HOW TO USE DATA ABOUT COAL COMBUSTION IN BUBBLING FLUIDIZED BEDS FOR DESIGN OF THE CIRCULATING FLUIDIZED BED BOILERS ?

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There are several methodologies for fuel testing in bubbling fluidized bed conditions now in use in the world. Those methodologies are supported by already standard set of experimental facilities, laboratory and pilot furnaces. Data obtained using mentioned methodologies are proven in practice in a number of cases by choosing concepts of the BFBC boilers, and making calculation of the main regime parameters and dimensions and determining type and capacity of the auxiliary boiler systems.

Fast development of the circulating fluidized bed boilers, posed the question of obtaining data necessary for choosing CFBC boilers concept and design and calculation of the main regime parameters and boiler dimensions. According to my knowledge, there is no in open literature published methodology for investigation of the coal suitability for CFB combustion, and for obtaining data for CFBC boiler design and calculation of the optimal design parameters and dimensions.

Considering available short discussions in few papers, data obtained in bubbling FBC conditions are used so far, for CFBC boiler design, due to the very expensive equipment for investigation processes in the circulating fluidized bed conditions. The question is if this is correct?

In the paper differences between aerothermodynamic conditions in BFBC and CFBC boilers are discussed. Based on the ITE methodology for investigation of coal suitability for BFBC combustion every specific data obtained is discussed in the light of the differences between combustion conditions in BFBC and CFBC boilers.

It was concluded on the bases of those analysis, that in the most cases using data obtained for BFBC conditions we are on the safe side when design CFBC boilers.

1. Problem

In spite of high fuel flexibility of the BFBC, and especially CFBC boilers, for making boiler concept, and even more for boiler design and calculation of the main parameters, is necessary to perform testing of the fuels to be used in the boiler, and to analyze behavior of fuel and ash in the furnace.

For fuel testing there are several methodologies now in use in the world. Those methodologies are oriented to the bubbling fluidized bed combustion and supported by already standard set of experimental facilities and laboratory and pilot furnaces [1-7]. Data obtained using mentioned methodologies are proven in practice in a number of cases by choosing concepts of the BFBC boilers, and making calculation of the main regime parameters and dimensions and determining type and capacity of the auxiliary boiler systems.

Practically, there are no in open literature published systematized methodologies for testing suitability of fuels for combustion in circulating fluidized bed [8-10]. Most probably, those methodologies are the industrial secret of the few large boiler manufacturers. It can be supposed, that if methodologies for fuel testing for CFBC exist, they comprise testing of fuel in pilot-size CFBC experimental facilities[8]. Those facilities are at least of the 1MWth in power, and rather expensive.

In many developing countries there are in use methodologies for fuel testing for BFBC boilers, supported by suitable experimental bases, including pilot-size experimental furnaces or boilers, or even industrial BFBC boilers, ready for fuel testing [7]. Based on the data obtained by using such methodologies, independent development of the original concepts and designs of BFBC boilers and hot-gas generators was effected. Scientific institutions, or BFBC boiler manufacturers, making R&D of the BFBC technology do not have pilot-size CFBC facilities, for fuel testing in close-to-real conditions.

In developing countries implementation of the CFBC technology, both in electric power generation and combined heat and electric energy generation in industry or for district heating, is in course. It become necessary previously to study behavior of local fuels (coal, biomass, and industrial waste) in circulating fluidized bed conditions, at least to obtain data for feasibility studies. Especially, comparison with pulverized coal combustion boilers are important. Feasibility studies are necessary, in spite of the fact that CFBC boilers will be designed and manufactured by one of the well known world's companies.

In such cases an important question arises: **IS IT POSSIBLE TO USE DATA ABOUT COAL COMBUSTION IN BUBBLING FLUIDIZED BEDS FOR DESIGN OF THE CIRCULATING FLUIDIZED BED BOILERS ?**

2. Questions and dilemmas ought to be solved for CFBC boiler design

Engineer designer is faced with the number of questions and dilemmas in the course of CFBC boiler design and calculation of main parameters and dimensions. Some of them are listed below. There are a lot of questions that are common for BFBC and CFBC boiler design, so the common questions will be listed first. Organization of combustion process in CFBC boilers is different compared to the combustion in BFBC boilers. As a consequence there are some questions and dilemmas that are different for CFBC boilers. Questions listed at the end are specific for CFBC boilers[11-15].

List of questions and dilemmas common for BFBC and CFBC boiler design:

- Is pre-treatment of coal is necessary (separation, washing, grinding, drying, etc.) or coal as received (or as mined) can be burned?
- Which coal particle size and size range is optimal?
- Location and number of coal feeding points?
- Primary to secondary air ratio?
- How to organize boiler start-up procedure?
- How to organize load following?
- Is the system for draining bed material is necessary, and system for return of the inert material in the furnace?
- Type of the gas cleaning system - cyclones, bag-filters or electrostatic precipitators?

Concerning the furnace itself, the following answers are necessary:

- Main dimensions of the furnace (cross section and height)?
- Main regime parameters (temperature, fluidization velocity, excess air)?
- Inert material particle size?
- Heat generated in furnace (split between bed and freeboard)?

- Molar Ca/S ratio?
- Efficiency of limestone to capture SO_2?
- Mass flow rate of all solid material in boiler - coal, ash, inert material, limestone?

List of questions and dilemmas specific for CFBC boilers:

- Are external FB heat exchangers are necessary, or heat transfer surfaces in the furnace are enough?
- Concentration (hold-up) of the inert material in furnace?
- Mass flow rate of recirculated material?
- Heat transferred in external FB heat exchangers?
- Heat transferred in convective part of the boiler?
- How deep substoichimetry has to be accepted in bottom bed?
- How many cyclones has to be previewed?
- What type of loop seal to use?

Obviously, some of listed parameters for CFBC boilers are known in advance, on the basis of the previous investigations or industrial experience:

- Fuel particle size 10-15 mm.
- inert material particle size - 150-250μm,
- fluidization velocity - 6-10 m/s,
- combustion temperature - 800-850^{o}C,
- cyclone cut-of particle size - 35-75μm,
- 50-100MWth per cyclone,
- 4-6.5MWth heat generated per m^2 of the furnace cross section,
- one fuel feeding point per m^2 of the furnace cross section.

Also, in CFBC always exists secondary air, and system for draining of inert material from the bed.

Answers on other questions and dilemmas depend on fuel characteristics, boiler duty regime, and have to be obtained on the basis of fuel testing. ITE-IBK methodology (and more or less all other known methodologies) for testing of fuel suitability for burning in BFBC boilers gives the following data [7,16].

From experiments in laboratory furnaces:

- Proximate and ultimate analysis,
- fuel particle size distribution as received (sometimes at feeding point),
- chemical composition of ash,
- ash melting point according to laboratory oven experiments,
- ash sintering temperature according to experiments in fluidized bed,
- critical coal particle diameter for primary fragmentation,
- coal ignition temperature and furnace start-up temperature,
- coal and char burning rate,
- limestone efficiency for sulfur capture,
- ash self sulfur capture.

From experiments carried out in pilot-size furnace, with and without limestone addition, burning coal as in real application:

- Optimal, maximal and minimal combustion temperature,
- optimal excess air,
- optimal amount of secondary air,
- fuel feeding on the bed surface or under the bed surface,
- ash splitting between bottom ash and fly ash,
- combustion efficiency,
- heat generation splitting between bed and freeboard,
- amount of heat extracted from the bed,
- amount of heat needs to be extracted in convective part of the boiler,
- particle size distribution of bottom and fly ash,
- energy losses with unburned carbon in fly ash and CO in flue gases,
- molar Ca/S ratio,
- desulfurization degree.

Based on those data, and looking at the general behavior of coal and ash during combustion in bubbling fluidized bed, it is possible to **define concept of the BFBC boiler**, to choose main parameters and to calculate dimenssions of the furnace and capacity and dimensions of all auxiliary systems [11,12,16].

To evaluate, if those data can be used also for **CFBC boiler design**, let us compare and analyze combustion conditions in BFBC and CFBC boilers.

3. Comparison of the combustion conditions in BFBC and CFBC boilers

Differences in combustion conditions between BFBC and CFBC boilers are a consequence of different hydrodynamics - smaller inert material particle size, higher fluidization velocity, different particle concentration, different mixing in bubbling and circulating fluidized beds, and fuel particle circulation up to the total burn-up. Two important parameters for combustion process are the same: combustion temperature, and excess air. In Table 1 main parameters (dimensions, working parameters) defining combustion conditions in BFBC and CFBC boilers are compared.

During consideration and analysis of the data given in Table 1, it has to be pointed out the following:

- In both types of boilers, temperature in the bed is practically the same (800-850^{o}C), but in CFBC boilers it is constant along the furnace height, while in BFBC boilers large difference between bed and freeboard temperature can exists, due to the volatile combustion in freeboard.
- Fluidization velocity is greater in circulating fluidized bed, but relative gas-to fuel particle velocity is practically the same in both cases. So, conditions for convective heat and mass transfer between fuel particles and bed are not too much different.
- Mixing of fuel particles in fluidized bed, gas mixing and inert particle mixing are more intensive in circulating fluidized bed regime.

Table 1. Dimensions and working parameters of the BFBC and CFBC boilers

No	Parameter	Dim.	BFBC boiler	CFBC boiler	Remarks
1	Inert particle size	mm	1-2	0.15-0.25	
2	Fluidization velocity	m/s	1.0-3.0	6-10	
3	Fuel particle size	mm	0-50	0-25	
4	Temperature in the furnace	^oC	800-850 higher in freeboard	800-850	In CFBC boilers temperature does not change along furnace
5	Combustion conditions	-	stoichiometri c	in bottom bed sub-stoichiomet ric	above secondary air inlet stoichiometric in CFBC
6	Excess air	-	1.2-1.3	1.1-1.3	
7	Particle concentration	kg/m^3	in bed 1000 in freeboard 0.1	20-250	
8	Heat transfer coefficient	W/m^2K	in bed 400-650 in freeboard 50	120-250	Moderate changes along the furnace height in CFBC
9	Specific heat generation	MW_t/m^2	1-2	4-6.5	
10	Height of the furnace	m	20-30	40-50	
11	Fly ash recirculation ratio	kg/kg	2-3	-	related to the fuel flow rate
12	Specific mass flow rate of recirulating particles	kg/m^2s	-	10-40	
13	Molar Ca/S ratio	-	3-5	1-2	
14	Limestone particle size	mm	0.3-0.5	0.1-0.2	
15	Fuel particle residence time in the furnace	s	very long 1-10min	5-10 Only one pass through	Total burn-up in several passes

- Particle convection component of the heat transfer is higher in CFBC conditions.
- Height of the furnace in CFBC boilers is chosen to allow total burn-up of the tinniest fuel particles in one pass. Large particles circulate up to the total burn-up. Due to this fact, combustion efficiency is higher in CFBC boilers.
- Limestone particle size is smaller, specific surface available for reaction is greater, limestone particles circulate in the furnace permanently, so desulfurization degree is much more greater than in BFBC boilers.

- Due to the splitting between primary and secondary air, and substoichiometric conditions in bottom part of the furnace, conditions in bottom bed are similar to the conditions in BFBC. In spite of this fact, heat generation is almost uniform along the furnace height.
- For the same coal and the same limestone, SO_2 emission in CFBC boilers is less than in BFBC boilers.
- Due to the staged combustion NO_x emission in CFBC boilers is smaller than in BFBC boilers.
- As fly ash, only particles less than 75μm will leave cyclones. All other particles will be returned in the furnace. System for bed draining is inevitable in CFBC boilers.

It can be stated that combustion efficiency in CFBC boilers is greater, but SO_2 and NO_x emissions are smaller than in BFBC boilers. Heat generation is uniform, and ash accumulation in furnace is more intensive in CFBC than in BFBC boilers.

4. Is it possible to use results obtained in BFBC conditions for analysis of coal behavior in CBFC conditions?

Methodology ITE-IBK (and other similar) for fuel testing for BFBC is based on the investigation of coal combustion in laboratory size and pilot size BFBC furnaces. Methodology for fuel testing for CFBC should be based on the investigation of coal combustion in circulating fluidized bed conditions. As it was said, CBFC pilot size furnaces are expensive and does not exists in developing countries. The same situation is in Laboratory for Thermal Engineering and Energy Research, in VINCA Institute. In such situation, we have been pushed to think about transfer of data obtained in BFBC conditions to CFBC conditions.

Considering mentioned similarities and differences of the combustion conditions in BFCB and CFBC, the following conclusions can be formulated:

Sintering temperature and possibility that bed agglomeration occurs in FBC depends mainly on coal and ash characteristics and intensity of particle agitation in the bed. For the same coal, sintering in CFBC conditions is less probable than in BFBC. Also, local overheating due to the uneven coal distribution is less probable in CFBC conditions. Using sintering temperature obtained in BFBC, we are on the safe side.

Coal particle primary fragmentation mainly depend on bed temperature. Heat transfer intensity to coal particles is not so important. Primary fragmentation, if exists, will occur in bottom bed, in conditions very similar to bubbling fluidized bed. Critical diameter for primary fragmentation in CFBC and BFBC can be assumed as same.

Char combustion rate is not too much greater in CFBC conditions**.** Char combustion rate obtained in BFBC conditions can be used to recalculate combustion rate for CFBC conditions. If we use the BFB char combustion rate for calculation of the furnace height we will obtain something higher furnace, but higher combustion efficiency.

Start-up temperature obtained in BFBC conditions using criterion of "enough high char combustion rate" (as it is assumed in ITE-IBK Methodology [7,16]) can be used in CFBC conditions. The start-up period for CFBC boilers will be in this case shorter.

Distribution of heat generation along the height of the BFBC furnace depends greatly on coal rank (volatile matter content), char reactivity and particle size distribution. Significant part of heat can be generated in the freeboard for high volatile coals and for large amount of particles with size less than 1 mm.

In CFBC boilers heat generation along the furnace height is almost uniform. By experiments in pilot-size BFBC furnace, it is possible approximately to get amount of heat generated in bottom bed of the CFBC boiler, having also in mind that in bottom bed substoichiometric conditions prevail, and differences in fluidization velocities.

Ash splitting on bottom ash and fly ash, obtained in BFBC conditions, can be used to recalculate, considering ash particle size distribution, intensity of ash accumulation in bottom bed of the CFBC boiler. Also ash particle load in convective part of the boiler, and in bag-filters can be defined.

Combustion efficiency (in most cases one pass efficiency) obtained in pilot-size BFBC furnace will be obviously less that in CFBC boiler with the same coal. Cut-of size of hot cyclones can also give possibility to calculate combustion efficiency.

Limestone efficiency for sulfur capture obtained in BFBC conditions, as by ITE-IBK Methodology is proposed, will be significantly less than in CFBC boilers. Self sulfur capture by coal ash will be the same in both cases. On the bases of this fact, it can be concluded that, using the same limestone in CFBC, SO_2 emission will be less than obtained in pilot-size BFBC furnace.

NO_x emission in CFBC boiler will be lees that obtained in pilot-size BFBC furnace, due to the staged combustion and higher char hold-up in the furnace.

Based on given short analysis it can be concluded that data obtained by testing coal suitability for BFB combustion using ITE-IBK Methodology (or similar), it is possible to chose safely CFBC boiler concept and to calculate main parameters and dimensions of the furnace and auxiliary equipment. If we make errors, they will be on the safe side. CFBC boiler will have better regime characteristics than it was predicted, and may be will be a little more expensive than necessary.

In addition to this opinion, it can be mentioned, that CSIRO (Commonwealth Scientific and Industrial Research Organization), Division of Mineral and Process Engineering recommend for analysis of coal suitability for CFBC to use methodology similar to ITE-IBK Methodology, based also on experiments in small BFBC furnaces [6].

Energy and Environmental Research Center, University of North Dakota, USA, published the only methodology for fuel testing for CFBC [8]. This methodology uses CFBC pilot furnace $1MW_{th.}$ in power, but also a number of small BFBC experimental furnaces similar to those used in ITE-IBK methodology.

The answer for the question posed in the title of this paper is: Yes, we can use data obtained by fuel testing in BFBC conditions for conceptual design and calculation of regime parameters and dimensions of the CFBC bolier, but we have to bear in mind differences between conditions in BFBC and CFBC to make necessary corrections and recalculations. Most probably we will be on the safe side.

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