-20%, sulfur content of 0.6-1% and average LHV of 18-24MJ/kg. In order to meet the sulfur dioxide emission standards limestone sorbent was fed into the combustion chamber. The purity of the limestone exceeded 90%, while the particle size was below 0.7mm.

In order to investigate the boiler's behaviour in detail, the CFBC was very well equipped with numerous pressure and temperature measurement taps located inside the furnace at 0.2m (10 pressure and 14 temperature measurement taps), 1.2m (4 pressure and 10 temperature taps), 5.8m (4 pressure and 10 temperature taps), and 35m (3 pressure and 4 temperature taps) above the air distributor. Furthermore, there were 10 pressure and 12 temperature measurement taps in the recirculation system that consisted of a downcomer, a loop seal, and a return leg.

## 3. DETERMINATION OF UNBURNED CARBON CONTENT IN CFB FLY ASHES

Since the temperature in CFB furnaces is usually maintained at 800-900$^0$C and since the limestone sorbent is injected directly into the combustion chamber for dry flue gas desulfurization process the CFB fly ash particles contain a certain amount of unreacted limestone and calcium oxide and are much more chemically 'reactive' compared to ash or slag from pulverized or stoker furnaces (Anthony et al., 2007; Hower et al., 2010). Accordingly, the way to determine unburned carbon content in the fly ash must be done in a different manner than just the commonly used 'LOI' (loss on ignition) technique (Brown and Dykstra, 1995; Fan and Brown, 2001; Li et al., 1997; Liu et al., 2010; Paya et al., 1998; Styszko-Grochowiak et al., 2004; Waller and Brown, 1996). In order to develop an accurate methodology numerous tests with synthetic fly ashes were conducted at the Czestochowa University of Technology in a TG-like device (Bis et al., 2004). Based on the results of those tests a new procedure was established to determine unburned carbon content in the CFB fly ashes. The procedure was consequently used to analyse all the samples described in the present paper. The procedure consisted of the following steps:

1. sample preparation,
2. heating of the fly ash sample to 120°C at 30°C/min in $N_2$ atmosphere,
3. sample held at 120°C for 15min in $N_2$ atmosphere,
4. heating of the sample from 120°C to 550°C at 20°C/min in $N_2$ atmosphere,
5. sample held at 550°C for 20 min in $CO_2$ atmosphere, and finally
6. sample held at 550°C for 60 min in air atmosphere.

The steps No. 2 and No. 3 were introduced in order to get rid of any moisture that might contaminate the sample and thus affect its mass loss, and, as a result, the unburned carbon content. The role of step No. 4 is to heat the sample and decompose any $Ca(OH)_2$ that could be formed as a result of the reaction between CaO in the fly ash and water vapors. Since decomposition of $Ca(OH)_2$ occurs at roughly 450$^0$C i.e. before oxidation of unburned carbon (cf. step 6) it does not affect the sample's mass loss and the results. In order to protect samples from any possible oxidation and uncontrolled mass loss during steps 2-4, they are kept in an inert gas atmosphere ($N_2$). The role of step No. 5, where fly ash samples are exposed to a pure $CO_2$ atmosphere, is to completely 'pacify' CaO in the ash by transforming it into $CaCO_3$ that is thermodynamically stable up to at least 700$^0$C otherwise the 'free' CaO in the fly ash may react with $CO_2$ evolved during carbon oxidation (step No. 6) and thus affect the sample's mass change and, accordingly, the unburned carbon content. The 'pacification' of CaO and transformation of calcium oxide into calcium carbonate before oxidation of unburned carbon in the fly ash (step No. 6) ensures that the change of the sample's mass during step No. 6 is only a result of carbon oxidation.

During all the stages the sample's mass was continuously determined by a strain gauge balance. After the test had finished unburned carbon content in the fly ash sample was determined as the mass loss brought about exclusively by oxidation of unburned carbon (step No. 6) divided by the sample's mass in the dry state i.e. just as it comes out from the real boiler (the end of step No. 3). The corresponding equation to calculate unburned carbon in the CFB fly ash is thus:

$$UC = \frac{m_{6start} - m_{6end}}{m_{3end}} \cdot 100\% \tag{1}$$

where:
$m_{6start}$ - mass of the sample at the beginning of step #6,
$m_{6end}$ - mass of the sample at the end of step #6, and
$m_{3end}$ - mass of the sample at the end of step #3, i.e. after any water is evaporated from the fly ash sample (dry state),

More details about the procedure are given elsewhere (Bis et al., 2004).

## 4. RESULTS AND DISCUSSION

The investigations and industrial tests at the power station were conducted in order to: 1/ find a way to decrease and control unburned carbon content in the CFB fly ash, and 2/ check an effect of various boiler parameters on unburned carbon content in the fly ash. The information given in the current paper are the results of the author's activities in that field that lasted a few years. During those years effects of the following parameters on boiler operation and unburned carbon content were studied: bed temperature, separation efficiency of the cyclones, particle size distribution of the fuel, grid design, boiler load, air flow rate, bed pressure, and fuel parameters. The main findings are presented below.

### *4.1. Effects of temperature*

The relationship between unburned carbon content in the fly ash and bed temperature is presented in Fig. 2. Although the bed temperature varied from roughly 830$^0$C to 880$^0$C hardly any direct correlation between those parameters could be seen.

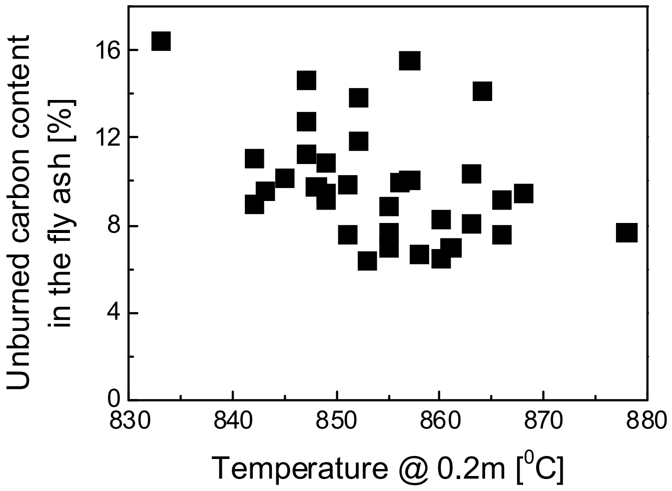

Fig. 2. The content of unburned carbon in the fly ash vs. bed temperature

### 4.2. Effects of cyclone separation efficiency

Due to modifications and improvements introduced into the cyclones, for some period the boiler was operated with cyclones of varied separation efficiency. The modifications in the cyclones were not, however, intentionally conducted in order to decrease content of unburned carbon in the fly ash but were mainly focused on improving the bed hydrodynamics and on providing conditions for a stable operation of the boiler. More details on the modifications and the reason why they had been performed are given elsewhere (Kobyłecki et al., 2005).

The summary results of the investigations are shown in Fig. 3. When the boiler was operated with cyclones of high separation efficiency the temperature in the lower part of the furnace was quite low and remained at roughly 740-800$^0$C. During that period unburned carbon content in the fly ash varied from 8% to 17%. Surprisingly, an increase of the furnace temperature to 820-880$^0$C (i.e. the case of ‘low’, as well as ‘medium’ separation efficiency cyclones) did not practically change the situation since the concentration of unburned carbon in the fly ash was still scattered quite widely (roughly 2-20% for ‘medium’ and 3-6% for ‘low’ separation efficiency cyclones, cf. Fig. 3). Although for the case of ‘low’ separation efficiency cyclones the concentration of unburned carbon seemed to be quite low, the long-time boiler operation at such conditions was unacceptable from the economical point of view since an enormous amount of sorbent was used in order meet the $SO_2$ emission standards. It is also interesting (cf. Fig. 3) that there were periods when the content of unburned carbon in the fly ashes for the ‘medium’ case was below the values obtained for the ‘low’ one.

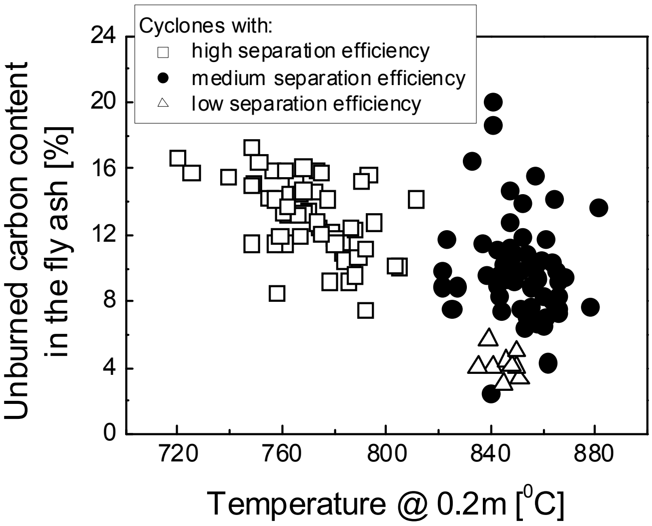

Fig. 3. The temperature in the lower part of the furnace vs. unburned carbon content for various cyclone separation efficiency

### 4.3. Effects of fuel particle size distribution

For a period of time the boiler was fired with a specially prepared coal of ‘coarser’ particle size distribution (PSD). The coal PSD was changed by adjusting the hammer crushers and, as a result, the median coal particle size, $d_{50}$, increased from roughly 0.7 to 2mm (cf. Fig. 4). Since such a ‘coarse’ fuel contained less fine particles that could be easily carried away unburned to the electrostatic precipitator (ESP) then firing the boiler with ‘coarse’ coal should be associated with a significant decrease of unburned carbon content in the fly ash samples. Surprisingly, the data in Fig. 5 indicate that there is almost no effect of fuel PSD on the content of unburned carbon in the fly ash. Since the results for 'coarse' and 'finer' coal are very similar they thus indicate that the elutriation of fines and attrition of coarse chars are not the main factor contributing to the overall content of unburned carbon in the CFB fly ash.

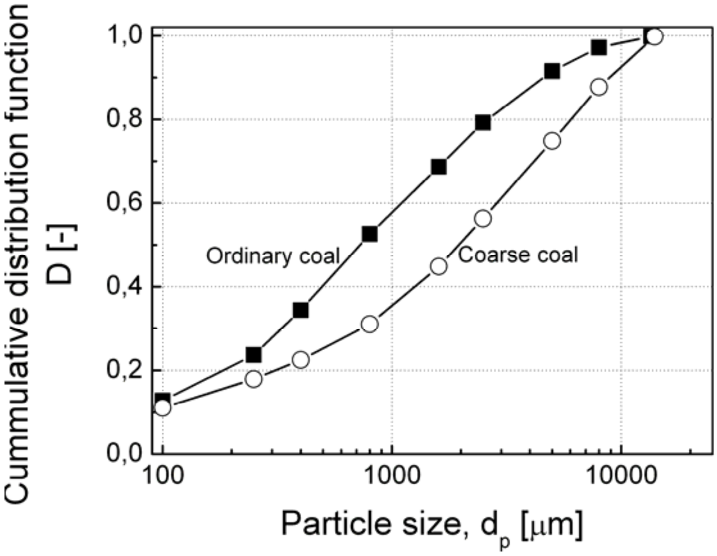

Fig. 4. The particle size distribution of coal

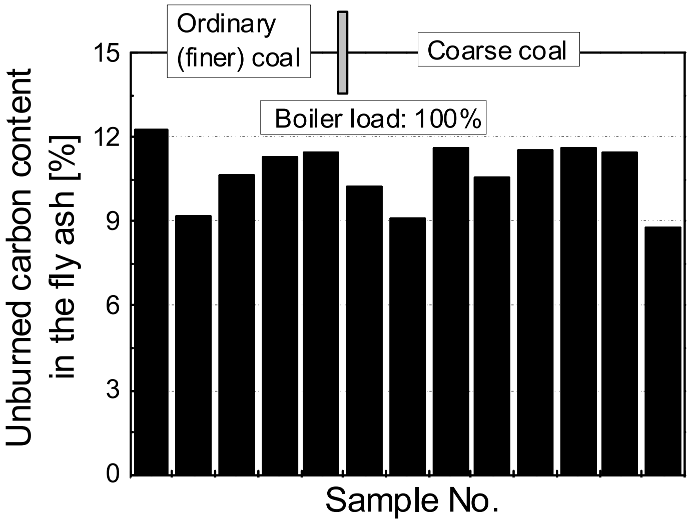

Fig. 5. The effect of coal particle size distribution on the unburned carbon content in the fly ash

### *4.4. Effects of boiler load and air flow rate*

The unburned carbon content vs. boiler load is shown in Fig. 6. The results indicate practically no correlation between the boiler load and the unburned carbon content in the fly ash.

Similar conclusion may be drawn from the data presented in Fig. 7. Even though the air flow rate was changed over a wide range (58-72 kg/s) the unburned carbon content in the fly ash remained constant at roughly 16-19%.

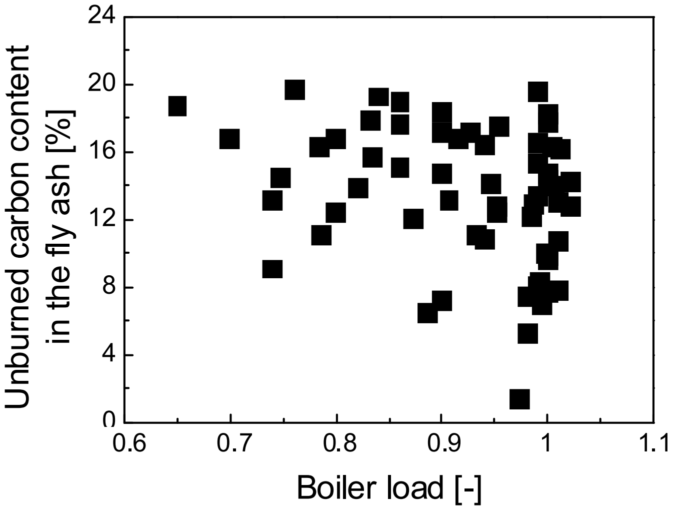

Fig. 6. The unburned carbon content in the fly ash vs. boiler load

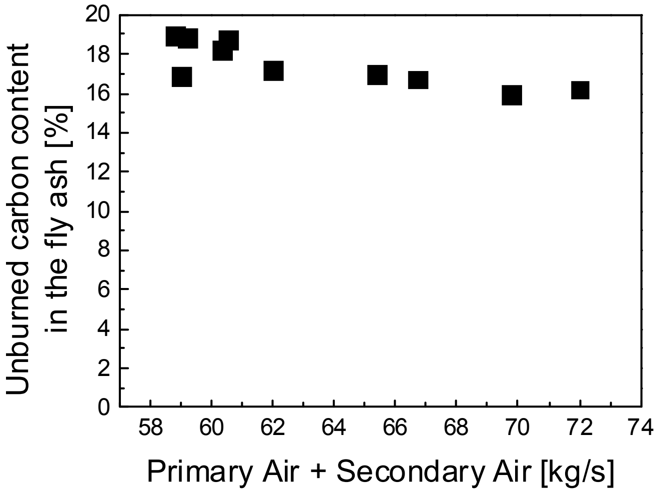

Fig. 7. The unburned carbon content in the fly ash vs. air flow rate

### *4.5. Effects of bed pressure*

The relationship between the bed static pressure and unburned carbon content is shown in Fig. 8. Since the bed pressure corresponds to the mass of solids in the boiler combustion chamber an increase of the bed pressure should affect unburned carbon content in the fly ash by e.g. just increasing the solids residence time in the furnace and thus providing conditions for better mixing and combustion. Surprisingly, although the bed pressure varied within quite a wide range the unburned carbon content in the fly ash remained almost constant at roughly 16-19%.

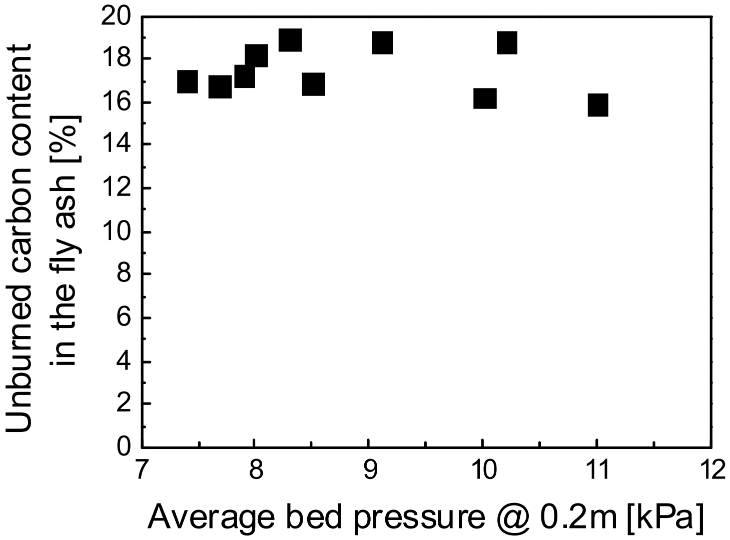

Fig. 8. The unburned carbon content in the fly ash vs. bed static pressure

### *4.6. Effects of grid design*

Another attempt to decrease unburned carbon content in the fly ash was the modification of the air distributor. Nozzles at some sections of the grid were modified in order to supply more air to the zones at the front and rear walls of the furnace and thus to improve solids mixing and fuel distribution. The results are shown in Fig. 9. Unfortunately, again no success was achieved since no satisfying effect of the grid design was found. The values of the unburned carbon content in the fly ash remained high and were furthermore scattered quite widely for a given boiler load. Although for the whole spectrum of boiler loads the average values for the new grid seem to be slightly lower compared to the data for the old one (cf. Fig. 9) there are also boiler loads where no effect or even an opposite effect may be seen (cf. e.g. the values for boiler loads of roughly 0.8 and 0.75, respectively).

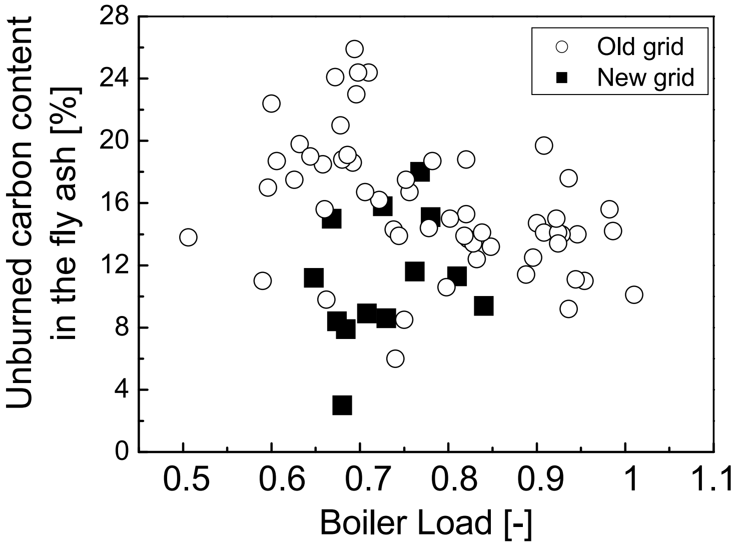

Fig. 9. The unburned carbon content in the fly ash vs. boiler load for two grid designs

### *4.7. Effects of fuel parameters*

The effect of some coal parameters on unburned carbon content in the fly ash is plotted in Figs. 10a-d. Although all the parameters varied within quite a wide range, no correlation between those parameters and the unburned carbon content was observed.

The analysis of the results in Figs. 2-10 clearly indicates that the unburned carbon content in the CFB fly ash remained quite high despite numerous changes and modifications introduced into the boiler.

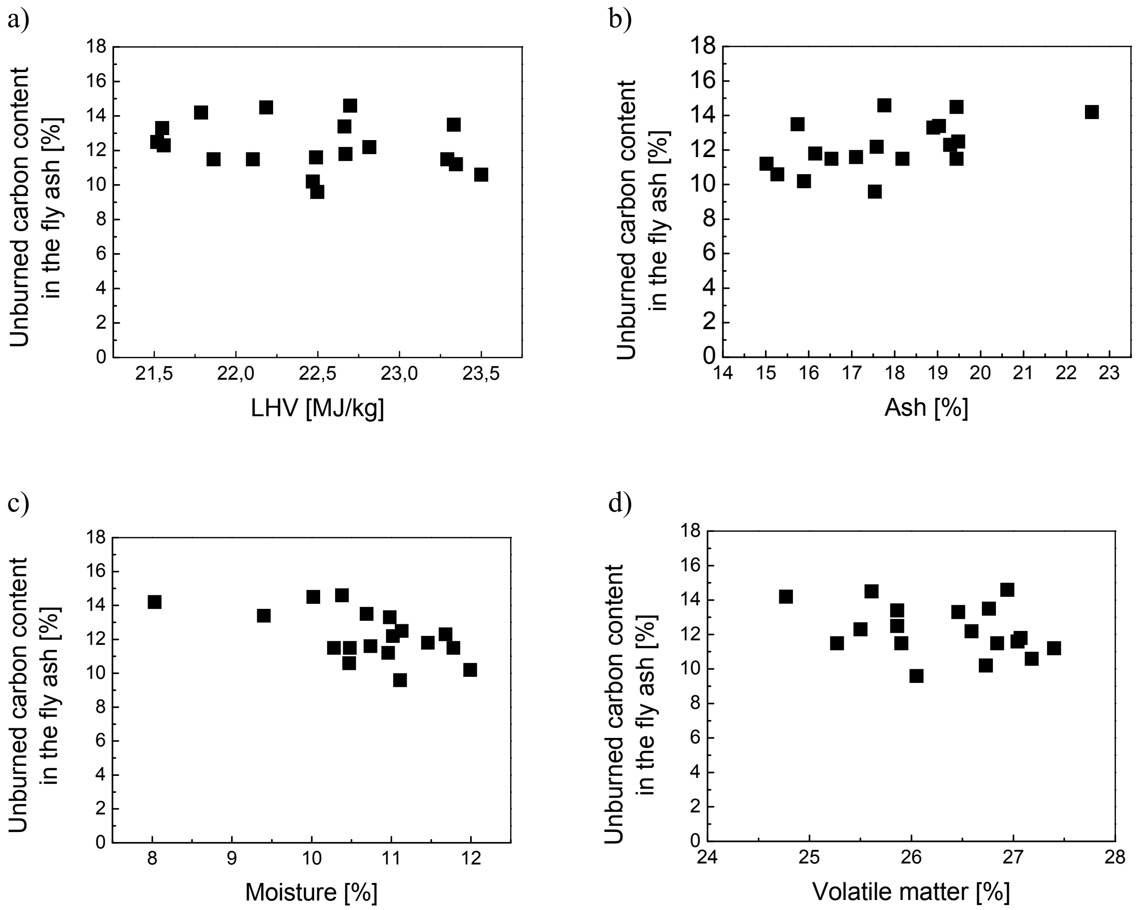

Fig. 10. The effect of some coal parameters on unburned carbon content in the fly ash: (a) LHV, (b) ash content, (c) moisture and (d) volatile matter content

### *4.8. Unburned carbon in the fly ash fractions*

Separation of the fly ash samples into several fractions and laboratory analysis of those fractions with respect to unburned carbon content indicated an interesting relationship: the finer the fraction (i.e. the smaller the size of the fly ash particles) the more unburned carbon it contained. The unburned carbon content determined in the finest ash fractions (e.g. less than 20μm) exceeded 20%, while the values determined in the coarser fractions (particle size over 70μm) remained quite low at roughly 5%. Some results are shown in Fig. 11.

The results in Fig. 11 indicate that the formation of unburned carbon in the CFB fly ash is probably not just the result of attrition and char fragmentation. That assumption is strongly supported by results of industrial tests since no satisfactory decrease of unburned carbon content in the fly ash was achieved despite conducting many tests (cf. Figs. 2-10). For example, as shown in Fig. 11, the finer the fly ash fraction the more unburned carbon it contains. Accordingly, since fine fuel particles burn under kinetic mode, any change of bed temperature should directly affect unburned carbon content in the fly ash. Unfortunately, the results in Fig. 3 do not show any direct correlation between those parameters since the unburned carbon content remained at roughly 4-18% despite the fact that the bed's temperature was changed from 720 to 880$^0$C.

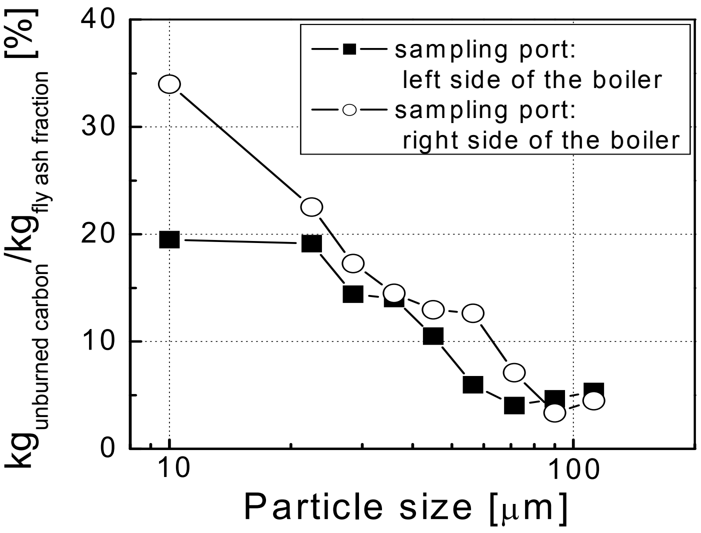

Fig. 11. The unburned carbon content vs. fly ash particle size

The data shown in Figs. 7-9 are also, to a certain extent, surprising since almost no effect of bed hydrodynamics on unburned carbon content in the CFB fly ash is seen. Since the processes of char attrition and elutriation of fines are directly affected by gas velocity, less unburned carbon in the fly ash samples could be expected in tests when less air was supplied into the furnace. Unfortunately (cf. Fig. 7), the unburned carbon content remained quite high at roughly 16-19%. Such surprising results may be, however, explained assuming that unburned carbon in the fly ash is formed under a different mechanism e.g. the mechanism where the processes of attrition and elutriation of fines are not the dominant ones.

## 5. CONCLUSIONS

Several industrial 'at the plant' tests were performed and several boiler parameters were changed in order to decrease unburned carbon content in the fly ash of a commercial large-scale coal fired CFBC. Despite so many actions and boiler modifications the results of industrial tests were, however, quite disappointing since unburned carbon content in the fly ash samples remained above the acceptable level (roughly 5%). Furthermore, no permanent decrease of unburned carbon content in the fly ash was determined.

Such results are probably associated with the specific character of the mechanism of unburned carbon formation. It is most likely that in case of a large-scale CFBC the processes of attrition and elutriation of fine char and coal particles are not the dominant ones and another factor is responsible for the formation of unburned carbon in the fly ash. In order to support that hypothesis a more detailed analysis of coal combustion in CFBC is required. Corresponding investigations have been conducted by the author and results and findings are the subject of a separate paper that is currently being prepared for publication.

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