Some chosen aspects of CFB boilers operation

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Abstract. Central Europe, particularly Poland, has been one of the areas of intensive development of fluidized bed combustion technology for over 25 years. This paper deals with a brief discussion on the results of industrial tests carried out by the authors and focused on the reduction of nitrogen oxide emission, solids deposition and unburned carbon content in the fly ashes. Some selected data has been presented and come remarks and counteractions to improve the operation of industrial large-scale circulating fluidized bed boilers are given.

1. Introduction
Despite design differences (e.g. boilers with a hot solids recycle, compact units, or combustors with heat exchangers in the recirculation system) the circulating fluidized bed (CFB) boilers are devices predestined for the simultaneous utilization of wide range of fuels with operational flexibility and low emission of pollutants [1]. Quite often, however, the operation of industrial combustors becomes difficult and is associated with plant malfunctioning or the existence of some unwanted phenomena, such as high emission of gaseous pollutants, corrosion, severe solids deposition or high concentration of unburned carbon in the fly ash [1]. The getting rid of those operational problems may be quite expensive and thus unacceptable for the operators. Therefore, simple tools and inexpensive counteractions focused on the minimization of the above problems are always very much welcomed by power engineers and CFB operational staff.

In this paper some chosen main aspects of the operation of various CFB facilities are presented and the results of authors’ investigations carried out at various CFB combustors are discussed and supported by industrial data from large-scale circulating fluidized bed combustion (CFBC) plants.

2. Results and discussion
In this section the data and results of some chosen authors’ experimental investigations are briefly presented. The measurements were carried out at industrial large-scale (>100 MW) CFB combustors operated at various locations in Central Europe.

2.1. $NO_x$
As stated e.g. in [2] the combustion conditions in the furnace and in the CFB loop directly affect the emission of gaseous species from CFB combustors. The most important parameter is the bed temperature that in case of CFB boilers has to be adjusted at roughly 840-860°C in order to meet the required level of the emission of $SO_2$ and $NO_x$. Unfortunately, quite often industrial CFB plants do not meet the designed values and temperature may vary roughly between 800-1000°C [1, 3]. Too high...
temperature brings about the increase of the emission of NO\textsubscript{x} and also higher consumption of sorbent to maintain dry desulfurization in the furnace. Since such operation is unwanted from economical point of view in some cases the temperature profile in the CFB loop has to be ‘corrected’ by better fluidization and improved bed hydrodynamics, e.g. by modification of the separation efficiency of the boiler cyclones. Such action took place in a roughly 40m high CFB boiler with a combustion chamber cross-section of roughly 90m\textsuperscript{2}. The boiler was fired with bituminous coal of average LHV 18-24MJ/kg. Limestone of purity >90\% and particle size <0.7mm was fed into the combustion chamber to maintain dry desulfurization process.

Two cyclones were coupled to the CFB facility were characterized by high solids separation efficiencies and were operated at very high loads (>1000 kg/s of solids). Due to some operational difficulties, however, the cyclone design had to be modified; in the first step the internal geometry of the cyclones was changed so that the cyclone separation efficiency was drastically decreased and then, after a few weeks of operation, the cyclone design was slightly corrected bringing about the increase of the separation efficiency as compared to the original cyclone design. Those actions brought the authors a unique opportunity to investigate the effect of the cyclone design on bed hydrodynamics and operation of the commercial CFB facility. The effect of those modifications could be observed by investigating the boiler parameters and the variation of the size of the solids circulating within the loop, as shown in figure 1. The better the cyclone the finer the solids in the loop. The median size, \textit{d}_{\text{50}} \textit{, of solids separated by the cyclone and recirculated into the furnace via the loopseal was roughly 80µm for original cyclones (high efficiency of separation), roughly 110µm for medium one, and roughly 130µm for low separation efficiency cyclones.}

![Figure 1](image_url)

**Figure 1.** Particle size distributions of the circulating solids in the CFB loop for three separation efficiencies of the cyclone (high, medium and low).

The effect of cyclone separation efficiency on the temperature profile along the furnace is shown in figure 2 vs. boiler relative load (the flowrate of the live steam). In order to maintain the emission at acceptably low level the temperature distribution profile in the furnace has to be maintained quite uniform (\textit{T\textsubscript{furnace outlet}/T\textsubscript{furnace bottom}=1) since the existence of any high temperature zones may bring about the formation of nitrogen oxides or increased consumption of limestone for the desulfurization. With respect to bed hydrodynamics and fluidization regime it may be seen that the boiler with cyclones of high separation efficiency easily maintains uniform temperature profile even at 60\% load while in case of low separating cyclones the temperature profile is strongly non-uniform and the differences may even exceed 10\%. As already mentioned earlier, such differences in temperature distribution affect local solids holdup and heat transfer within the furnace and are responsible for increased emission of some unwanted gaseous species, such as NO\textsubscript{x}. In case of the investigated boiler the operational data indicated that a non-uniform temperature profile corresponds to increase of the emission of NO\textsubscript{x} up to even 500 mg/Nm\textsuperscript{3} i.e. significantly over the limit required by the IED Directive. On the other hand,
uniform temperature profile in the furnace (medium cyclone separation efficiency) provided the conditions for easy maintaining the emission of both SO$_2$ and NO$_x$ at less than 150-200 mg/Nm$^3$ with acceptable consumption of limestone. As one can conclude from the data in figure 2 the most uniform temperature profile in the combustion chamber was obtained for the boiler operated with medium separation efficiency cyclones.

![Figure 2](image1.png)

**Figure 2.** The temperature quotient in the upper and lower part of the combustion chamber vs. boiler load for various cyclone separation efficiencies.

2.2. Deposits and fouling

The formation of deposits is quite often associated with the combustion of solid fuels and may become a serious problem for CFB boiler operators as it may reduce the heat transfer rate and bring about higher operation and overhaul costs. From operational point of view any on-line system for the monitoring of the deposit formation rate could contribute to the reduction of those costs. A simple solution for the investigation of solids accumulation on heat transfer tubes in the convective sections of commercial combustors may be the application of a ‘sampling probe’ shown in figure 3. The probe was designed by the authors and consisted of ring-shaped steel samples placed on a special rod. The probe was immersed into the gas-solids flow between the cyclone and the convective section of a >400MW CFB boiler.

![Figure 3](image2.png)

**Figure 3.** The head of a simple probe for the investigation of the deposit formation rates in commercial CFB boilers.

The advantage of the application of such probe is lack of boiler shutdown during the application of the probe and a ‘quasi on-line’ analysis and direct monitoring the the deposit formation rates. The investigation of the structure and thickness of the deposits after some chosen time period may be carried out at the plant providing immediate information about the current solids formation rate – such data are particularly important in case the boiler is cofired with mixtures of various fuels. As it is shown in figure 4 the switching of the fuels may bring about significant and immediate increase of the deposit formation...
rate. Without any information on the current conditions at the plant the deposit formation may soon become so severe that an emergency shutdown of the boiler may be required to remove the deposits.

Figure 4. Relative fouling rates for various mixtures of coal, biomass and agromass combusted at a commercial CFB boiler (test 1: the boiler fired with coal+sunflower pellets, test 2: coal+sunflower pellets+woodchips, test 4: coal+coal slurry, test 5: coal+agromass).

Detailed analysis of the test samples shown in figure 3 after their residence in the CFB boiler confirmed the suitability of the proposed method and indicated that it may be very helpful to assess potential damage to heat transfer tubes due to the change of fuel type and its physicochemical parameters (e.g. particle size distribution, chemical composition, etc.). Those results may be supported by other more sophisticated investigations e.g. focused on a SEM-analysis of the deposit cross-sections. Comparison of the structure and morphology of the deposits may provide data on the effect of fuel type and bed hydrodynamics on the development and rate of corrosion – some example results are shown in figure 5. The replacement of coal by coal/biomass mixture brings about the formation of a more ‘porous’ deposits (case b) – due to those cracks the corrosion rate may significantly increase and be a few times higher than during the combustion of only coal.

Figure 5. View of the ash deposits at the surfaces of steel rings exposed to standard conditions (fuel: coal – case a) and cofiring (fuel: coal/biomass mixture – case b).

2.3. Unburned carbon in the fly ash
The presence of unburnables (mainly unburned carbon) in the CFB boiler fly ash is mainly the result of insufficient mixing of fuel and oxidizer, too low temperature, or too short residence time. Since all those requirements are quite difficult to meet at real plants the presence of some low (usually <2%)
concentration of unburned carbon in the fly ash is commonly acceptable for boiler operators, particularly that it does not affect the properties of the fly ash with respect to its use in civil engineering. However, the problem becomes economically unacceptable in case the amount of unburned carbon in the ash exceeds roughly 8-10%. In such plants some counteractions must be taken to improve the combustion and fuel burnout.

Microscopic analysis of the CFB fly ash samples (cf. figure 6a) indicated that significant contribution to the overall unburnables is provided by tar. Its formation may become significant particularly in high temperature low oxygen zones of the furnace and may sometimes bring about even the necessity of boiler emergency shutdown due to the stoppage of solids flowrate within the CFB recirculation system, as shown e.g. in figure 6b.

![Figure 6. View of a CFB boiler fly ash (case a; magnification 200x) and the formation of tar in a return leg of one of CFBCs (case b).](image)

The formation of tar is an important contributor to the formation of unburned carbon in the CFB fly ash and, unfortunately gives the operator less possibilities to control the process by e.g. adjustment of the fuel particle size. As it is shown in figure 7 the results of two industrial tests carried out with fine and coarse coals indicated no effect of the fuel particle size on the content of unburned carbon in the fly ash that remained at roughly 2% of the initial carbon flowrate.

Since significant contribution to the formation of unburned carbon in the fly ash is made by tar and other carbon-rich liquids the level of unburned carbon in the CFB fly ash might be reduced by the switching to less-swelling coals. In order to verify the above thesis on the effect of tar to the overall concentration of unburned carbon in CFB fly ash some industrial tests were conducted for various fuels of roughly similar composition (with respect to their proximate analyses) but characterized by significantly different amount of tar and swelling properties (cf. figure 8). The industrial tests indicated that switching to ‘less-swelling’ coals may bring about significant (roughly 100%) reduction of the unburned carbon content in the fly ash (cf. figure 9) due to the reduction of the amount of tar that may cover the surface of fine ash particles and is quite difficult to ignite and burnout in CFBC conditions.

![Figure 7. The particle size distributions of the combusted coal and the concentration of unburned carbon in the CFB fly ash.](image)
Figure 8. Surfaces of selected coal particles during the softening phase: a) Fuel A (sintering index=8), b) Fuel B (sintering index=6), c) Fuel C (sintering index=2). Magnification: 100x.

Figure 9. The concentration of unburned carbon in CFBC fly ash for various fuels burned.

3. Summary
The results of experimental investigations carried out at industrial CFB facilities and briefly described in the present paper may be summarized as follows:
1. The modification of cyclone separation efficiency is a very good way to control the temperature profile within the CFB loop and the consumption of limestone and the emission of nitrogen oxides.
2. The application of simple steel probe may provide immediate information of the deposit formation rate in the convective section of the CFB boiler. The data are particularly crucial when various fuel mixtures are combusted and may help to maintain the corrosion rate at low level.
3. The swelling properties of fuels and the amount of tar formed on the surfaces of solids during fuel softening are important factors affecting the content of unburned carbon in CFB fly ashes. The process may be controlled by fuel switching and combustion of ‘less-swelling’ coals or fuel pretreatment in order to minimize the amount of tar formed within the CFB furnace.

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